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GEOLOGICAL SURVEY OF CANADA
BULLETIN 567

FRASER RIVER DELTA, BRITISH COLUMBIA: ISSUES OF AN URBAN ESTUARY

Edited by
B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback

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Cover illustration

Aerial oblique view of a portion of the Fraser River delta intertidal estuary, showing a dyke with a roadway along the high-tide mark, farmland on the landward side of the dyke, urbanized forested uplands in the background, and mountains of the Cascadia range in the distance. Photograph by D.C. Mosher. GSC 2003-495

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SUMMARY

David C. Mosher

The papers in this bulletin derive from presentations made at a special session on issues of the Fraser River Estuary, part of a conference of the Pacific Section of the American Association for the Advancement of Science (AAAS). The special session was multidisciplinary in order to address the complexity of issues facing the Fraser River delta and estuary. The conference occurred in 1995; through a variety of circumstances, it has taken some time to produce this Bulletin. Although authors, as experts in their respective fields, may feel that the information they have presented is now dated, the issues remain relevant still. The papers in this volume are eclectic, to provide a sampling of issues surrounding the Fraser River delta. It is only through integrated scientific and social studies, such as those presented here, that we can minimize problems and maximize effective planning for stewardship and further development of the Fraser River delta. The editors would like to thank the authors for their patience in the production of this Bulletin.

Humankind has been attracted to river deltas throughout history. They are rich, fertile, and productive regions for hunting, fishing, and harvesting. They are also amenable to the establishment of transportation corridors, whether on land or on water (river or ocean), and are highly suited to the establishment of villages, towns, and cities because of the flat and level landscape, loose soil conditions, and ready availability of construction material (e.g. wood and aggregate). River deltas are also highly productive areas for flora and fauna, and are very dynamic hydrological and geological environments. As a consequence of these factors, the river delta is a geographic location where humans interact with and impact the natural environment more than anywhere else. The Fraser River delta is certainly no exception.

The Fraser River delta was a major centre of activity for First Nations people prior to the arrival of European settlers, and is now the focus of a population in excess of two million direct inhabitants, as well as a corridor of access to most of western Canada. In its short modern history, it has been affected dramatically by human activity. The focus of this volume is to discuss human impact on the Fraser River delta, and how the delta in turn impacts or has the potential to impact its human inhabitants.

Paper summaries

Geology and geography

In order to contextualize the discussion of issues concerning the inhabitation of the Fraser River delta and its environs, it is necessary to understand the geological development and present geological setting of the area. Groulx and Mustard provide an insightful overview. The first-order control on the geography is tectonics.

SOMMAIRE

David C. Mosher

Les articles dans ce volume tirent leur origine dans des exposés présentés à l'occasion d'une session spéciale sur les enjeux de l'estuaire du fleuve Fraser, dans le cadre d'une conférence de la section du Pacifique de l'American Association for the Advancement of Science (AAAS). Les responsables de cette session ont voulu lui donner un caractère multidisciplinaire, afin de traiter dans toute leur complexité les questions qui touchent le delta et l'estuaire du Fraser. La conférence a eu lieu en 1995; diverses circonstances ont toutefois retardé la production du présent bulletin. Si les auteurs, à titre d'experts dans leurs domaines respectifs, ont peut-être l'impression que l'information qu'ils ont présentée est maintenant dépassée, les enjeux qu'ils ont évoqués conservent toute leur pertinence. Le présent volume réunit des articles portant sur des sujets divers, dans le but de présenter un éventail d'enjeux relatifs au delta du Fraser. Ce n'est qu'au moyen d'études scientifiques et sociales intégrées, comme celles que nous présentons ici, que nous parviendrons à réduire les problèmes au minimum et à maximiser l'efficacité de la planification de l'intendance et du développement à venir du delta du Fraser. Les coordonnateurs de ce volume tiennent à remercier les auteurs de la patience dont ils ont fait preuve.

Tout au long de son histoire, l'humanité a été attirée par les deltas, qui sont des régions riches, fertiles et productives pour la chasse, la pêche, la cueillette et l'agriculture. En outre, ces régions se prêtent bien à l'établissement de voies de transport terrestre ou maritime (fleuve ou océan) et sont des endroits idéaux pour établir des villages et des villes, à cause de leur topographie plane et unie, de leurs sols meubles et de la disponibilité de matériaux de construction (p. ex. le bois et les granulats). Les deltas sont aussi des zones très productives en termes de faune et de flore, ainsi que des milieux hydrologiques et géologiques des plus dynamiques. Tous ces facteurs font des deltas des régions où, plus que partout ailleurs, les humains interagissent avec les milieux naturels et ont des impacts sur ces milieux.

Le delta du Fraser ne fait certes pas exception à la règle. Le delta du Fraser, qui était déjà un centre d'activité important pour les Premières nations avant l'arrivée des colons européens, rassemble aujourd'hui une population de plus de deux millions d'habitants, en plus de servir de corridor d'accès à la majeure partie de l'Ouest canadien. Pendant sa courte histoire moderne, il a été fortement touché par les contrecoups de l'activité humaine. Le présent volume traite des effets de l'activité humaine sur le delta du Fraser, et de la façon dont celui-ci à son tour influe ou pourrait influer sur ses habitants humains.

Sommaire des articles

Géologie et géographie

Pour mettre en contexte la discussion d'enjeux relatifs à l'occupation humaine du delta du Fraser et de ses environs, il faut comprendre le développement géologique de la région ainsi que son cadre géologique actuel. Groulx et Mustard présentent une vue d'ensemble riche d'enseignements. La tectonique exerce une influence de premier ordre sur la géographie. La région est située dans

The area lies within a tectonically active region, with the Juan de Fuca oceanic plate converging with and subducting beneath the North American plate at this location. The resulting tectonic forces are responsible for the construction of the Coast Range Mountains, which provide source sediment for the Fraser River, and of the Georgia Basin, into which the Fraser River flows and deposits its sediment load, forming the Fraser River delta. The second-order control on the geographic setting is glaciation. The area has been covered with ice sheets numerous times over the last few million years; the latest was the Cordilleran Ice Sheet during the Fraser Stade glacial epoch, between 25 000 and 10 000 years ago. These glaciers are responsible for sculpting the landscape, giving rise to the steep-walled Fraser River valley, and depositing thick layers of sediment on the valley floor and walls. Fluvial processes resulting from the flow of the Fraser River exert the third and most direct form of control on the development of the delta. The high flow velocity, water volume, and sediment load of the Fraser River as it merges with the Strait of Georgia have resulted in the formation of the modern Fraser River delta, creating more than 625 km^2 of new land within the Strait of Georgia in just the last 10 000 years.

The same geological forces that created the Fraser River delta also present significant potential hazards. Damaging earthquakes can result from the tectonic setting, and the steep terrain and soft soil conditions can result in landsliding and soil liquefaction. Mosher, Christian, Hunter, and Luternauer discuss potential geohazards associated with the region's high seismicity, and present a review of modern techniques used to identify and assess these risks. Their geotechnical data, in association with analysis of ground-surface responses from recent earthquakes, suggest that the top 10 to 20 m of sediment over much of the delta, on- and offshore, are susceptible to seismic liquefaction — leading to possible flowsliding — in the event of a significant earthquake (M>5.0). The region, nonetheless, is becoming highly developed, as communities such as Richmond, Delta, and Ladner grow along with supporting infrastructures that include highways, railways, and port facilities, to say nothing of the industries that the delta supports (e.g. farming, fishing, aggregate mining). These significant hazards must be considered during further development of the Fraser River valley and delta. Geological knowledge, therefore, plays an important role and should be considered as the first step toward informed and effective land-use decisions.

Kostaschuk and Luternauer address the issue of sedimentary processes in the river channels of the Fraser River estuary, and how they are linked to the transportation pathways of contaminants. In the main channel, sedimentary processes are controlled by river discharge and sediment load, by tidal conditions, and by the intrusion of salt water into the channel. During this past century, the river channels have been confined and therefore not allowed to migrate, as they are prone to do naturally. Sand is dredged from the river bed to maintain

une zone de grande activité tectonique où la plaque océanique Juan de Fuca rencontre la plaque nord-américaine et glisse sous celle-ci par subduction. Les forces tectoniques qui en résultent sont à l'origine de la chaîne Côtière, source de sédiments pour le fleuve Fraser, ainsi que du bassin de Géorgie, dans lequel le Fraser se jette et dépose sa charge de sédiments, formant ainsi le delta. La glaciation exerce une influence de second ordre sur la géographie. Au cours des quelques derniers millions d'années, la région a été recouverte plusieurs fois par des nappes glaciaires, la dernière ayant été l'Inlandsis de la Cordillère, au cours du stade glaciaire de Fraser, il y a de 25 000 à 10 000 ans. Ces glaciers ont sculpté le paysage, creusant la vallée aux parois escarpées et en couvrant le fond et les parois d'épaisses couches de sédiments. Les processus fluviaux résultant de l'écoulement du Fraser exercent la troisième forme d'influence, la plus directe d'ailleurs, sur le développement du delta. La rapidité du courant, l'important volume d'eau et l'énorme charge sédimentaire du Fraser à sa jonction avec le détroit de Georgia ont entraîné la formation du delta dans sa forme actuelle en créant plus de 625 km^2 de nouvelles terres dans le détroit de Georgia au cours des 10 000 dernières années seulement.

Les forces géologiques qui sont à l'origine du delta du Fraser sont aussi une source de risques considérables. Le cadre tectonique est susceptible de causer des tremblements de terre destructeurs; en outre, le terrain abrupt et le sol meuble sont favorables aux glissements de terrain et à la liquéfaction du sol. Mosher, Christian, Hunter et Luternauer examinent les risques posés par la forte sismicité de la région et présentent un survol des techniques modernes qui servent à identifier et à évaluer ces risques. Leurs données géotechniques, ainsi que l'analyse des mouvements du sol liés aux tremblements de terre récents, suggèrent que la couche sédimentaire de 10 à 20 m d'épaisseur qui recouvre une grande partie du delta, sur terre comme au large, est susceptible à la liquéfaction — pouvant entraîner des glissements — dans l'éventualité d'un tremblement de terre important (M>5,0). La région se développe toutefois de plus en plus : la croissance de collectivités comme Richmond, Delta et Ladner s'accompagne de l'expansion des infrastructures de soutien, notamment les routes, les chemins de fer et les installations portuaires, sans parler des industries soutenues par le delta (p. ex. l'agriculture, la pêche, l'extraction de granulats). Il faudra tenir compte de ces risques importants au cours du développement futur de la vallée et du delta du Fraser. Les connaissances géologiques jouent donc un rôle de premier plan; il faut les considérer comme point de départ si on veut en arriver à des décisions éclairées et efficaces quant à l'utilisation du territoire.

Kostaschuk et Luternauer discutent des processus sédimentaires qui prennent place dans les chenaux de l'estuaire du Fraser, et des liens entre ces processus et les voies de transport des contaminants. Dans le chenal principal, les processus sédimentaires sont régis par le débit et la charge solide du fleuve, par les marées et par l'intrusion de l'eau salée. Au cours du dernier siècle, on a confiné les chenaux fluviaux, ce qui les a empêchés de migrer comme ils ont tendance à le faire naturellement. On retire du sable du lit fluvial par dragage afin de préserver les voies de navigation et d'obtenir des granulats pour la construction. Le confinement et le dragage ont pour effet de navigation channels and to supply construction aggregate. The effect of this containment and dredging is to channelize flow and confine sand movement to a narrow corridor, resulting in sediment deposition at the river mouth. This accumulation eventually fails through mass-transport processes, and slides down the foreslope of the delta into the deep water of the Strait of Georgia. Sand that once replenished sediment removed by coastal erosion of the tidal flats is now lost to deep water. This loss of sediment affects intertidal habitat and may increase slope erosion elsewhere on the delta.

canaliser l'écoulement et de limiter le mouvement du sable à un étroit corridor, ce qui entraîne le dépôt de sédiments à l'embouchure du fleuve. Les matériaux accumulés finissent par glisser, par des processus de mouvement de masse, le long de la pente frontale du delta jusque dans les eaux profondes du détroit de Georgia. Le sable qui remplaçait autrefois les sédiments enlevés par l'érosion côtière des bas-fonds intertidaux se perd maintenant en eau profonde. Cette perte de sédiments se répercute sur l'habitat intertidal et risque d'accélérer l'érosion des pentes ailleurs dans le delta.

Wildlife habitat

Adams and Williams, Harrison and Dunn, and Levings examine the impact of loss and protection of habitat on fauna in the Fraser River estuary. Many species use multiple habitats to complete their life cycle, making the definition of species-specific critical habitats exceedingly complex. Underscoring this complexity is an understanding that there currently is relatively little investment in research to document the dynamics of change in these biophysical regions. Other major estuaries on the west coast of North America have had the benefit of far more ecological research and monitoring.

Subtidal, intertidal, and even agricultural areas sustain important habitat for fish and wildlife. Salinity and tidal inundation, related to the location of the salt wedge within the estuary, govern the distribution of plant species (and hence animal species) within these regions. Distinct salt-, brackish-, and freshwater species assemblages occur throughout the estuary as a result of these influences. In recent history, tidal regions have been subjected to sediment starvation and erosion through removal of sediment supply and construction of infrastructures on the tidal flats; intertidal regions have been modified through dyke construction; wetland areas in the Fraser Lowland have been reduced to about one quarter of their original extent in this past century through infilling and irrigation; and farmland has been under constant urban-development pressure. Extraction of fresh water for irrigation has allowed the salt wedge to drive further inland than previously experienced.

The impacts of urbanization are not always negative, however. Infrastructures such as the Vancouver Deltaport and the British Columbia Ferry Corporation terminal have affected the region profoundly; nonetheless, the seagrass beds of southern Roberts Bank, Boundary Bay and Semiahmoo Bay have expanded in recent decades due to improved growing conditions and the introduction of dwarf eelgrass. The habitat appears resilient to many environmental changes. The eelgrass regions support a diversity of wildlife, in particular waterfowl.

Habitat faunique

Adams et Williams, Harrison et Dunn, puis Levings examinent les effets de la perte et de la protection des habitats sur la faune de l'estuaire du Fraser. Beaucoup d'espèces fréquentent plusieurs habitats au cours de leur cycle de vie, ce qui rend extrêmement complexe la définition des habitats essentiels particuliers à chaque espèce. Cette complexité est accentuée par le fait qu'il y a relativement peu d'investissement dans la recherche visant à documenter la dynamique du changement dans ces régions biophysiques. D'autres grands estuaires de la côte ouest de l'Amérique du Nord ont bénéficié de recherche et de surveillance écologiques beaucoup plus poussées.

Les régions subtidales, intertidales et même agricoles renferment des habitats essentiels pour la faune. La salinité et l'inondation due à la marée, qui sont liées à la position du coin salé dans l'estuaire, régissent la répartition des espèces végétales (et donc celle des espèces animales) dans ces régions. Ces influences donnent lieu à des assemblages distincts d'espèces d'eau salée, saumâtre ou douce dans différentes parties de l'estuaire. Dans le passé récent, les régions intertidales n'ont reçu qu'une faible sédimentation et se sont érodées, suite à l'élimination de l'apport sédimentaire et à la construction d'infrastructures sur les bas-fonds intertidaux; les régions intertidales ont été modifiées par la construction de digues; la superficie des milieux humides des basses terres du Fraser a au cours du dernier siècle été réduite des trois quarts par le remplissage et l'irrigation; et les terres agricoles ont constamment subi la pression du développement urbain. L'extraction de l'eau douce pour l'irrigation a permis au coin salé de se déplacer plus loin que jamais vers l'intérieur des terres.

Les effets de l'urbanisation ne sont cependant pas toujours négatifs. Des infrastructures telles que le Deltaport de Vancouver et la gare maritime de la British Columbia Ferry Corporation ont eu des impacts profonds sur la région; néanmoins, les herbiers marins du sud du banc Roberts, de la baie Boundary et de la baie Semiahmoo gagnent en superficie depuis quelques décennies à cause de l'amélioration des conditions de croissance et de l'introduction de l'espèce *Zostera japonica*. L'habitat semble résister à bien des changements environnementaux. Les régions où poussent les zostères servent d'habitat à une faune variée, dont notamment des oiseaux aquatiques.

Pollution and contamination

Many organic and inorganic contaminants are adsorbed onto mud particles that are transported in suspension and deposited within the estuary and in the Strait of

Pollution et contamination

De nombreux contaminants organiques et inorganiques sont adsorbés sur les particules de boue qui sont transportées en suspension et se déposent dans l'estuaire et dans le détroit de Georgia; ce sujet est

Georgia; this topic is addressed by Vingarzan and Sekela, and by Bendell-Young and others. The input of contaminants at any point along the river is of concern, as they can be eventually transported and deposited in the estuarine sediments. Sources of organic contaminants include pulp-and-paper mills, municipal wastewater-treatment facilities, urban runoff, sawmills, wood-treatment facilities, agricultural runoff, and aerial deposition. Dioxins, furans, chlorophenolics, and resin acids were found in higher concentrations at sites up to 300 km downstream of pulp-and-paper mills than at unaffected reference sites. Seasonal hydrological changes clearly influenced contaminant concentrations, however. Levels of dioxins and furans were found to have decreased dramatically since the implementation of abatement measures at the mills, and none of the contaminants were found to exceed federal water-quality guidelines or provincial criteria for the protection of aquatic life.

Bendell-Young and others are particularly concerned with the biogeochemistry of the intertidal mud flats of the Fraser River delta. Specific areas within the intertidal region have been subjected to point sources of pollution, such as the Iona Island sewage treatment plant, which have introduced trace metals and organic contaminants into these highly productive regions. It is imperative to obtain a good understanding of the biogeochemical processes that occur within these intertidal regions in order to appreciate the long-term effects of the introduction of these pollutants. Brand and Thompson attempt to investigate the effects of pollutants through toxicological studies of fish and invertebrates in the Fraser River estuary. They focus their investigations on several 'indicator' species in which toxicological effects can be observed and identified. Local effects of pollution appear in the invertebrate community as changes in species diversity or as shifts to more pollution-tolerant species. Several fish species, such as bottom-feeding flat fish, are exposed to a variety of sediment-bound contaminants, either by direct contact or through consumption of contaminated food organisms. Biomarkers such as detoxification enzymes, bile metabolites, and precancerous and/or cancerous lesions have been found in these fish in the estuary.

As with any urban centre, significant human health-care issues arise as a result of urbanization and of the quality of the community's health-care infrastructure. Hertzman points out that two of the more significant health hazards associated with urbanization are exposure to lead among children and threats to respiratory health from particulate air pollution. Exposure to lead has been significantly reduced since regulations were employed to eliminate the addition of lead to gasoline. Air pollution, however, continues to be a health concern. Jackson examines atmospheric impacts of urbanization in the Lower Mainland. When humans alter a natural landscape into an urbanized one, a number of atmospheric environmental impacts result. Perhaps the most potentially serious of these is air pollution. Among the

traité par Vingarzan et Sekela, ainsi que par Bendell-Young et d'autres. Quel que soit le point d'entrée des contaminants dans le fleuve, leur présence porte à l'inquiétude, car ils peuvent finir par se déplacer et se déposer dans les sédiments estuariens. Les principales sources de contaminants organiques sont les usines de pâtes et papiers, les installations municipales de traitement des eaux usées, le ruissellement urbain, les scieries, les installations de traitement du bois, le ruissellement agricole et le dépôt par voie atmosphérique. Jusqu'à 300 km en aval des usines de pâtes et papiers, on a trouvé des dioxines, des furanes, des dérivés chlorophénoliques et des acides résiniques en concentrations plus élevées que dans des lieux de référence non touchés. Les variations hydrologiques saisonnières ont cependant une influence évidente sur la teneur en contaminants. On a constaté que la teneur en dioxines et en furanes avait beaucoup diminué depuis la mise en œuvre de mesures de dépollution dans les usines; par ailleurs, aucun contaminant n'est présent en concentrations supérieures aux valeurs seuils indiquées par les directives fédérales sur la qualité de l'eau ou par les critères provinciaux pour la protection de la vie aquatique.

Bendell-Young et d'autres se préoccupent particulièrement de la biogéochimie des vasières intertidales du delta du Fraser. Des secteurs spécifiques de la zone intertidale ont subi l'influence de sources ponctuelles de pollution, telles que l'usine de traitement des eaux usées de l'île Iona, qui ont introduit des métaux à l'état de traces et des contaminants organiques dans ces régions très productives. Il est impératif de bien comprendre les processus biogéochimiques qui s'opèrent dans ces régions afin d'évaluer les effets à long terme de l'introduction de ces polluants. Brand et Thompson tentent d'établir les effets des polluants par l'étude toxicologique de poissons et d'invertébrés de l'estuaire du Fraser. Leur recherche se concentre sur plusieurs espèces indicatrices chez lesquelles des effets toxicologiques peuvent être observés et identifiés. Les effets locaux de la pollution se manifestent dans la communauté des invertébrés par des variations de la diversité des espèces ou par le remplacement de certaines espèces par d'autres plus tolérantes à la pollution. Plusieurs espèces de poissons, notamment les poissons plats qui se nourrissent sur le fond, sont exposées, soit par contact direct ou par la consommation d'organismes contaminés, à divers contaminants liés aux sédiments. Dans l'estuaire, on a trouvé des biomarqueurs tels que des enzymes de détoxification, des métabolites de la bile et des lésions précancéreuses ou cancéreuses chez ces espèces.

Comme dans tout centre urbain, l'urbanisation et la qualité de l'infrastructure communautaire des soins de santé peuvent être à l'origine d'importants problèmes de santé humaine. Hertzman signale que l'exposition des enfants au plomb et la menace que pose la pollution par les matières en suspension sont deux des plus importants dangers pour la santé qui accompagnent l'urbanisation. L'exposition au plomb a diminué considérablement depuis que des règlements ont éliminé l'ajout de plomb à l'essence. La pollution atmosphérique demeure toutefois préoccupante pour la santé. Jackson examine les effets atmosphériques de l'urbanisation de la région du delta. Lorsque l'on urbanise un milieu naturel, il en résulte un certain nombre d'effets environnementaux sur l'atmosphère, dont la pollution est peut-être le plus sérieux. Parmi les composantes de la « soupe chimique » en suspension au-dessus de la région du delta du Fraser, l'ozone et les particules inhalables sont celles qui portent le 'chemical soup' that hangs over the Fraser River delta region, people are most concerned about ozone and inhalable particulates because of their effects on the ecosystem (ozone primarily) and on human health (ozone and particulates). Steps being taken by the regional government should reduce or at least stabilize air-pollution levels in the region.

plus à l'inquiétude, à cause de leurs effets sur l'écosystème (surtout l'ozone) et sur la santé humaine (l'ozone et les particules). Les mesures prises par l'administration régionale devraient réduire, ou tout au moins stabiliser, le niveau de pollution atmosphérique dans la région.

Climate

Extreme climatic events make the low-elevation regions of the Fraser River delta susceptible to flooding, as noted by Woods in this volume. The Fraser River, with a drainage basin encompassing some 233 000 km^2, is the largest river in British Columbia. Depending on ground elevation and on location along the river, flooding of the estuary and delta can be caused by winter storm surges originating from the Strait of Georgia, and/or by high spring-freshet flows on the Fraser River. As well, heavy fall and winter rainfalls, exacerbated by poor drainage and high tide levels, combine to cause high water tables and overland flows within dyked areas. Significant and damaging floods occurred in 1894, 1948, and 1969. The delta is presently surrounded by a system of dykes and pumping stations, to protect the emergent areas from river floods and storm surges with wave runup. It must be noted that many of these dykes and facilities predate building codes and were not constructed to withstand earthquake forces.

Current issues relating to flood control include the maintenance of works in light of changing public priorities and of environmental conflict. Future consideration could be given to upgrading existing works to higher standards, justified by the rapidly increasing population and development levels in the affected areas. Specifically, upgrades should address the effects of sedimentation, earthquakes, relative sea-level changes, and possible changes in climatic conditions.

Climate significantly affects the diversity and abundance of flora and fauna and the biomass productivity in the Fraser River delta and surrounding area. It also is a factor attracting humans to the region as a place to live. Jackson summarizes the characteristics of the local climate and the physiographic features most important in modulating the weather and climate, ranging from large-scale to small-scale effects. The ocean, mountains, valleys, and urbanization all contribute to creating unique and locally variable climate characteristics. For example, the city of Vancouver can experience temperatures 7°C higher than rural areas, due to the urban heat-island effect, and the nearby mountains can experience three times the precipitation of the adjacent lowlands. These variations, combined with spatial variations in ground materials, have a significant influence on the ecology of the region and on the potential impact of humans.

Climat

Les basses terres du delta du Fraser sont susceptibles d'être inondées si des phénomènes climatiques extrêmes se produisent, comme le remarque Woods dans le présent volume. Le Fraser, dont le bassin hydrographique couvre environ 233 000 km^2, est le plus important cours d'eau en Colombie-Britannique. Les inondations de l'estuaire et du delta peuvent, selon l'altitude et la position le long du fleuve, être causées par les ondes de tempête qui prennent naissance dans le détroit de Georgia ou par le débit élevé dû aux crues printanières du Fraser. En outre, les fortes pluies automnales et hivernales, conjuguées au drainage médiocre et au haut niveau des marées, causent l'élévation de la surface des nappes d'eau souterraines et l'inondation des zones endiguées. Des inondations importantes et destructrices se sont produites en 1894, en 1948 et en 1969. Le delta est maintenant entouré d'un ensemble de digues et de stations de pompage destinées à protéger les zones émergentes des crues du fleuve et des ondes de tempête avec jets de rive. Il est à noter que la construction de bon nombre de ces digues et installations de pompage est antérieure à l'instauration des codes du bâtiment, et qu'elles n'ont pas été conçues pour résister aux tremblements de terre.

Une des questions d'actualité par rapport à la lutte contre les inondations a trait à l'entretien des ouvrages compte tenu de l'évolution des priorités gouvernementales et des conflits reliés à l'environnement. On pourrait envisager de moderniser les ouvrages existants en fonction de normes plus strictes, ce que justifie l'ampleur de la croissance démographique et du développement dans les zones touchées. Plus particulièrement, la modernisation devrait prendre en compte les effets de la sédimentation, des tremblements de terre, des variations relatives du niveau de la mer et d'éventuels changements climatiques.

Le climat a un effet important sur la diversité et l'abondance de la faune et de la flore et sur le rendement en biomasse dans le delta du Fraser et la région environnante. En outre, c'est l'un des éléments qui incitent les gens à s'installer dans la région. Jackson résume les caractéristiques du climat local et de la topographie qui contribuent le plus à moduler le temps et le climat, et en dégage les effets à grande et petite échelle. L'océan, les montagnes, les vallées et l'urbanisation contribuent tous à créer des conditions climatiques uniques qui varient à l'échelle locale. Par exemple, la température à Vancouver peut dépasser de 7 °C celle des régions rurales, en raison de l'effet d'îlot de chaleur qu'exerce la ville, et il arrive que les montagnes environnantes reçoivent une précipitation trois fois plus abondante que les basses terres adjacentes. Ces variations, ainsi que les variations spatiales des matériaux du sol, exercent une nette influence sur l'écologie de la région et sur les effets éventuels de l'activité humaine.

The supply of fresh water is also critical to the flora and fauna of the Fraser Lowland (including humans, of course). Typically, there is a surplus of precipitation in winter (December through April), and a shortage in summer as evaporation exceeds precipitation. Paving of natural surfaces dramatically alters the hydrology of an urban area, causing increased runoff and alteration or removal of natural watercourses. In addition, farming irrigation and other anthropogenic uses of water further draw down the water table in summer, allowing salt water from the adjacent Strait of Georgia to penetrate further beneath the delta and potentially contaminate water supplies.

The climate further ensures that the Fraser River delta is rich in ecological diversity, as discussed by Schaefer. The region sustains abundant marshes, old fields, bogs, and agricultural land, which are interconnected with surrounding marine ecosystems and with the urban forests of Vancouver to the north and of the Surrey uplands to the south. As a consequence, the delta is of global significance as a major stopover point for migrating birds along the Pacific Flyway and as a vital support to the salmon runs of the Fraser River. Natural ecosystems of the delta, however, have been significantly degraded and continue to be threatened by urbanization and population growth. Several major short- and long-term programs are in place to restore and manage several of the affected areas.

'What will be the effects of a changing climate on the Fraser River estuary?' is the question addressed by Taylor. Rising concentrations of greenhouse gases threaten to increase the average global temperature and total precipitation. Unchecked, the atmospheric concentration of carbon dioxide will have doubled relative to pre-industrial times within the next 50 to 80 years. This increase may cause regional climate patterns and sea level around the world to change substantially. The magnitude and timing of these regional climate changes can only be estimated, making it difficult to accurately predict how physical and biological systems will change in the Fraser River delta or anywhere else in the world. Responses could range from a substantial rise in sea level, which could threaten the dyking systems of the Fraser River delta, to increased immigration pressure on the Fraser River delta from environmental refugees fleeing climate-change-ravaged homelands outside Canada. Knowledge of the potential changes that might put pressure on the Fraser River delta will be useful in planning the development of the delta for the future.

Trade and commerce

Indigenous people inhabited the fertile Fraser River valley for perhaps as much as 9000 years before the arrival of European settlers. Kew provides a brief history of the first towns of the Fraser estuary, occupied by the First Nations Halkomelem society of the Coast Salish Culture.

L'approvisionnement en eau douce est également d'une importance cruciale pour la faune et la flore des basses terres du Fraser (y compris les humains, bien entendu). En général, on observe un surplus de précipitation en hiver (de décembre à avril) et une pénurie en été, alors que la perte en eau due à l'évaporation excède l'apport en eau des précipitations. Le revêtement des surfaces naturelles a un effet énorme sur l'hydrologie des zones urbaines, puisqu'il entraîne un ruissellement accru et la modification ou la suppression des cours d'eau naturels. En outre, l'irrigation agricole et les autres utilisations anthropiques de l'eau abaissent encore plus la surface de la nappe d'eau souterraine en été, ce qui permet à l'eau salée du détroit de Georgia de pénétrer plus avant sous le delta, voire de contaminer les réserves d'eau.

Le climat assure également au delta du Fraser sa riche diversité écologique, comme l'explique Schaefer. La région abonde en marais, vieux champs, tourbières et terres agricoles, tous reliés aux écosystèmes marins environnants ainsi qu'aux forêts urbaines de Vancouver (au nord) et à celles des hautes terres de Surrey (au sud). Grâce à cette richesse, le delta revêt une importance mondiale en tant que halte pour les oiseaux migrateurs qui empruntent la voie migratoire du Pacifique, ainsi qu'en raison du soutien vital qu'il apporte aux migrations des saumons sur le Fraser. Cependant, les écosystèmes naturels du delta se sont sensiblement dégradés et sont toujours menacés par l'urbanisation et la croissance démographique. De grands projets de restauration et de gestion à court ou long terme sont en place dans plusieurs des zones touchées.

Quels effets l'évolution du climat aura-t-elle sur la région de l'estuaire du Fraser? Voilà la question dont traite Taylor. L'accroissement des concentrations de gaz à effet de serre risque de provoquer une élévation de la température moyenne du globe, ainsi qu'une augmentation de la précipitation totale. Sans intervention, la concentration atmosphérique de dioxyde de carbone sera d'ici 50 à 80 ans le double de ce qu'elle était avant la révolution industrielle. Cette hausse pourrait provoquer des modifications importantes du régime climatique et du niveau de la mer partout dans le monde. On ne peut qu'estimer l'ampleur et la chronologie des éventuels changements climatiques régionaux, ce qui complique la tâche de prévoir avec exactitude l'évolution des systèmes physiques et biologiques dans la région du delta ou ailleurs au monde. Les conséquences possibles vont d'une élévation substantielle du niveau de la mer, susceptible de menacer les systèmes d'endiguement du delta du Fraser, à l'accroissement de la pression d'immigration exercée sur le delta par des réfugiés environnementaux fuyant des pays ravagés par les changements climatiques. La connaissance des changements éventuels qui pourraient exercer des pressions sur le delta du Fraser sera utile à la planification du développement de la région.

Échange et commerce

À l'arrivée des premiers colons européens, des peuples autochtones habitaient déjà la vallée fertile du Fraser depuis peut-être bien 9 000 ans. Kew présente un bref historique des premiers villages de la région de l'estuaire, occupés par la société Halkomelem des Premières nations, une représentante de la culture salish du littoral.

The Fraser River and adjacent Strait of Georgia served as a transportation corridor for aboriginal people, and thus the Fraser River delta was a meeting place and trade centre for many of the indigenous communities of southwestern British Columbia and of the Pacific Northwest. The indigenous people of the Fraser Lowland had a highly evolved societal structure and infrastructure that survived for thousands of years. Their societal infrastructure was analogous in many aspects — industry, trade and commerce, leadership, and housing — to that of the modern civilization at this site. The First Nations' long history of stable and bountiful use of the land can serve as an example to focus thinking about the underpinning concepts of sustainability. Kew emphasizes that in order for our modern culture and society to sustain itself, we must understand that humans are an integral component of the ecological system, much as the First Nations societies did.

As the Fraser Lowland was a centre of trade and commerce for aboriginal people in centuries past, in these modern times it has become a centre for global trade and commerce. Davis and Hutton explain how the Greater Vancouver Regional District is a critical economic gateway to Pacific Rim nations. During the twentieth century, this region evolved from a centre of administrative, distributive, and commercial services for the province into a gateway for the increasingly integrated network of urban economies on the Pacific Rim. Two related phenomena have been central to this transformation: a restructuring of the metropolitan economy and a reorientation of the economy's export markets. The restructuring of the Vancouver economy has resulted primarily from a shift of the region's employment from extractive (agriculture, mining, forestry, and fishing) and manufacturing activities to service activities. This shift has resulted in the rise to dominance of producer services: those professional and technical services (e.g. engineering, telecommunications, and management consulting) that are information-intensive and require a highly skilled labour force. As producer services become increasingly valued in global markets, their exportation from the region continues to expand. The most rapidly growing markets for these exports are located on the Pacific Rim. Links with the Pacific Rim include travel and tourism, immigration, finance and investment, and a growing Asian social and cultural orientation within the metropolitan region.

Management and sustainability

Integration of all of the above-mentioned issues, sometimes with competing or incompatible interests, is a complex problem in management. Dorcey places this management issue in the context of FREMP, the Fraser River Estuary Management Program. This body facilitates co-ordination among the activities of more than one hundred different agencies in implementing the Estuary Management Plan established for the Fraser

Le fleuve Fraser et le détroit de Georgia dans lequel il se jette servaient de corridor de transport aux peuples autochtones; le delta du Fraser était donc un lieu de rencontre et d'échange pour bon nombre de communautés autochtones du sud-ouest de la Colombie-Britannique et du Nord-Ouest de la côte du Pacifique. Les Autochtones des basses terres du Fraser avaient une structure et une infrastructure sociales très évoluées, qui ont survécu pendant des millénaires. Leur infrastructure sociale était analogue sous bien des aspects — industrie, échange et commerce, leadership, logement — à celle de la civilisation qui occupe aujourd'hui cette région. La longue histoire de l'utilisation durable d'une terre généreuse par les Premières nations peut servir d'exemple pour aider à réfléchir aux concepts fondamentaux de la durabilité. Comme le souligne Kew, pour que notre culture et notre société modernes puissent perdurer, nous devons comprendre, comme les sociétés des Premières nations, que les humains font partie intégrante du système écologique.

Tout comme les basses terres du Fraser étaient un centre d'échange et de commerce pour les Autochtones des siècles passés, elles sont aujourd'hui un centre de commerce international. Davis et Hutton expliquent le rôle essentiel que joue le District régional de Vancouver en tant que point d'accès aux pays côtiers du Pacifique. Au cours du vingtième siècle, cette région s'est transformée d'un centre provincial de services administratifs, de services commerciaux et de services de distribution en un point d'accès au réseau de plus en plus intégré des économies urbaines du littoral du Pacifique. Deux phénomènes connexes sont au cœur de cette transformation : la restructuration de l'économie métropolitaine et la réorientation des marchés d'exportation. La restructuration de l'économie vancouvéroise résulte principalement d'un déplacement d'emplois dans la région depuis des activités d'extraction (agriculture, mines, forêts et pêches) et de fabrication vers des activités de service. Ce déplacement a eu pour effet la domination progressive des services à la production, soit les services professionnels et techniques (p. ex. le génie, les télécommunications et les services conseils en gestion) à forte composante d'information qui nécessitent une main-d'œuvre hautement qualifiée. Comme les services à la production acquièrent de plus en plus de valeur sur les marchés mondiaux, leur exportation à partir de la région poursuit sa croissance. Les marchés d'exportation qui connaissent l'essor le plus rapide dans ce domaine sont situés sur le littoral du Pacifique. Les principaux liens entre la région de Vancouver et le littoral du Pacifique sont les voyages et le tourisme, l'immigration, la finance et les placements, ainsi que l'orientation sociale et culturelle du Grand Vancouver, qui se tourne de plus en plus vers l'Asie.

Gestion et durabilité

L'intégration de tous ces enjeux, aux intérêts parfois concurrents ou incompatibles, est un problème de gestion fort complexe. Dorcey situe ce problème dans le contexte du programme de gestion de l'estuaire du fleuve Fraser (Fraser River Estuary Management Program). Cette initiative facilite la coordination des activités de plus d'une centaine d'organismes pour la mise en œuvre du plan de gestion de l'estuaire du Fraser, qui a pour but d'améliorer la qualité

River estuary. The goal of the plan is to improve environmental quality in the Fraser River estuary while providing economic development opportunities and sustaining the quality of life in and around the estuary.

Management of the Fraser River estuary is not simply a scientific problem; it involves the legal community as well, especially with respect to resolving issues involving competing interests. Paisley presents a paper that describes the legal framework for Fraser River estuary governance and analyzes the role of laws and of the legal system in the conservation and protection of the natural resources of the Fraser River estuary, in particular the Pacific salmon resource. He concludes that there needs to be a great deal more emphasis on compliance, enforcement, the creative utilization of scientific information in environmental decision-making, and the harnessing of market forces in order for the resources of the Fraser River estuary to be sustainable in the twenty-first century.

The intent of sound management practice for the Fraser River estuary is ultimately to allow the numerous stakeholders, including the natural environment, to coexist in a sustainable way. Since the Lower Mainland of British Columbia was first settled, it has been altered by development for human purposes, largely in an unsustainable way. Mooney examines a landscape ecological model of sustainability for the Fraser River estuary, compares it with the current compartmentalization model of development, and proposes that the landscape ecological model and the concept of diversity in landscape planning and development provide a basis for achieving sustainable land use. Perhaps we should apply the lessons of the First Nations people and provide sound stewardship of the natural environment so that we may live in harmony with it and reap benefits from it for the centuries to come.

In the final paper in this bulletin, Woollard and Rees attempt to come to terms with the definition of sustainability and question the role of science in addressing the complex issues surrounding threats to the environment and environmental degradation in the Fraser River estuary. They argue that the key to sustainability lies in our ability to build robust cross-linkages between science and other intellectual traditions and the humanities, to build bridges that will allow us to better understand our collective values, better apply our knowledge-gathering and -disseminating tools, better understand the ecological consequences of human action, and better assist our political and social structures in acquiring the knowledge required for taking wise action.

de l'environnement tout en offrant des perspectives de développement économique et en aidant à maintenir la qualité de la vie dans l'estuaire et la région environnante.

La gestion de l'estuaire du Fraser ne se résume pas à un problème scientifique; elle met également en jeu la communauté juridique, notamment en ce qui concerne le règlement de conflits entre intérêts concurrents. Dans son article, Paisley décrit le cadre juridique de l'intendance de l'estuaire du Fraser et analyse le rôle des lois et du système juridique dans la conservation et la protection des ressources naturelles de l'estuaire du Fraser, tout particulièrement le saumon du Pacifique. Il conclut qu'il faudra mettre beaucoup plus d'accent sur l'observation et l'application de la loi, l'utilisation créative d'information scientifique pour la prise de décisions relatives à l'environnement, et la mise en oeuvre des forces du marché afin d'assurer la durabilité des ressources de l'estuaire du Fraser au XXI[e] siècle.

Le but ultime des pratiques de saine gestion pour l'estuaire du Fraser est de permettre aux nombreux intéressés, y compris le milieu naturel, de coexister d'une façon durable. Depuis l'arrivée des premiers occupants dans la vallée du bas Fraser, cette région a été modifiée, en grande partie de façon non durable, par le développement effectué en fonction des humains. Mooney examine un modèle de durabilité fondé sur des principes d'écologie du paysage pour la région de l'estuaire du Fraser, le compare au modèle de développement actuel, qui est fondé sur des principes de compartimentation, et propose comme bases pour l'utilisation durable du territoire l'adoption du modèle fondé sur l'écologie du paysage et l'incorporation de la notion de diversité dans la planification et le développement du paysage. Nous devrions peut-être suivre les leçons des Premières nations et assurer une judicieuse intendance à notre milieu naturel, de manière à pouvoir vivre en harmonie avec ce dernier et en tirer avantage pour les siècles à venir.

Dans le dernier article de ce bulletin, Woollard et Reese tentent de cerner le concept de durabilité et mettent en question le rôle de la science dans la réponse aux problèmes complexes posés par la dégradation environnementale et les risques pour l'environnement dans la région de l'estuaire du Fraser. Les auteurs soutiennent que la clé de la durabilité consiste à tisser des liens solides entre les sciences naturelles et autres traditions intellectuelles, d'une part, et les sciences humaines, d'autre part; de construire des ponts qui nous permettront de mieux comprendre nos valeurs collectives, mieux utiliser les outils dont nous disposons pour recueillir et disséminer l'information, mieux comprendre les conséquences écologiques de nos actions, et mieux aider nos structures politiques et sociales à acquérir les connaissances requises pour agir de façon judicieuse.

Understanding the geological development of the Lower Mainland: the first step to informed land-use decisions

Bertrand J. Groulx[1] and Peter S. Mustard[2]

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Abstract: The landscape of the Lower Mainland has been shaped by tectonic, glacial, and fluvial processes. The tectonic process of oceanic crust subducting beneath continental crust poses a threat of damaging earthquake and associated hazards such as soil liquefaction and slope failures. Past glaciers have sculpted the landscape into steep-walled valleys and deposited thick layers of sediment. These steep slopes are potential sites of mass movements of soil and rock that threaten transportation corridors in the eastern Fraser River valley and along Howe Sound. Thick sediments deposited by glaciers contain valuable groundwater aquifers and accommodate development with limited hazards. River deposits have created more than 625 km^2 of new land at the mouth of the Fraser River in just the last 10 000 years. The low elevation and physical properties of these young, river-deposited sediments make them prone to flooding, liquefaction during an earthquake, and submarine slides on the delta slope.

Résumé : Le paysage de la vallée du bas Fraser a été formé par des processus tectoniques, glaciaires et fluviaux. Le processus tectonique de subduction de la croûte océanique sous la croûte continentale pose la menace d'un tremblement de terre destructeur, ainsi que des risques connexes tels que la liquéfaction du sol et les ruptures de versants. Les glaciers du passé ont sculpté le paysage en vallées aux parois escarpées et y ont déposé d'épaisses couches de sédiments. Ces pentes abruptes sont des sites possibles de mouvements de masse du sol et des roches, qui menacent les voies de transport dans la partie est de la vallée du Fraser et le long de la baie Howe. Les épaisses accumulations de sédiments déposés par les glaciers renferment de précieux aquifères et permettent au développement de se produire sans risque important. Les dépôts du fleuve ont créé plus de 625 km^2 de nouvelles terres à l'embouchure du Fraser au cours des 10 000 dernières années seulement. La faible altitude et les propriétés physiques de ces jeunes sédiments déposés par le fleuve les prédisposent aux inondations, à la liquéfaction en cas de tremblement de terre et aux glissements sous-marins sur le front du delta.

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SETTING OF THE LOWER MAINLAND

The Lower Mainland of southwestern British Columbia includes metropolitan Vancouver, the Fraser Lowland consisting of the Fraser River delta and estuary, and the low-elevation land of the Fraser River valley lying east of the town of Mission, as well as the surrounding mountainous regions (Fig. 1). It is Canada's third largest urban region, containing one-half of British Columbia's population. Settlement has concentrated in the Fraser Lowland, bounded by the Coast Mountains to the north, the Cascade Mountains to the east, the Chuckanut hills to the south, and the Strait of Georgia to the west (Fig. 1). The area has been inhabited by native communities for at least 9000 years (*see* Kew, 2004) and was first visited by Europeans in 1791 when José Narváez explored the southern portion of the Strait of Georgia. A year later, Captain George Vancouver, after whom the city was eventually named, surveyed the entire northwest Pacific coast. By the mid-1800s, settlers moved into the Lower Mainland, drawn to the region largely by discoveries of placer gold along the Fraser River. The population increased dramatically between 1881 and 1891 due to speculative development associated with construction of the Canadian Pacific Railway. In 1887 the rail line was extended from Port Moody to Vancouver to take advantage of the sheltered harbour and availability of flat land for industrial development. Less than a decade after the railway's arrival, Vancouver was transformed from a collection of small milltown shacks to a city of more than 13 000 people (Farley, 1979). Vancouver continued to grow rapidly throughout the first half of the twentieth century, due largely to the exploitation of resources of the province's interior. In the second half of the century, metropolitan Vancouver's economy matured with the continued expansion of the services sector and an increased role as a gateway to the integrated network of urban economies on the Pacific Rim (*see* Davis and Hutton, 2004).

During the last few decades, the Lower Mainland has experienced rapid growth and is expected to reach a population of 2.6 million by the year 2021. Residential and industrial development have spread to cover much of the Fraser Lowland. The availability of geologically suitable locations to accommodate new growth is limited, resulting in increasing pressure to develop in potentially more hazardous regions. Much development in the Lower Mainland has occurred in areas where there is a potential for serious geological hazard or where such hazards have already occurred (e.g. Fraser River floodplain, Lions Bay, Britannia; *see* Appendix A). The threat to life, property and social infrastructure imposed by serious hazards such as earthquakes, floods, and mass wasting (the downslope movement of soil and rock, including debris flows, landslides, and rockfall) necessitates proactive mitigation. Such mitigation should be based on an understanding of the geological processes and associated hazards occurring in a specific region, and includes setting building codes to withstand potential earthquakes, fortifying dykes to predicted flood levels to protect homes already built in the floodplain, zoning areas as hazardous to prevent loss of life or damage to property before development occurs, and developing effective emergency response programs in the event of disaster. The costs of a proactive stance are far less in the long term than dealing with 'after-the-fact' repairs (*see* Appendix A). Scientific study and detailed site investigations can inform us about hazardous processes by identifying and understanding the clues left behind by previous geological events. Geologists, geographers, and engineers can contribute to geologically informed and responsible land-use decisions and potentially enhance the liveability of a rapidly expanding urban region.

Geology is the study of the planet Earth — the materials of which it is made, the processes that act on these materials, the products formed, and the history of the planet and its life forms. It is the ultimate four-dimensional puzzle with the three dimensions of the Earth's architecture continually evolving during the fourth dimension, time. Geology is also a science of landscape philosophy, but one that considers processes of unfathomable power acting over periods of time dwarfing any concept of human history. This immense scope of geology often makes it difficult for many people to understand how the geosciences can possibly provide tangible insights into many of the serious issues that the Lower Mainland faces today. This paper provides a short description of the geological processes, earth materials, hazards, and resources of the Lower Mainland. The intent is to illustrate the necessity of geological understanding for effective and informed land-use decisions. A list of additional sources of geoscience information about this region is provided in Appendix B.

Geological knowledge: the first step to informed land-use decisions

The surface of the Earth is constantly changing and the rate of change varies with location and through time. Though the Earth is thought to be about 4.6 billion years old, the landscape of the Lower Mainland largely reflects geological processes that have occurred during the last 30 million years, with the most dramatic changes occurring in just the last 30 000 years. Geological processes consist mainly of two opposing types: building processes (resulting from tectonic forces) and erosional processes. Typically, tectonic forces cause deformation and uplift, whereas climate, water, ice, and gravity join forces to erode and shift sediments to lower places where they are deposited. It is estimated that if all geological building processes were to cease, the Earth's land surface would erode to a flat plain in just 15 to 110 million years (Schumm, 1963). We live on a dynamic landscape that is constantly changing and being reworked. As a result, scientists must rely on a limited number of clues in their effort to understand the history of a landscape and the processes which formed it. Technological and conceptual breakthroughs have together extended our understanding of the changes in the Earth's surface billions of years beyond that provided by just historical observation. The Lower Mainland has only been populated for the last 9000 years, with written records for only the last 200 years; thus we have been witnesses to very little of what geological processes can accomplish. We have experienced some episodic events such as floods and earthquakes, but these should be perceived as part of a geological

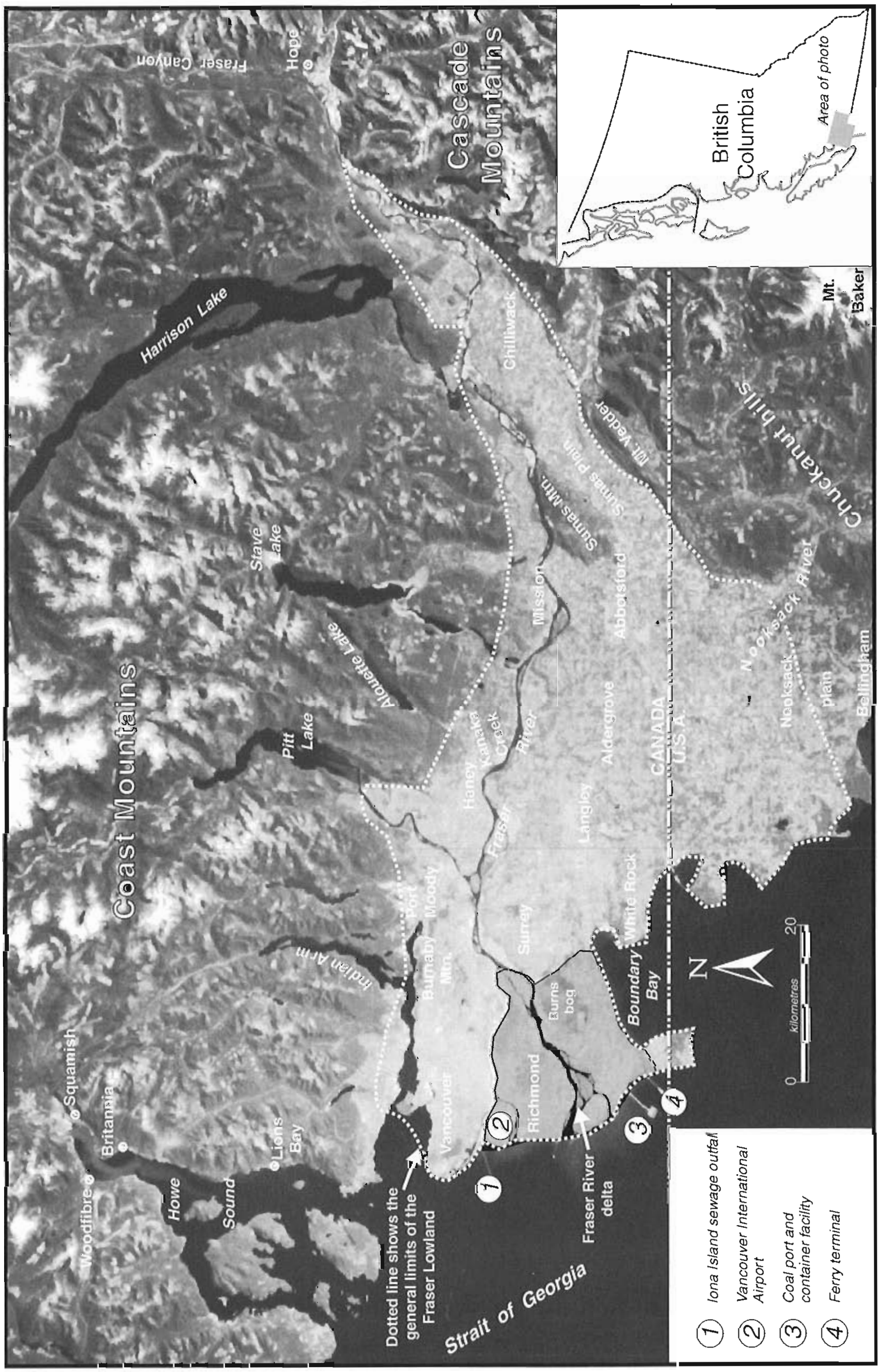

Figure 1. *Location map showing the extent of the Lower Mainland of southwestern British Columbia and other geographic terms used in this paper. The extent of the Fraser Lowland is outlined by white dots. The Fraser River delta is highlighted in grey. The Fraser valley is the portion of the Fraser Lowland that lies east of the town of Mission* (modified from Turner et al., 1998).

continuum. The following section outlines the history of the landscape in terms of the major geological processes that shape it. By understanding geological processes we can achieve three things: a better assessment of future geological activity, characterization of earth materials produced by these processes, and insights into how human activity will impact or will be influenced by these materials and processes. This basic understanding is vital to proactive, integrated, and informed land-use planning.

The design of our landscape: history and nature of geological processes

The landscape of the Lower Mainland reflects the collective actions of a multitude of geological processes; however, three geological processes dominate the design of the Lower Mainland: tectonic, glacial, and fluvial (or river-related) processes. These processes have operated at different intensities over time, some continuously (e.g. river deposition of a delta and coastal erosion), whereas others are episodic (e.g. large earthquakes, volcanic eruptions, landslides, and floods). An understanding of these processes shaping the landscape

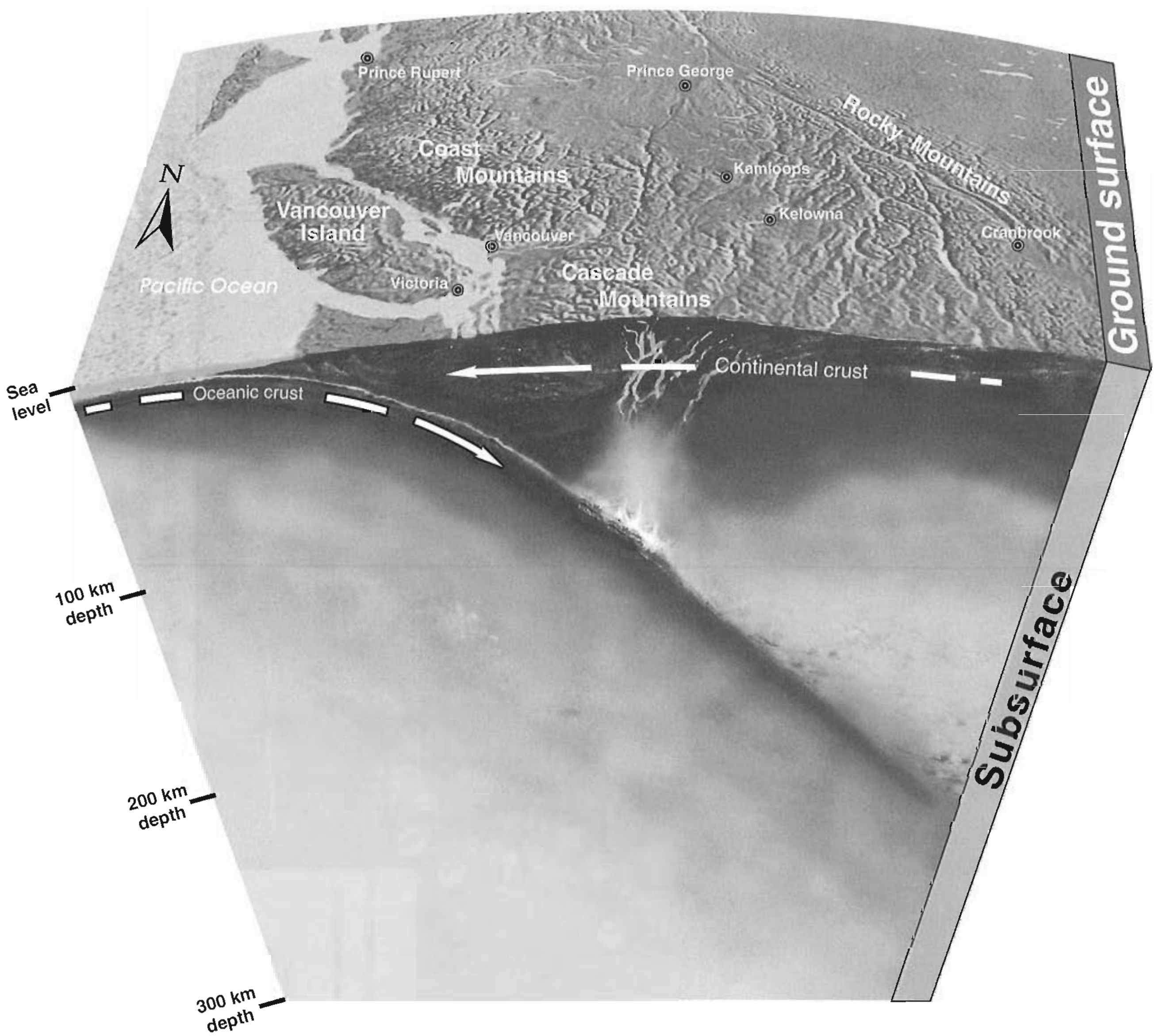

Figure 2. An artistic representation of the tectonic setting of southwestern British Columbia illustrating the convergence that forces oceanic crust to move or subduct beneath continental crust.

provides us with insights into earth material properties and helps decide when, where, and how to proceed with future development.

Tectonic processes have been acting on the region for hundreds of millions of years, creating the mountainous landscape of western North America. The driving force of this tectonism over the last 145 million years has been the movement or subduction of approximately 13 000 km of ocean crust (approximately 30% of the Earth's circumference) beneath the west coast of North America (Engebretson et al., 1992). The current tectonic setting of the Lower Mainland is shown in Figure 2. The most striking effect that tectonic processes impose on residents of the region is earthquakes and associated hazards (Mosher et al., 2004). Glaciation, the second major process, is cyclic and has affected the region several times during the last one million years, although currently it is limited to regions of high elevation. Glaciers were responsible for carving out steep U-shaped mountain valleys and coastal fiords, leaving behind thick deposits of sediments. The 'over-steepening' of these U-shaped valleys directly contributes to mass wasting such as landslides, rockfall, and debris flows. Thick glacial deposits in the Lower Mainland form the gently rolling uplands shown in Figure 3. The fluvial process, the third major agent acting on the landscape, is one produced by the action of a stream or river, and has been active as long as there has been water on the planet. With the retreat of glaciers 13 000 years ago, fluvial processes took over as the dominant agent changing the landscape of the Lower Mainland. The abundance of easily erodible materials left behind by glaciation, heavy winter precipitation, and the steep topography in the region have all contributed to the rapid development of the Fraser River floodplain and delta (shown as lowland modern sediments in Fig. 3). In just 10 000 years, more than 625 km^2 of new land have been created by the Fraser River (Fig. 4).

Tectonic processes

One of the great revolutions in science has been the emergence of the plate tectonic theory during the 1960s. The hypothesis that the Earth includes a mobile outer crust of separate plates (the lithosphere) sliding under, past, and away from one another provided the key unifying concept to explain the Earth's major surface features and geological processes. The locations of major mountain belts, volcanic chains, and earthquakes all reflect plate tectonic processes. The present-day tectonic setting of western North America and related geological features are shown in Figures 2 and 5.

Tectonic processes and regional bedrock basements to the Fraser Lowland

Tectonic processes influencing the setting of the Fraser Lowland are mostly confined to the last 200 million years. During this time, the western boundary of this part of the North America Plate has been one of subduction or translation, where oceanic crust has been consumed beneath or slid past this margin of the continent. A complex history of accumulation of land to this margin, through a combination of volcanism, magmatism (the production of molten rock), addition of older land masses, and the horizontal movement of one rock body with respect to another along discrete breaks called strike-slip faults, reflects the changing relative motion of the continental plate and oceanic plates. During most of this time, oceanic plates were converging with the North America Plate, causing overall subduction of the oceanic crust and resultant magmatism along the western margin. On occasion, large blocks of crust riding on these oceanic plates were joined to the western North America margin rather than being entirely subducted; however, there were also long periods of essentially strike-slip motion at the western margin, where subduction of oceanic material was minimal and magmatism was less important.

The setting of the Lower Mainland in general reflects this complex tectonic evolution, but is unusual in that it is at a junction of three very different regional 'basement' complexes (Fig. 6). The western member of this regional basement is a terrane called Wrangellia, a composite of old (about 400–150 million years) igneous and sedimentary rock types that were joined to the North American western margin about 100 to 150 million years ago. Remnants of Wrangellia now make up most of Vancouver Island, the Queen Charlotte Islands, and some portions of the western part of the Lower Mainland. The southern basement of the Lower Mainland is termed the 'Northwest Cascades System', a complex series of oceanic, volcanic, and sedimentary rocks. The northern basement rocks are the southern extension of the Coast Mountains. These are dominated by granitic rocks which formed mostly between about 175 million and 60 million years ago, several kilometres to tens of kilometres below the surface. They have been exposed mostly in the last 10 million years by a period of major uplift and accompanying erosion.

Two thick sequences of sedimentary rocks overlie these regional 'basements' and in turn are overlain by younger glacial and modern sediments. These sedimentary rocks occupy two old sedimentary basins in this area. Rocks of the oldest sedimentary basin comprise the Nanaimo Group, a succession of marine and nonmarine sandstone, conglomerate, mudstone, and significant coal deposited about 90 to 65 million years ago in a basin that broadly coincides with the present Georgia Depression (Fig. 6; Mustard, 1994). Rocks of the Nanaimo Group are exposed in Stanley Park and North Vancouver and dip gently to the south beneath the Fraser River delta, reaching a thickness exceeding 1300 m. Overlying the Nanaimo Group in the Lower Mainland is a succession of sedimentary rocks termed the Huntingdon Formation, part of the Chuckanut Basin (Fig. 6; Mustard and Rouse, 1994). This nonmarine succession of sandstone, conglomerate, and minor mudstone was deposited between about 58 million and 35 million years ago by river systems in a basin controlled by regional strike-slip faulting. These rocks are exposed on the northern edge of greater Vancouver in areas including Burnaby Mountain, Kanaka Creek, and Sumas Mountain (Fig. 1; Jackson, 2004, Fig. 11). These sedimentary rocks also provide the foundation material (along with a thin veneer of glacial sediments) for the buildings of Vancouver and Burnaby. The Huntingdon Formation is at least 2 km thick beneath much of the Fraser River delta, overlying the

Nanaimo Group and overlain in turn by a thin, discontinuous succession of unnamed sedimentary rocks and by ice age and modern sediments. The sedimentary basin in which the Huntingdon Formation was deposited was larger than the present Fraser Lowland, extending to the south beneath the Nooksack plain (*see* Fig. 1) and making up the Chuckanut hills in the Bellingham area (where the rocks are termed the Chuckanut Formation).

About 40 million years ago, the interaction of tectonic plates changed from one where the oceanic plates were moving at a highly oblique angle to the North America Plate to one of near orthogonal convergence of the plates (Monger and Journeay, 1994). This created a plate boundary setting that has been maintained to the present, with the western margin of the North America Plate overriding the oceanic Juan de Fuca Plate at about 45 mm per year (Fig. 5; Riddihough and Hyndman, 1991). A consequence of this plate subduction was a renewal of the magmatic arc on the continental crust, with

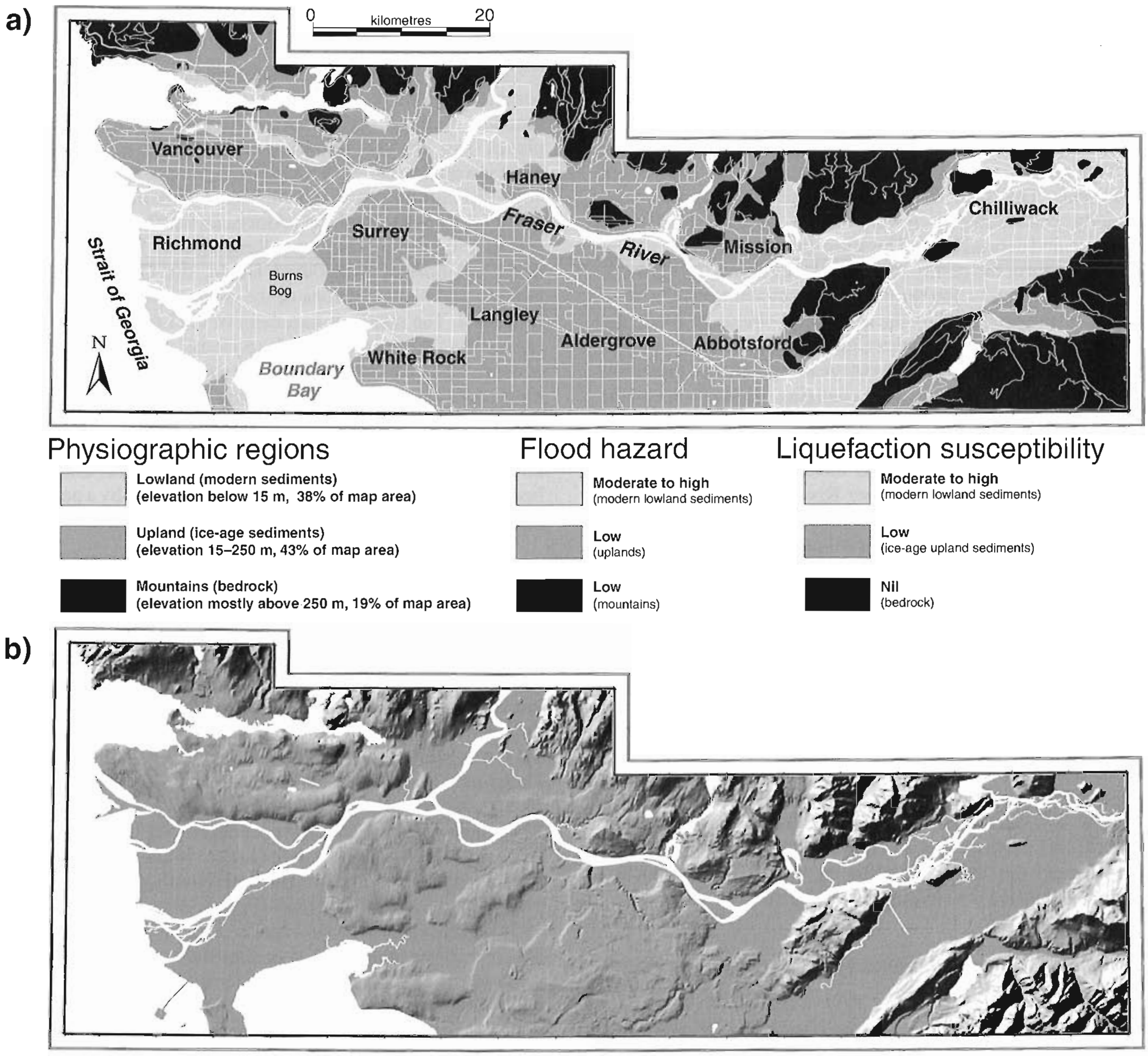

Figure 3. *Fraser Lowland and adjacent mountainous areas.* ***a)*** *Physiographic regions and their associated flood and liquefaction risk. Development has been mostly confined to the lowland and upland areas.* ***b)*** *Digital Elevation Model showing ground surface expression. Derived from TRIM data. Surface expression of the different physiographic regions. Both maps are* modified from *Turner et al. (1998).*

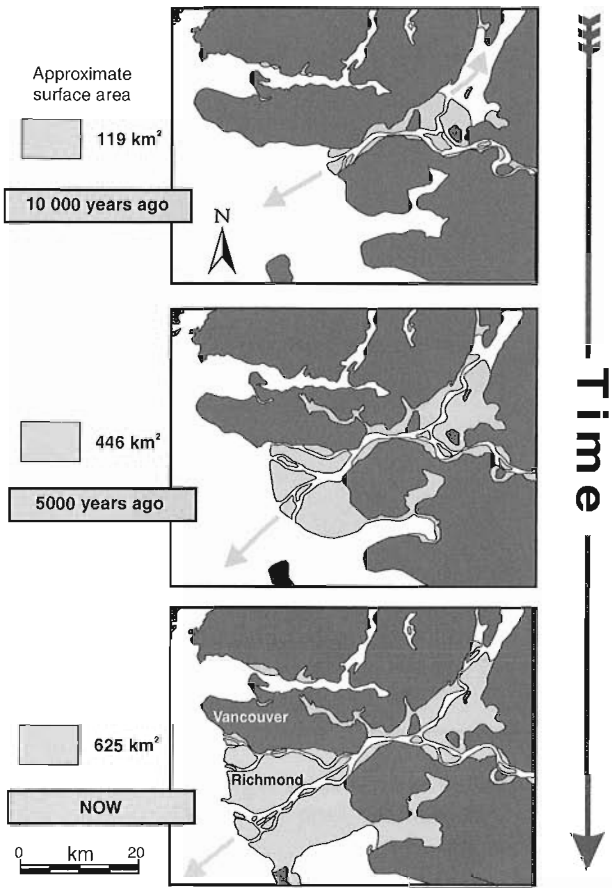

Figure 4. Growth of the Fraser River delta and floodplain (shown in light grey) over the last 10 000 years (modified from *Clague, 1994, p. 188). Arrows show the direction of delta growth.*

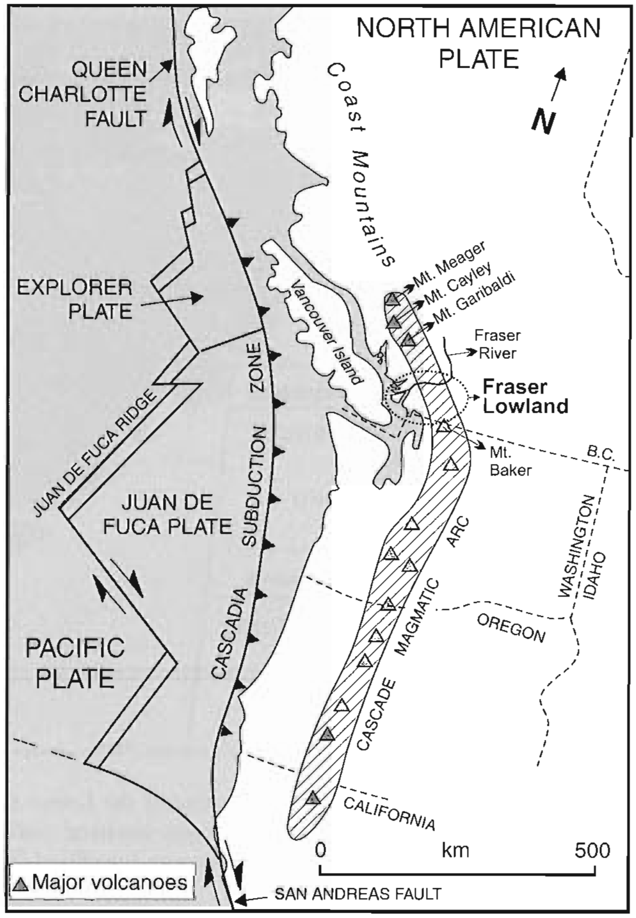

Figure 5. Present-day major tectonic features of western North America, showing the Cascade magmatic arc east of the subducting Juan de Fuca and Explorer plates and the main volcanoes near the Lower Mainland (modified from *Riddihough and Hyndman, 1991, p. 439).*

volcanic flows, sills, and plugs forming in the Vancouver area. These include the sills and dykes preserved at Stanley Park, Sentinel Hill, and Little Mountain in the present Fraser Lowland, which are about 31 to 34 million years old. These are early examples of the long-lived volcanic arc that has persisted on this margin and continues today as the Cascade magmatic arc (Fig. 5; Hickson, 1994).

Neotectonics and the modern setting of the Fraser Lowland

The Georgia Depression is the modern topographic low centred on the Strait of Georgia. The depression merges with the depression of the Fraser Lowland in the Vancouver area. These are active sedimentary basins, which have been receiving sediments at least since the last glacial retreat or for the last 10 000 to 12 000 years. The general physiography and major drainage patterns of the area largely reflect tectonic deformation processes of the last 100 million years. For example, a strong pattern of generally northwest-trending faults and fractures exists in this region, especially evident in the Chuckanut hills to the south and the Coast Mountains to the north of the Fraser Lowland (Fig. 7). This structural trend reflects several deformation events, including southwest-directed thrusting about 90 million years ago, a similar deformation event about 45 million years ago (England and Calon, 1991; England et al., 1997), and northwest-trending strike-slip faulting that was active about 35 to 85 million years ago (Monger and Journey, 1994). These older structural trends have influenced major drainage patterns in the Coast Mountains. The main north-northwest trend of the Fraser River east of the Fraser Lowland follows the trend of the Fraser Fault, a major strike-slip fault. Harrison Lake is situated on another major strike-slip fault, the Harrison Lake Fault. Smaller rivers draining into the main lakes north of the Fraser Lowland are also located in valleys controlled by these northwest-oriented fault or fracture systems. A generally younger northeast- to north-trending system of faults and fractures is superimposed on the older features in the Lower Mainland. Most of these features appear to have formed in the last 30 million years, although no recently active faults are currently known (Monger and Journeay, 1994; Clague (1996) and references therein). This northeast fabric also has strongly

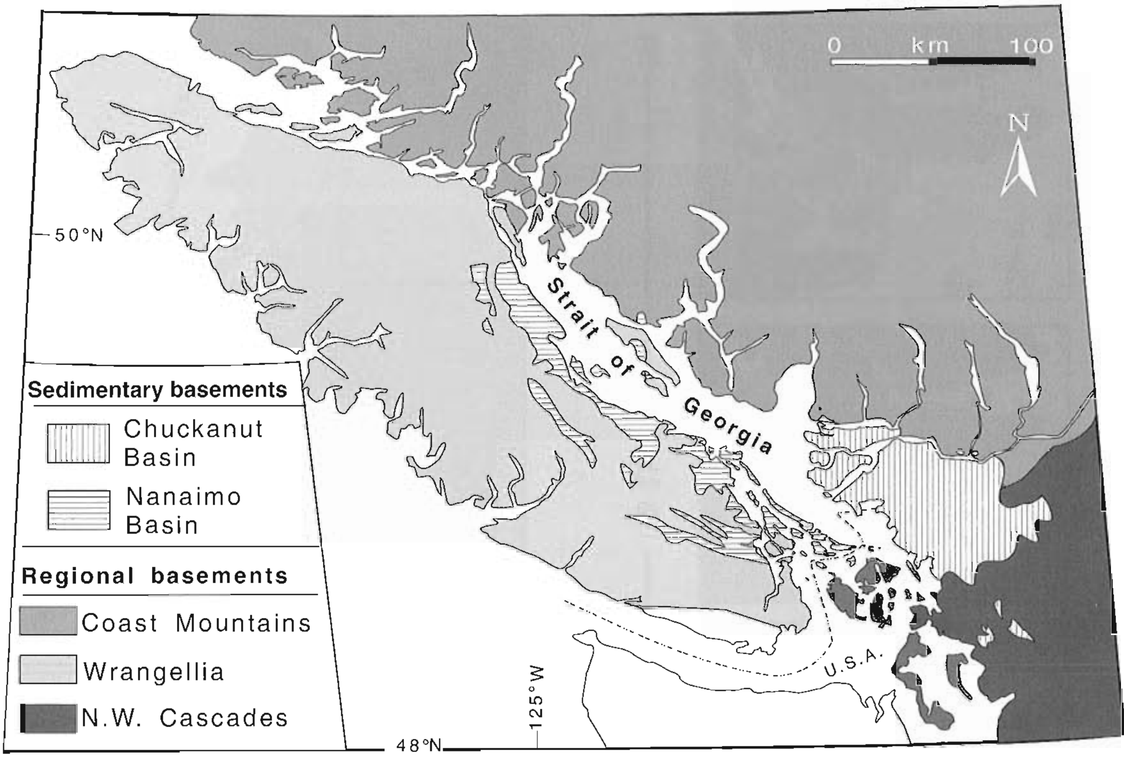

*Figure 6. Regional setting of the Lower Mainland, emphasizing three contrasting regional basements, with two superimposed sedimentary basins which together form the main geological base to the region (*modified from *Mustard, 1994, p. 28).*

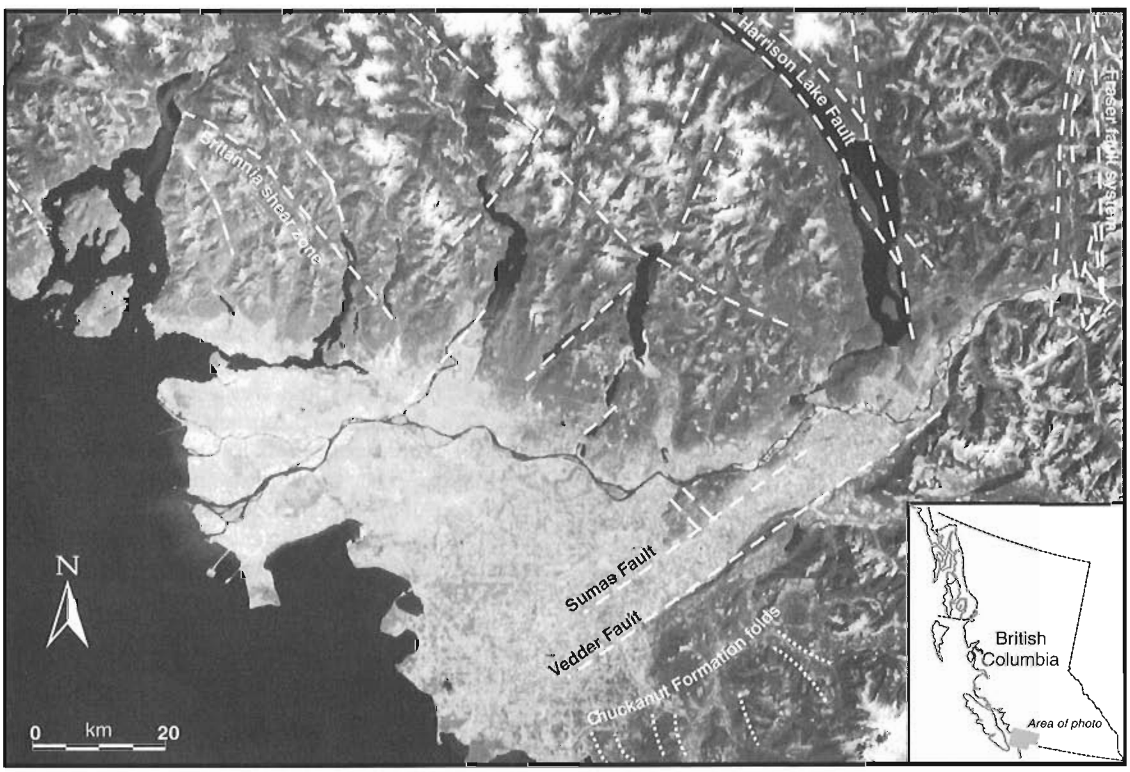

Figure 7. Major structural trends in the Lower Mainland that have affected modern physiography. The white dashed lines represent major fractures or faults (none presently active). The dotted lines form the axes of folds in the Chuckanut hills.

influenced the physiography of the region. Many of the inlets, lakes, and rivers in the southern Coast Mountains of this area tend to parallel these structures (e.g. Alouette Lake, Pitt Lake, Pitt River, Stave Lake). Sumas Mountain and Vedder Mountain in the eastern Fraser Lowland are fault-bounded bedrock blocks separated by a prominent northeast-trending, downdropped fault block (i.e. graben), the site of the Sumas Prairie. The general northeast trend of the Fraser River between the Mission and Hope areas is also probably a reflection of old fault or fracture trends in this area.

The topographic lows of the Georgia Depression and Fraser Lowland also reflect the long-term deformation of this region. Geodetic data suggest that these areas are presently subsiding at a rate of about 1 to 2 mm/year and that both the western Coast Mountains and western Vancouver Island are rising at rates of about 2 to 4 mm/year (Fig. 8; Holdahl et al., 1989; Dragert et al., 1994). Studies of more long-term uplift rates suggest that the southern Coast Mountains and Vancouver Island mountain ranges have been slowly uplifting for at least the last 30 million years, with significant uplift of 2 to 3 km in these mountain areas in the last 10 million years (Fig. 8; Parrish, 1983). These long-lived areas of subsidence and uplift again reflect the plate tectonic margin of the last 40 million years. Uplift may be caused by thermal expansion due to high heat flow in the volcanic arc areas of the western margin (Parrish, 1983); underplating of material to the base of the western margin of Vancouver Island by the young, buoyant, subducting Juan de Fuca Plate (Monger and Journey, 1994); or lithospheric flexure due to compressive stress at this margin, as suggested by Yorath and Hyndman (1983) for the Queen Charlotte Basin to the north (Monger and Journeay, 1994). Subsidence causing the Georgia Depression may also be explained by this lithosphere flexure model, or may reflect phase changes in the subducting oceanic crust beneath the Georgia Depression (Rogers, 1983).

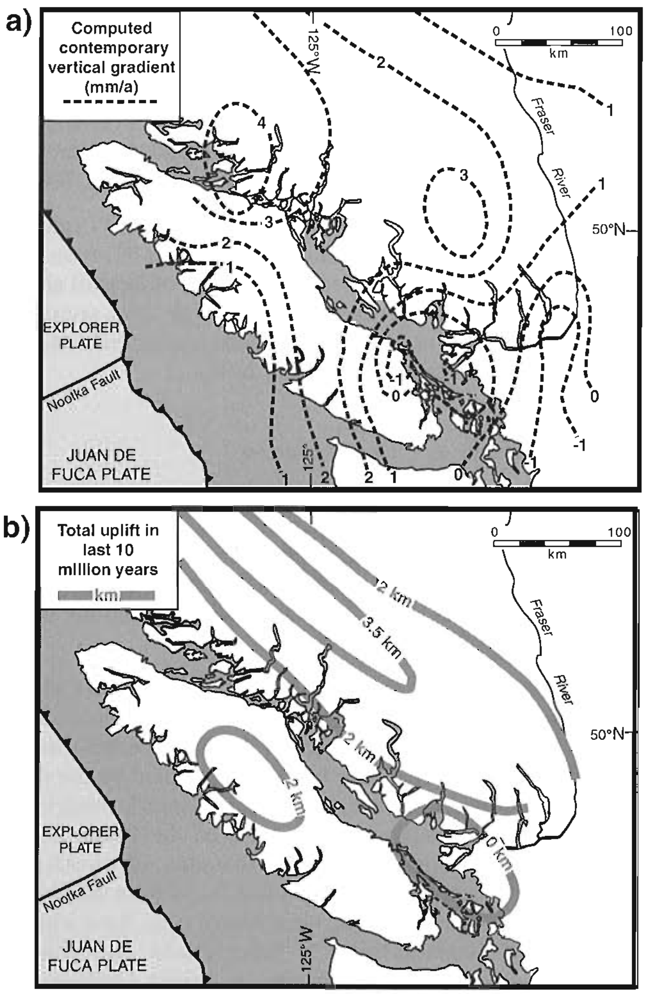

*Figure 8. a) Present rates of uplift (*modified from *Holdahl et al., 1989) and b) total uplift in the last 10 million years (Parrish, 1983) in southwestern British Columbia.* See *Parrish (1983) for a discussion of assumptions involved in estimating Neogene and Quaternary uplift.*

Glacial processes

Glacial processes reflect the effects of seasonal precipitation and temperature. If winter precipitation exceeds the summer melt, glaciers will grow and advance downvalley. If summer melt exceeds winter snowfall, then glaciers recede. Extended climatic periods allowing glacial advance result in the coalescence and thickening of glaciers to produce large ice sheets. Periods of glaciation have occurred on a cyclic basis at least eight times in the last million years, covering large portions of northern North America and northern Europe. During glaciation, sea levels drop by 100 to 150 m due to the large volume of water extracted from oceans to create these ice sheets (Barry and Chorley, 1982).

The extent of glacier cover has varied with each glaciation. During lesser glaciations, much of the Lower Mainland and the Strait of Georgia may have been ice-free, although they were areas where meltwater from the glaciers did deposit sediments (Clague, 1994). The Cordilleran Ice Sheet (Fig. 9) last formed during the Fraser Glaciation, which began about 25 000 years ago. At this time, ice advanced southeast down the Strait of Georgia and moved westward across the Fraser Lowland. During its maximum (Fig. 9), the ice surface was above 2300 m elevation and more than 2000 m thick over major valleys (Ryder et al., 1991). The maximum extent of glaciation in southwestern British Columbia was achieved about 15 000 years ago, and the large ice sheets had disappeared about 10 000 years ago (Clague et al., 1980; Clague, 1981).

Glacial erosion — scouring and steepening

The immense power of these thick ice sheets scoured mountain valleys and coastal regions to create steep-walled, U-shaped valleys; sharp-crested mountain peaks; and deep fiords, some of which extend as far as 150 km inland and have water depths up to 755 m (Peacock, 1935; Picard, 1961). This

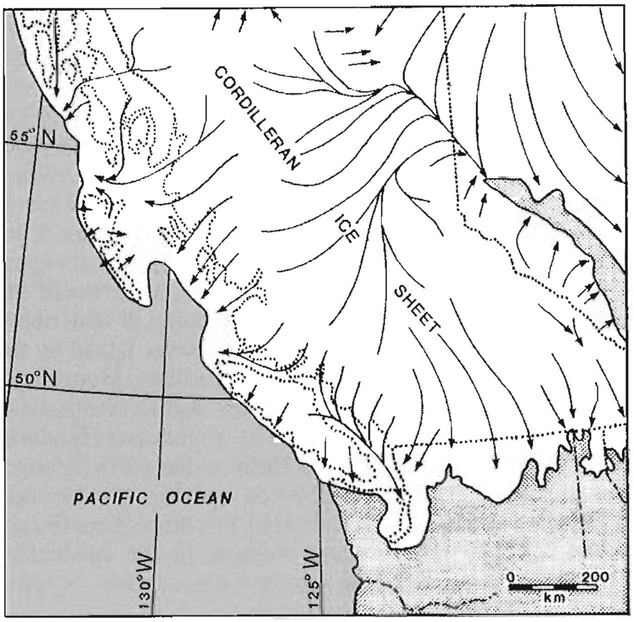

Figure 9. Cordilleran Ice Sheet at the maximum of the last glaciation, about 15 000 years ago. The generalized ice-flow pattern is indicated by the arrows (after *Clague, 1996, p. 183).*

steep topography is subject to intense winter rainfalls (Jackson, 2003) which can trigger slope instabilities such as debris flows, landslides, and rockfall.

Glacial deposition — materials and their properties

The erosive actions of the glaciers produced massive volumes of sediments that were deposited in valleys and lowlands as layers of sediments up to 1 km thick. They form the majority of the gently rolling uplands (15–250 m elevation) shown in Figure 3 (Armstrong, 1984). These sediments include till (unstratified sediment deposited directly by the glacier without reworking by meltwater); sand and gravel deposited by streams flowing from the melting ice (outwash); marine clay and silt; and beach sand and gravel. These rolling upland sediments are good foundation materials and are generally not susceptible to developing a liquid consistency (a process known as liquefaction) during an earthquake. Soils developed on sand and gravel are well drained, whereas those developed on silt, clay, and some till deposits are poorly drained. Flooding in these upland glacial deposits is limited to narrow valley bottoms of small streams that flow through the uplands. Deposits that are older than the last glaciation are exposed only as steep escarpments along the margins of uplands (Fig. 3). The bases of some of these escarpments are being actively eroded by streams and ocean waves. Many residential areas extend to the edges and bases of escarpments, where even small slides can damage or destroy houses, roads, and other infrastructure (Turner et al., 1998).

Fluvial processes

The Fraser River floodplain and delta form almost half of the urbanized region of the Lower Mainland (Fig. 3). The delta extends over 1000 km^2, which includes 349 km^2 protected by dykes, 244 km^2 of intertidal area, and greater than 400 km^2 formed by the submarine delta slope. The floodplain and delta were formed by continuous deposition of Fraser River sediments during the last 10 000 years, following the end of the last glaciation (Fig. 4). Continued deposition occurs on the slope of the delta, on the intertidal flats, and within the channels of the Fraser River, thus requiring dredging for shipping purposes. The Fraser River supplies an average of 17.3 million tonnes of sediment to the delta annually, of which 35% is sand (McLean and Tassone, 1991). Sediment deposition on the delta is dominantly controlled by the interplay of tidal and fluvial processes in the high-energy, semi-enclosed marine basin of the Strait of Georgia (Luternauer, 1980). The high tidal range of 4 to 5 m produces a saltwater intrusion or 'salt-wedge' that moves up and down the bottom of distributary channels depending on river discharge and tidal height. Tidal processes and saltwater intrusion up the channel influence estuary plant distributions (*see* Adams and Williams, 2004), sediment transport and contaminant concentrations (*see* Kostaschuk and Luternauer, 2004), and contaminant distributions on the tidal flats (*see* Bendell-Young et al., 2004).

The lowlands, labelled in Figure 3, lie below 15 m elevation and consist of the floodplains of the Fraser River and its tributaries, the Fraser River delta, and areas of landfill along shorelines. High spring runoff and very high tides impose a serious flood threat to agriculture, industry, and communities built on the floodplain (*see* Woods, 2004).

Fluvial materials and their properties

Lowland sediments were deposited on the remnant surface of glacial processes following deglaciation. This interface is irregular and results in varied thicknesses of these recent river deposits. The present sedimentary environments of the Fraser River include the floodplain, bogs, tidal flats, and the delta slope.

The floodplain of the Fraser River and distributary channels was deposited over thousands of years by seasonal floodwaters that covered these lowlands. The natural deposition of these flood-related materials has been disrupted by the construction of dykes. Flood deposits occur as interlayered sediments with varied composition. Most of the Fraser River floodplain and delta are underlain by fine sand, silty sand, and silt. These materials commonly present foundation and drainage problems, form important agricultural soils, have a moderate to high susceptibility to liquefaction, and can be important groundwater reservoirs (aquifers) (Armstrong, 1984; Mustard et al., 1998; Turner et al., 1998).

Bogs, swamps, and marshes all produce partially decomposed plant material called peat. The high compressibility of peat makes it an extremely poor foundation material. Several bogs have been mined for sphagnum peat moss or used for growing blueberries and cranberries. Recognition of the ecological importance of bogs and their role in sustaining summer stream flows has led to increased efforts to protect them from development (Turner et al., 1998). Burns Bog is the largest urban green area in metropolitan Vancouver (Fig. 1). It provides refuge and habitat to a large number of animal species and acts as a large reservoir for groundwater recharge to nearby aquatic habitats (Schaefer, 2004).

The delta front is a narrow zone, as much as 9 km wide, that lies along the western edge of a broad area of very gently sloping tidal flats and separates the tidal flats from the submarine delta slope. The slope of the delta increases to an average of 2 to 3°. (but ranges from 1–23°) towards the marine basin of the Strait of Georgia and terminates in water 300 m deep, 5 to 10 km west of the delta front. To the south, the submarine slope of the delta has a gentler gradient and terminates at a depth of only 30 m due to the shallower seafloor in this area (Luternauer et al., 1994). The delta continues to grow westward as new sediments are deposited on the delta front and delta slope; these sediments are loose and water-saturated and therefore prone to failure. During an earthquake, the steeper portions of the delta front could fail (Mosher et al., 2004).

GEOLOGICAL HAZARDS AND RESOURCES

The Lower Mainland is the fastest growing urban area in Canada, with a population that surpassed 2 million people in 2001. This active tectonic region is bordered by steep mountain slopes and receives high annual rates of precipitation. These conditions make the region prone to a range of geological hazards. The area is also rich in Earth resources important to a growing population centre, such as an abundant supply of aggregate material, extensive groundwater aquifers, and surface-water supplies, and soils generally well suited to agriculture.

Hazards from direct geological processes

The two most serious hazards related directly to geological processes are earthquakes and volcanic eruptions. A major earthquake or volcanic eruption would be a direct consequence of the active tectonic setting of this area. Either could cause significant economic damage to the area, whereas large earthquakes also could cause great loss of life.

Volcanic hazards

The Cascade volcanic chain extends across southwestern British Columbia and includes the potentially active volcanoes of Mount Garibaldi, Mount Meager, and Mount Cayley (Fig. 5; Hickson, 1994); however, the most significant volcanic threat to the Lower Mainland is from Mount Baker in northwestern Washington State, last active in 1872. Ash fallout from a volcanic eruption poses the greatest hazard to the Fraser Lowland. Ground shaking and eruptive flows would be limited to the immediate vicinity of the volcano. Floods or volcanic debris flows could extend down river valleys such as the Nooksack River, but are unlikely to extend into the Canadian portion of the Fraser Lowland. Hoblitt et al. (1987) estimates that on average 10 cm of ash can be expected to fall in the Fraser Lowland once every 10 000 years, 1 cm once in 1000 years, and smaller amounts more frequently. The ash particles are an abrasive and a contaminant, which pose significant hazards to aircraft and machinery (Casadevall, 1994); they also create a health hazard, especially to asthmatics or other people with pre-existing breathing problems; however, Hickson (1994) pointed out that most of the population base of the Fraser Lowland is located west of Mount Baker and prevailing wind conditions are east-flowing (*see* Jackson, 2004), lessening the likelihood of significant ash accumulation in metropolitan Vancouver.

Seismic hazards

The western margin of British Columbia is one of the most seismically active areas in Canada. There have been nine major earthquakes with magnitudes of 6 to 7.4 in historic time in the regions of Puget Sound and the Strait of Georgia. Magnitude values refer to the Richter scale, a numerical scale where each value is ten times the previous value (i.e. a magnitude three earthquake is ten times stronger than a magnitude two). There also is strong geological evidence for even larger earthquakes in the recent prehistoric past (summarized *in* Clague (1996) and references therein; *see* Mosher et al., 2004). Rogers (1994) provides details of earthquake hazards in the Vancouver area (*see also* Clague (1996) and references therein; Mustard et al., 1998). This summary is compiled from these sources unless otherwise noted.

Earthquakes at this margin occur in three different crustal settings. The most common are relatively shallow earthquakes within the continental crust (North America Plate) and are caused by compressive stress parallel to the continental margin. These earthquakes are relatively common and usually of low magnitude, but several historic earthquakes of larger (6–7.4) magnitude were of this type, including the 1946 earthquake of magnitude 7.3 under central Vancouver Island. Deeper earthquakes occur within the subducting oceanic plate at depths of about 45 to 65 km. These deep-seated earthquakes are also relatively common and include relatively high-magnitude events. An example is the 1965 earthquake of magnitude 6.5, with an epicentre in Puget Sound near Seattle. Earthquakes of the third type, referred to as megathrust or subduction earthquakes, are rare but very large. They are produced when stress built up at the boundary between the subducting oceanic plate and the overriding North America Plate is suddenly released. Predicted magnitudes for a subduction earthquake at the Cascadia subduction zone range from magnitude 8 to greater than 9, which would place them among the largest recorded seismic events on Earth. There is now abundant evidence that the plates at the Cascadia subduction zone are locked and the strain is accumulating for a future event. The last subduction earthquake in this zone is thought to have occurred on January 26, 1700 (Satake and Tanioka, 1996). The average repeat rate of these major earthquakes is believed to be in the order of several hundreds of years (Adams, 1990; Clague (1996) and references therein).

The effects of a major earthquake on the Fraser Lowland could be considerable. Direct seismic shaking would damage buildings and other infrastructure and could cause secondary damage due to liquefaction, fire, and slope failures. Slope failure is a major problem on steep slopes, on submarine slopes such as the Fraser River delta slope, and along narrow mountain corridors that connect Vancouver to the east and north. Large tsunamis could be triggered by a major subduction earthquake, but the Fraser Lowland should be protected from the main force of a tsunami by Vancouver Island. Although a magnitude 8 to 9 subduction earthquake would affect a much larger area than smaller crustal earthquakes, it is important to recognize that the probability of occurrence of a subduction earthquake is about 50 times less than that of a magnitude 6 to 7 earthquake (Clague (1996) and references therein). The impact of a crustal earthquake of magnitude 6 to 7 with an epicentre within or near the Fraser Lowland could also be considerable, as demonstrated by similar magnitude earthquakes near other major urban areas (e.g. Los Angeles, 1994, magnitude 6.7, U.S. $20 billion damage; Kobe, Japan, 1995, magnitude 6.9, damage estimated at U.S. $130 billion; Appendix A).

Hazards from earth material properties

Both unconsolidated and consolidated earth materials in the region of the Fraser Lowland are susceptible to failure. Types of failure include liquefaction along with a diversity of mass-wasting processes such as landslides, rockfall, debris flows, and debris torrents. The type and nature of failures depend on the geotechnical properties of the local materials, topographic relief, steepness of slope, and whether the event is associated with seismicity or high rainfall.

Liquefaction is a partial or total loss of cohesion of sediment, usually as a result of seismic shaking. Liquefaction can significantly reduce the bearing capacity of a sediment. Figure 3 shows areas most susceptible to seismic liquefaction in the Lower Mainland (*see also* Watts et al. (1992) and references therein; Clague (1996) and references therein). Liquefaction-prone areas include the Fraser River delta and floodplain in young, water-saturated, near-surface sand (Monahan et al., 1993). Areas of artificial fill, shorelines, and near-shore areas of the Strait of Georgia and Burrard Inlet also could be affected.

Landslides and rock falls are common in the Lower Mainland. A full review of the characteristics and history of major events in this area is contained in Evans and Savigny (1994). Several landslides have caused extensive damage and loss of life, in addition to creating secondary effects such as river blockage or triggering large destructive waves in existing lakes. Significant hazard exists along the Hope–Chilliwack corridor, where steep slopes prone to extreme rainfall events border a relatively narrow section of the lowland. Smaller, but destructive landslides also have occurred in the main part of the Fraser Lowland. A large mass of late Pleistocene glaciomarine sediments failed and flowed into the Fraser River near Haney in 1880, causing extensive damage to docking facilities and one fatality (Appendix A; Eisbacher and Clague, 1981, 1984).

Debris flows and torrents are mixtures of organic material, sediment, soil, rock, and water, which can travel with destructive force down steep slopes or in channels. In the Lower Mainland they are most common on the high-relief, steep slopes of the Coast Mountains. Small, but destructive debris flows and avalanches are triggered on these slopes by heavy rains (Eisbacher and Clague, 1984). Between 1958 and 1983, large debris flows caused loss of life and millions of dollars of damage along the eastern side of Howe Sound, a steep-walled fiord north of Vancouver (Fig. 10). These flows prompted construction of major debris dams, deflection structures, and channel linings to reduce the potential hazards in these areas (Hungr et al., 1987).

Slope failures are not limited to the terrestrial environment. The Fraser River delta front has historically been subject to large failures at the head of submarine channels (McKenna et al., 1992). Seismic profiles through the delta slope and toe have found other suspected failure complexes (Hart et al., 1993). Large failures may be triggered by seismic events, rapid sedimentation, or interstitial gas. Major industrial development at the delta front, such as sewage outfalls, submarine cables, a major ferry terminal, and Canada's largest coal and container export facility, could be threatened by large failure events (Fig. 1; *see* Mosher et al., 2004, Fig. 3).

Flooding is another major hazard in the lowland area shown in Figure 3. Although not technically a hazard from earth material properties, major floods of the Fraser River are important erosive and sediment redistribution events in the region. Floods from both the Fraser River and its tributaries such as the Sumas and Vedder rivers have caused major damage. The largest recorded historic flood to affect the Fraser Lowland was in 1894 when the area was sparsely inhabited; the most destructive flood was in 1948 and caused more than $20 million in damage (1948 values). Since the 1948 flood, industrial and residential development have continued in the floodplain. To reduce the risk of additional flood damage, a total of about $146 million has been spent since 1968 towards improving dykes in the Fraser Lowland (*see* Woods, 2004).

Earth resources in the Lower Mainland

The main earth resources exploited in the Lower Mainland are water and aggregates. Increasing population densities are causing both depletion of these resources and increased levels of contamination of water supplies — a particular concern for groundwater.

Groundwater supplies about 44% of total water needs of the urbanized Lower Mainland (1981 figures, Halstead (1986)), evenly distributed between agricultural and/or industrial uses and domestic drinking water (Dakin, 1991). Ricketts and Liebscher (1994) and Ricketts (2000) summarized groundwater issues in the Lower Mainland. Most of the groundwater resources in the Lower Mainland are within thick, unconsolidated, ice-age sand and gravel. These include

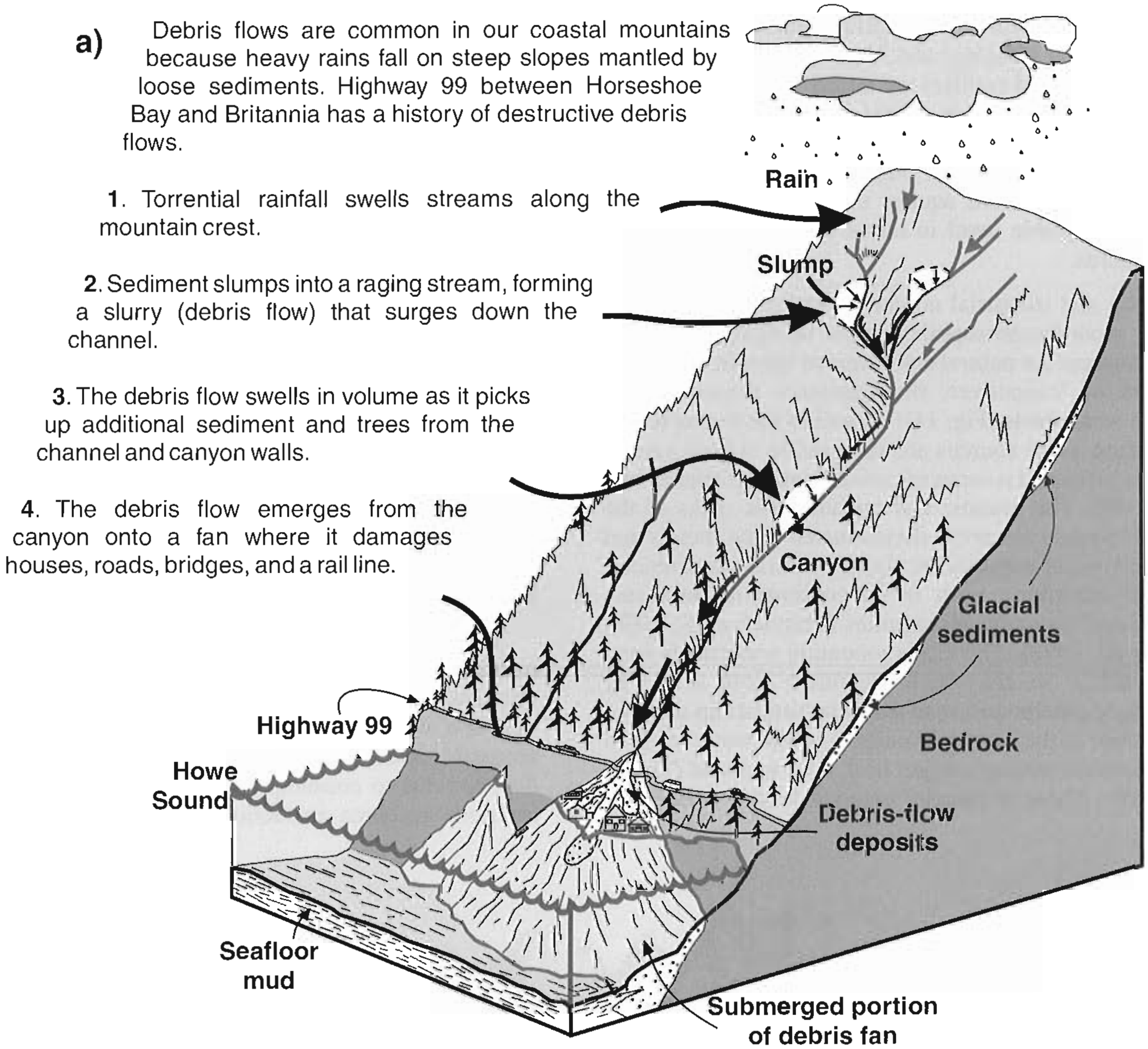

Figure 10.

__a)__ Anatomy of a debris flow in the Howe Sound area (after Turner et al., 1996), __b)__ Photograph showing the aftermath of a debris flow that swept through Lions Bay in February 1983, killing two people (after *Turner et al., 1996).*

large and heavily exploited shallow aquifers such as the Brookswood (near Langley) and Abbotsford aquifers. These and other unconfined aquifers are susceptible to contamination from sources such as septic waste, pesticides, and organic fertilizers because of heavy agricultural use. For example, Liebscher et al. (1992) reported local levels of nitrate in the Abbotsford aquifer that were four times the maximum acceptable level in terms of Canadian drinking water standards.

Drinking and industrial and/or agricultural water needs not met by groundwater supplies are met using surface water. The main sources are natural and dammed lakes in the mountains north of Vancouver; the Capilano, Seymour, and Coquitlam watersheds (Fig. 11); as well as the Fraser River. These surface water sources are susceptible to both natural and human-produced sources of contamination (Delaney and Turner, 1994). The granitic and metamorphic rocks of the Coast Belt contain common disseminated trace metals and many small metal sulphide bodies as natural occurrences. These can contribute high metal contents to both surface-water and groundwater supplies (Matysek et al., 1990; Sibbick et al., 1992). The city's mountain watersheds have naturally acidic waters which are made more acidic by increased acid precipitation caused by industrial and automobile emissions in the Lower Mainland; acidic water tends to corrode pipes dissolving copper, iron, zinc, and lead (Turner et al., 1996). These mountain watersheds also experience landslides that wash mud into the reservoirs and into the water system. This cloudy water does not pose a direct health risk, although sediments in the water can reduce the ability of chlorine to kill bacteria and other organisms. Logging and related road construction in the watersheds can increase the incidence, frequency, and extent of landslides.

Fraser River pollutants are derived from a variety of sources. These include chemicals such as hydrocarbons, dioxins, and furans used in industries situated along the river (Servizi, 1989; Standing Committee on the Fraser River Estuary Water Quality Plan, unpub. report, 1990; Church et al., 1992; *see* Brewer and Sekela, 2004) as well as trace metals and other contaminants from sewage, industrial effluent, and urban runoff. The final site of deposition for these contaminants is the tidal flats or delta slope of the Fraser River delta or the adjacent Strait of Georgia, all important areas of bird, fish, and invertebrate habitat (Macdonald et al., 1991; B.E. Anderson, unpub. report, 1993; Delaney and Turner, 1994; Luternauer et al., 1994; *see* Bendell-Young et al., 2004; *see* Brand and Thompson, 2004).

Aggregate supplies extracted from the Lower Mainland include sand and gravel, clay, till, and crushed rock. These are vital components for fill, concrete, asphalt, and other construction uses. Supplies of these materials are relatively accessible and abundant, but the local supply is being rapidly depleted due to consumption and exclusionary zoning that prohibits resource extraction (Leaming, 1968; Hora and

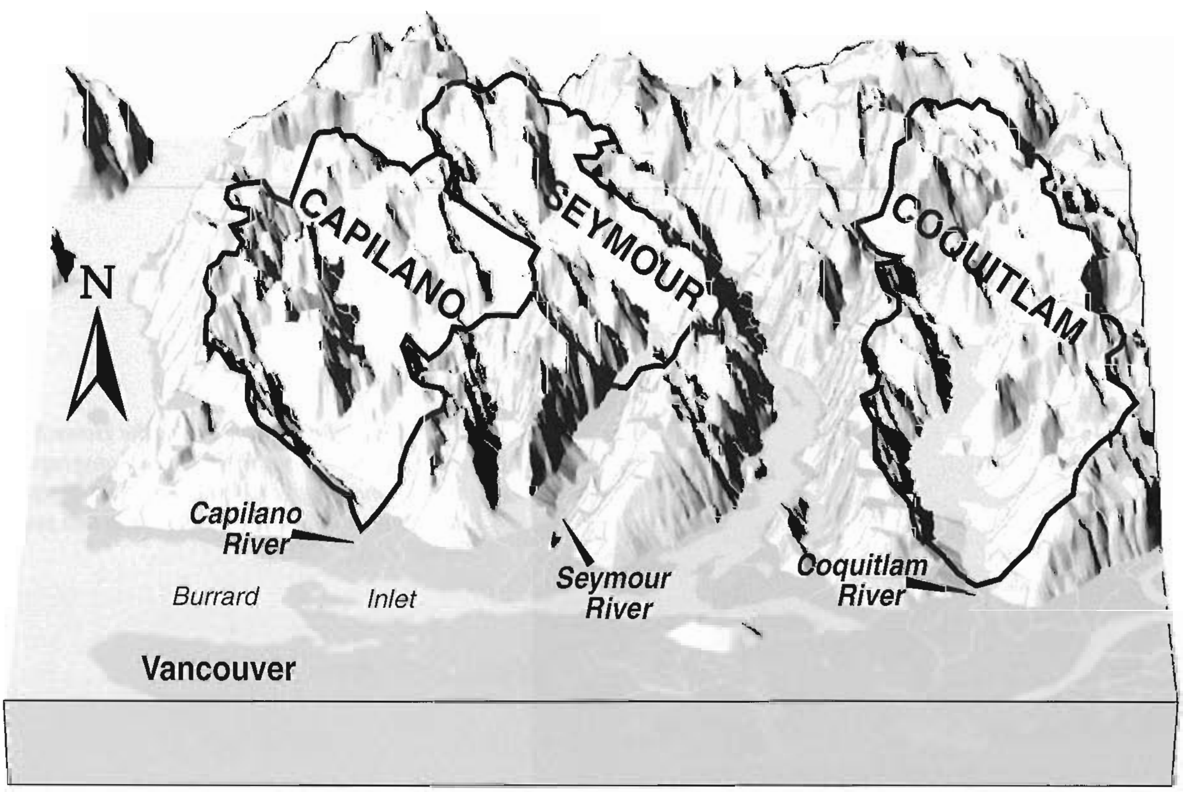

Figure 11. *Extent of the three major watersheds that supply drinking water to parts of the Fraser Lowland. Vertical exaggeration is three times (*after *Turner et al., 1996).*

Basham, 1981). Most of the sources for gravel and sand are large pits currently operating in the glacial sediments in the Haney, Mission, and Aldergrove areas. Clay has been mined in the past for structural clay products (brick, industrial piping, etc.). The clay industry has ceased operation in the region except for the mining of fireclay from sedimentary rocks on Sumas Mountain (Mustard et al., 1998). Granitic rocks are quarried at a few sites in the Lower Mainland (e.g. near the Pitt River south of Pitt Lake) to produce crushed rock and riprap — large fragments of broken rock used to armour slopes along sea walls, dykes, and dams to prevent erosion from waves and currents.

SUMMARY

The three main types of geological processes that have shaped the landscape are tectonic, glacial, and fluvial processes. Tectonic processes have controlled the regional framework of southwestern British Columbia, causing uplift and deformation as oceanic crust is subducted beneath continental crust. The most significant impact to humans is the threat of a damaging earthquake and associated hazards such as liquefaction and slope failures. Glaciers have sculpted the landscape creating steep-walled valleys and depositing thick sequences of sediment. The steep slopes left behind play host to a variety of mass movements and often threaten transportation corridors such as the eastern Fraser River valley or along Howe Sound. The thick sediments deposited by glaciers contain valuable groundwater aquifers and accommodate development with limited hazards. Fluvial processes have created more than 625 km^2 of new land in just the last 10 000 years. The low elevation and the physical properties of fluvial sediments make them prone to flooding, liquefaction in the event of an earthquake, and submarine landslides on the delta slope.

Population and economic growth are placing increasing demands on this landscape. Significant development has occurred in parts of the Lower Mainland with a significant risk of flood, liquefaction, and slope hazard. Land-use decisions must deal with many challenging questions: Should we focus development in areas with the least geological risk? Should we continue to develop where we know there is serious risk of hazard, while counting on protective measures to minimize this risk? Should we increase the amount of development in mountainous regions, where flooding and liquefaction risk is low, but where slope hazards are prevalent? Should we take strong measures to protect our groundwater and surface-water resources?

The Lower Mainland faces many serious issues including atmospheric pollution, ecological degradation, geological hazards, and societal challenges. By avoiding geological problems through a proactive and informed decision-making process, we can minimize the negative effects on the health and economic well-being of society. To develop where the effects of a known hazard or problem cannot be mitigated is irresponsible stewardship of the land. Integrated scientific study can provide the insights necessary to minimize problems and maximize effective planning.

Geological knowledge plays an important role and should be considered as the first step towards informed and effective land-use decisions.

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REFERENCES

Adams, J.
1990: Paleoseismicity of the Cascadia Subduction Zone: evidence from turbidites off the Oregon–Washington margin; Tectonics, v. 9, p. 569–583.

Adams, M.A. and Williams, G.L.
2004: Tidal marshes of the Fraser River estuary: composition, structure, and a history of marsh creation efforts to 1997; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Armstrong, J.E.
1984: Environmental and engineering applications of the surficial geology of the Fraser lowlands, British Columbia; Geological Survey of Canada, Paper 83-23, 54 p.

Barry, R.G. and Chorley, R.J.
1982: Atmosphere, Weather, and Climate; (fourth edition), Methuen and Co., New York, New York, 407 p.

Bendell-Young, L., Yin, K., Thomas, C., Harrison, P.J., Feeney, T., Arvai, J.L., Levings, C.D., and Ross, L.
2004: Biogeochemistry of the intertidal area of the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Brand, D.G. and Thompson, J.A.J.
2004: Toxicological studies of fish and invertebrates in the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Casadevall, T.J. (ed.)
1994: Volcanic Ash and Aviation Safety; Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety; United States Geological Survey, Bulletin 2047, 450 p.

Church, M., McLean, D.G., Kostaschuk, R.A., MacFarlane, S., Tassone, B., and Walton, D.
1992: Channel Stability and Management of Lower Fraser River – Field Excursion Guide; Environment Canada, Inland Waters Directorate, Water Resources Branch, Water Survey of Canada, Vancouver, British Columbia, 99 p.

Clague, J.J.
1981: Late Quaternary geology and geochronology of British Columbia; part 2: summary and discussion of radiocarbon-dated Quaternary history; Geological Survey of Canada, Paper 80-35, 41 p.
1994: Quaternary stratigraphy and history of south-coastal British Columbia; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 181–192.
1996: Paleoseismicity and seismic hazards, southwestern British Columbia; Geological Survey of Canada, Bulletin 494, 88 p.

Clague, J.J., Armstrong, J.E., and Mathews, W.H.
1980: Advance of the Late Wisconsin Cordilleran Ice Sheet in southern British Columbia since 22 000 yr B.P.; Quaternary Research, v. 13, p. 322–326.

Dakin, R.A.
1991: Groundwater contamination from agricultural sources in the lower Fraser Valley; The BC Professional Engineer, October 1991, p. 30–32.

Davis, H.C. and Hutton, T.A.
2004: Metropolitan Vancouver: an economic gateway to the Pacific Rim; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Delaney, T.A. and Turner, R.J.W.
1994: A preliminary directory of trace element databases available in the Vancouver map area; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 299–316.

Dragert, H., Hyndman, R.D., Rogers, G.C., and Wang, K.
1994: Current deformation and the width of the seismogenic zone of the Northern Cascadia Subduction Thrust; Journal of Geophysical Research, v. 99, p. 653–668.

Eisbacher, G.H. and Clague, J.J.
1981: Urban landslides in the vicinity of Vancouver, British Columbia, with special reference to the December 1979 rainstorm; Canadian Geotechnical Journal, v. 18, p. 205–216.
1984: Destructive mass movements in high mountains: hazard and management; Geological Survey of Canada, Paper 84-16, 230 p.

Engebretson, D.C., Kelley, K.P., Cashman, H.P., and Richards, M.A.
1992: 180 million years of subduction; Geological Society of America Today, v. 2, p. 93–100.

England, T.D.J. and Calon, T.J.
1991: The Cowichan Fold and Thrust System, Vancouver Island, southwestern British Columbia; Geological Society of America, Bulletin, v. 103, p. 336–362.

England, T.D.J., Massey, N.W.D., Roden-Tice, M.K., Currie, L.D., and Miller, D.S.
1997: Apatite fission-track dating of the Cowichan Fold and Thrust System, southern Vancouver Island, British Columbia; Canadian Journal of Earth Sciences, v. 34, p. 635–645.

Evans, S.G. and Savigny, K.W.
1994: Landslides in the Vancouver–Fraser Valley–Whistler region; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 251–286.

Farley, A.L.
1979: Atlas of British Columbia: People, Environment, and Resource Use; University of British Columbia Press, Vancouver, British Columbia, 136 p.

Halstead, E.C.
1986: Groundwater supply – Fraser Lowland, British Columbia; Environment Canada, Inland Waters Directorate, National Hydrology Research Institute, Paper No. 26, Scientific Series No. 145, 80 p.

Hart, B.S., Barrie, J.V., Christian, H.A., Hamilton, T.S., Davis, A.M., and Law, L.K.
1993: Marine geological, geophysical and geotechnical investigations of the submarine portions of the Fraser Delta: implications for submarine failures; *in* Proceedings of the 1993 Canadian Coastal Conference (Vancouver, B.C.): Coastal Zone Engineering Program, National Research Council of Canada, Ottawa, Ontario, v. 2, p. 851–865.

Hickson, C.J.
1994: Character of volcanism, volcanic hazards, and risk, northern end of the Cascade Magmatic Arc, British Columbia and Washington State; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 231–250.

Hoblitt, R.P., Miller, C.D., and Scott, W.E.
1987: Volcanic hazards with regard to siting nuclear-power plants in the Pacific Northwest; United States Geological Survey, Open File Report 87-297, 196 p.

Holdahl, S.R., Faucher, F., and Dragert, H.
1989: Contemporary vertical crustal motion in the Pacific Northwest; *in* Slow Deformation and Transmission of Stress in the Earth, (ed.) H.C. Cohen and P. Vanicek; American Geophysical Union, Geophysical Monograph 49, v. 4, p. 17–29.

Hora, Z.D. and Basham, F.C.
1981: Sand and gravel study 1980, British Columbia Lower Mainland; British Columbia Ministry of Energy, Mines, and Petroleum Resources, Paper 1980-10, 74 p.

Hungr, O., Morgan, G.C., VanDine, D.F., and Lister, D.R.
1987: Debris flow defenses in British Columbia; *in* Debris Flows/Avalanches: Process, Recognition, and Mitigation, (ed.) J.E. Costa and G.F. Wieczorek; Geological Society of America, Reviews in Engineering Geology, v. 7, p. 201–222.

Jackson, P.L.
2004: Climatological setting of the Fraser River delta and its urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Kew, M.
2004: First towns of the Fraser estuary: a brief history of Fraser valley Halkomelem society; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Kostaschuk, R.A. and Luternauer, J.L.
2004: Sedimentary processes and their environmental significance: lower main channel, Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Leaming, S.
1968: Sand and gravel in the Strait of Georgia area; Geological Survey of Canada, Paper 66-60, 149 p.

Liebscher, H., Hii, B., and McNaughton, D.
1992: Nitrates and pesticides in the Abbotsford Aquifer, southwestern British Columbia; Environment Canada, Vancouver, British Columbia, 83 p.

Luternauer, J.L.
1980: Genesis of morphological features on the western delta front of the Fraser River, British Columbia – status of knowledge; *in* The Coastline of Canada, Littoral Processes and Shore Morphology, (ed.) S.B. McCann; Geological Survey of Canada, Paper 80-10, p. 381–396.

Luternauer, J.L., Barrie, J.V., Christian, H.A., Clague, J.J., Evoy, R.W., Hart, B.S., Hunter, J.A., Killeen, P.G., Kostaschuk, R.A., Mathewes, R.W., Monahan, P.A., Moslow, T.F., Mwenifumbo, C.J., Olynyk, H.W., Patterson, R.T., Pullan, S.E., Roberts, M.C., Robertson, P.K., Tarbotton, M.R., and Woeller, D.J.
1994: Fraser River delta: geology, geohazards and human impact; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 197–220.

Macdonald, R.W., Macdonald, D.M., O'Brien, M.C., and Gobeil, C.
1991: Accumulation of heavy metals (Pb, Zn, Cu, Cd), carbon and nitrogen in sediments from Strait of Georgia, B.C., Canada; Marine Chemistry, v. 34, p. 109–135.

Matysek, P.F., Gravel, J.L., Jackaman, W., and Feulgen, S.
1990: British Columbia regional geochemical survey, stream sediment and water geochemical data, Vancouver – NTS 92G; British Columbia Ministry of Energy, Mines and Petroleum Resources, RGS 26, 115 p. (*also* Geological Survey of Canada, Open File 2184).

McKenna, G.T., Luternauer, J.L., and Kostaschuk, R.A.
1992: Large-scale mass-wasting events on the Fraser River delta front near Sand Heads, British Columbia; Canadian Geotechnical Journal, v. 29, p. 151–156.

McLean, D.G. and Tassone, B.L.
1991: A sediment budget of the lower Fraser River; *in* Proceedings, 5th Federal Interagency Sedimentation Conference, Las Vegas, Nevada, p. 2-33–2-40.

Monahan, P.A., Luternauer, J.L., and Barrie, J.V.
1993: A delta topset "sheet" sand and modern sedimentary processes in the Fraser River delta, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 93-1A, p. 263–272.

Monger, J.W.H. and Journeay, J.M.
1994: Basement geology and tectonic evolution of the Vancouver region; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger, Geological Survey of Canada, Bulletin 481, p. 3–25.

Mosher, D.C., Christian, H.A., Hunter, J.A., and Luternauer, J.L.
2003: Onshore and offshore geohazards of the Fraser River delta; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Mustard, P.S.
1994: The Upper Cretaceous Nanaimo Group, Georgia Basin; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 27–95.

Mustard, P.S. and Rouse, G.E.
1994: Stratigraphy and evolution of Tertiary Georgia Basin and subjacent Upper Cretaceous sedimentary rocks, southwestern British Columbia and northwestern Washington State; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 97–169.

Mustard, P.S., Clague, J.J., Hickson, C.J., Jackson, L.E., Jr., Luternauer, J.L., Monger, J.W.H., Ricketts, B.D., Tnrner, R.J.W., and Woodsworth, G.J.
1998: Geology and geohazards of the Greater Vancouver region; *in* Geology of Canadian Cities, (ed.) P.F. Karrow and O.L. White; Geological Association of Canada, Special Paper 42, p. 39–70.

Parrish, R.R.
1983: Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia; 1; fission track dating, apparent uplift rates, and patterns of uplift; Tectonics, v. 2, p. 941–994.

Peacock, M.A.
1935: Fiord-land of British Columbia; Geological Society of America, Bulletin, v. 46, p. 633–696.

Picard, G.L.
1961: Oceanographic features of inlets in the British Columbia mainland coast; Fisheries Research Board of Canada Journal, v. 18, p. 907–999.

Ricketts, B.D. (ed.)
2000: Mapping, Geophysics, and Groundwater Modelling in Aquifer Delineation, Fraser Lowland and Delta, British Columbia; Geological Survey of Canada, Bulletin 552, 131 p.

Ricketts, B.D. and Liebscher, H.
1994: The geological framework of groundwater in the Greater Vancouver area; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 287–298.

Riddihough, R.R. and Hyndman, R.D.
1991: Modern plate tectonic regime of the continental margin of Western Canada; *in* Chapter 13 of Geology of the Cordilleran Orogen in Canada, (ed.) H. Gabrielse and C.J. Yorath; Geological Survey of Canada, Geology of Canada, no. 4, p. 433–455 (*also* Geological Society of America, The Geology of North America, v. G-2).

Rogers, G.C.
1983: Seismotectonics of British Columbia; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 247 p.
1994: Earthquakes in the Vancouver area; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 221–229.

Ryder, J.M., Fulton, R.J., and Clague, J.J.
1991: The Cordilleran Ice Sheet and the glacial geomorphology of southern and central British Columbia; Géographie physique et Quaternaire, v. 45, p. 365–377.

Satake, K. and Tanioka, Y.
1996: Tsunami heights along the Pacific Northwest computed from the M=9 earthquake of January, 1700; (abstract) Geological Society of America, Cordilleran Section Annual Meeting, Abstracts with Programs, v. 28, p. 108.

Schaefer, V.
2004: Ecological setting of the Fraser River delta and its urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Schumm, S.A.
1963: The disparity between present rates of denudation and orogeny; United States Geological Survey, Professional Paper 454-H, 13 p.

Servizi, J.A.
1989: Protecting Fraser River salmon (*Ochorhynchus* spp.) from wastewaters: an assessment; *in* Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks, (ed.) C.D. Levings, L.B. Holtby, and M.A Henderson; Canadian Special Publication of Fisheries and Aquatic Sciences, v. 105, p. 136–153.

Sibbick, S.J., Matysek, P.F., Cook, S.J., and Jackaman, W.
1992: Influence of geology on metal concentrations within the Howe Sound Watershed; *in* Proceedings of the Howe Sound Environmental Science Workshop, (ed.) C.D. Levings, R.J.W. Turner, and B.D. Ricketts; Fisheries and Oceans Canada, Canadian Technical Report of Fisheries and Aquatic Sciences, no. 1879, p. 35–42.

Turner, R.J.W., Clague, J.J., and Groulx, B.J.
1996: Geoscape Vancouver – living with our geological landscape; Geological Survey of Canada, Open File 3309, 1 sheet.

Turner, R.J.W., Clague, J.J., Groulx, B.J., and Journeay, J.M.
1998: GeoMap Vancouver; Geological Survey of Canada, Open File 3511, 1 sheet.

Vingarzan, R. and Sekela, M.
2004: Organic contaminants in suspended sediment upstream of the Fraser River delta; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Watts, B.D., Seyers, W.C., and Stewart, R.A.
1992: Liquefaction susceptibility of Greater Vancouver area soils; *in* Geotechnique and Natural Hazards; BiTech Publishers, Vancouver, British Columbia, p. 145–157.

Woods, P.
2004: Flooding in the Fraser River delta and urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Yorath, C.J. and Hyndman, R.D.
1983: Subsidence and thermal history of the Queen Charlotte Basin; Canadian Journal of Earth Sciences, v. 20, p. 30–40.

APPENDIX A

A compilation of geological hazards that have affected human activity in the Lower Mainland and surrounding areas. Earthquake and flood information for other regions have been provided for the purpose of comparison.

Table A1. Earthquake damage examples

Location and date	Description	Reference
Port Alberni and other coastal areas, British Columbia, March 28, 1964	A tsunami generated by a magnitude 8.4 earthquake in Alaska caused $10 million damage (1964 dollars)	Sokolowski, 2001
Northridge, California, January 17, 1994	Magnitude 6.7 Damage estimated at $20 billion 57 killed, more than 7000 injured	Mori, 1996
Kobe, Japan, January 17, 1995	Magnitude 6.9 Direct economic loss estimated at $130 billion Economic loss including business disruption estimated at $100 billion 5096 killed, 27 000 injured	Somerville, 1995
Vancouver, British Columbia	Predicted damage for a magnitude 6.5 earthquake in the Strait of Georgia or a magnitude 7.5 close to Vancouver is estimated at $14.3–$32.1 billion.	Munich Reinsurance Company of Canada, 1992

References

Sokolowski, T.J.
2001: The great Alaskan earthquake and tsunamis of 1964; West Coast and Alaska Warning Center, website report http://wcatwc.arh.noaa.gov/64quake,htm.

Mori, J. (ed.)
1996: USGS response to an urban earthquake: Northridge 1994; United States Geological Survey, Open File Report 96-263, 94 p.

Somerville, P.
1995: Kobe earthquake: an urban disaster; EOS, v. 76, no. 6, p. 49–51.

Munich Reinsurance Company of Canada
1992: Earthquake: Economic Impact Study; Toronto, Ontario, 99 p.

APPENDIX A (cont.)

(This includes landslides, rockfall, debris flows, debris torrents and submarine landslides.)

Table A2. Mass wasting examples, British Columbia

Location and date	Description	Reference
Rubble Creek (32 km north of Squamish), 1856	The most recent of a series of large failures in steep volcanic rock occurred in 1856 at the head of Rubble Creek. In 1980 the Rubble Creek area along Highway 99 was designated as too hazardous for human habitation and property owners were bought out or relocated at a cost of $17.4 million.	Evans and Savigny (1994)
Haney, 1880	A large landslide in glaciomarine sediments occurred on Jan. 30 (*see* Fig. 3). There was one fatality, and substantial wave damage to docking facilities along the Fraser River.	Evans and Savigny (1994)
Fraser Canyon (Hells Gate), 1914	Rockfall in the Fraser Canyon added to an obstruction initiated a year earlier by railway construction. The return of spawning salmon was obstructed with long-term fishery implications. Between 1951 and 1978 there was a $1.7 billion (1978 dollars) loss to the sockeye fishery alone due to this 1914 obstruction. Between 1944 and 1966 fishways were constructed at a cost of $1.36 million to allow fish to pass the obstruction.	Evans and Savigny (1994)
Britannia, 1915	A rock avalanche on Britannia Mountain (Jane Camp) killed 56 people.	Evans and Savigny (1994)
Britannia Beach, 1921	During heavy rains an embankment collapsed causing a debris flood. The failure was attributable to a blocked culvert. The debris flood destroyed 60 houses and caused 37 deaths.	Evans and Savigny (1994)
Woodfibre, 1955	There was $500 000 to $700 000 damage to warehouses and wharf facilities as the delta slope of Woodfibre Creek failed. The Squamish and Fraser deltas both demonstrate potential for this type of failure.	Evans and Savigny (1994)
Hope Slide, Highway 3 (15 km southeast of Hope), 1965	A large landslide occurred on January 9, blocking Highway 3 for several kilometres. The landslide buried three vehicles claiming four lives.	Evans and Savigny (1994)
Lions Bay area, 1958 to 1983	Between 1958 and 1983, 14 debris torrents occurred on 6 creeks resulting in 12 deaths, destruction of 11 bridges, 4 houses, and other property damage. These events are triggered by intense rains on steep coastal fiord walls (Fig. 10). The two latest tragic events: 1) Oct. 13, 1981, bridge destroyed and 9 killed; 2) Feb. 1983, train and highway bridges damaged, 4 homes destroyed, 2 people killed. Sophisticated protection structures were built on 4 creeks at a total cost of $20 million; they include debris dams, deflection structures, and channel lining.	Evans and Savigny (1994)
Hope–Chilliwack Corridor, July 1987	Extreme rains triggered at least 14 debris flows. There was no loss of life, but one house engulfed. Road and railway repairs were estimated to be $300 000.	Evans and Savigny (1994)
Howe Sound, October 1990	Rockfall on Sea to Sky Highway along Howe Sound blocked the highway for 12 days. Seven million dollars spent for repairs and construction of preventative structures.	Evans and Savigny (1994)

APPENDIX A (cont.)

Table A3. Flood damage examples

Location and date	Description	Reference
Fraser River, 1894	The greatest flood on the Fraser River in historical record. No damage estimates are available.	Woods (2001)
Fraser River, June 1948	Flood waters caused $20 million (1948 dollars) damage. Over the period 1968–1995, expenditures to dyke improvements have totalled about $148 million.	Woods (2001)
Saguenay region, Quebec, July 1996	Damages are estimated at $800 million, and 2 dead.	Brooks and Lawrence, 2000
Red River Basin, North Dakota and Manitoba, 1997	Flood damages exceed $1 billion U.S.	International Red River Basin Task Force, 2000

References

Brooks, G.R. and Lawrence, D.E.
2000: Geomorphic effects and impacts from the July, 1996 severe flooding in the Saguenay area, Quebec: Geological Survey of Canada, unpub. website report, http://sts.gsc.nrcan.gc.ca/page1/geoh/saguenay/saguenay.htm

International Red River Basin Task Force
2000: Final report of the International Red River Basin Task Force to the International Joint commission; the Next Flood: Getting Prepared, Washington, D.C., International Joint Commission, 167 p.

APPENDIX B

BIBLIOGRAPHY: ADDITIONAL GEOLOGICAL INFORMATION FOR THE LOWER MAINLAND

Maps

Armstrong, J.E.
1980: Surficial geology, Chilliwack (west half), British Columbia; Geological Survey of Canada, Map 1487A, scale 1:50 000.
1980: Surficial geology, Mission, British Columbia; Geological Survey of Canada, Map 1485A, scale 1:50 000.

Armstrong, J.E. and Hicock, S.R.
1979: Surficial geology, Vancouver, British Columbia; Geological Survey of Canada, Map 1486A, scale 1:50 000.
1980: Surficial geology, New Westminster, British Columbia; Geological Survey of Canada, Map 1484A, scale 1:50 000.

Journeay, J.M. and Monger, J.W.H.
1995: Geology and crustal structure of the southern Coast and Intermontane belts, southern Canadian Cordillera, British Columbia; *in* Guide to the Geology and Tectonic Evolution of the Southern Coast Mountains, (ed.) J.W.H. Monger and J.M. Journeay; Geological Survey of Canada, Open File 2490, scale 1:50 000.

Roddick, J.A.
1965: Geology, Pitt Lake (Vancouver, east half), British Columbia; Geological Survey of Canada, Map 1151A, scale 1:253 440.
1965: Geology, Vancouver North, British Columbia; Geological Survey of Canada, Map 1152A, scale 1:63 360.
1965: Geology, Coquitlam, British Columbia; Geological Survey of Canada, Map 1153A, scale 1:63 360.

Turner, R.J.W., Clague, J.J., and Groulx, B.J.
1996: Geoscape Vancouver – living with our geological landscape; Geological Survey of Canada, Open File 3309, 1 sheet.

Turner, R.J.W., Clague, J.J., Groulx, B.J., and Journeay, J.M.
1998: GeoMap Vancouver; Geological Survey of Canada, Open File 3511, 1 sheet.

Publications

Armstrong, J.E.
1984: Environmental and engineering applications of the surficial geology of the Fraser Lowland, British Columbia; Geological Survey of Canada, Paper 83-23, 54 p.
1990: Vancouver geology; Geological Association of Canada, Cordilleran Section, Vancouver, British Columbia, 128 p.

Monger, J.W.H. (ed.)
1994: Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia; Geological Survey of Canada, Bulletin 481, 316 p.

Mustard, P.S., Clague, J.J., Hickson, C.J., Jackson, L.E., Jr., Luternauer, J.L., Monger, J.W.H., Ricketts, B.D., Turner, R.J.W., and Woodsworth, G.J.
1998: Geology and geohazards of the Greater Vancouver region; *in* Geology of Canadian Cities, (ed.) P.F. Karrow and O.L. White; Geological Association of Canada, Special Paper 42, p. 39–70.

Roddick, J.A.
1965: Vancouver North, Coquitlam, and Pitt Lake map-areas, British Columbia; Geological Survey of Canada, Memoir 335, 276 p.

Digital sources of geoscience information

Databases

(The following is a list of publicly available geoscience databases and related information for the Lower Mainland).

Bélanger, J.R. and Harrison, J.E.
1976: Vancouver subsurface information data bank; Geological Survey of Canada, Open File 382.
British Columbia Ministry of Energy, Mines and Petroleum Resources, 1990, MINFILE for Vancouver NTS map sheet (92G) 1990;. British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Survey Branch, Victoria, British Columbia (5 maps, scale 1:25 000 and microfiche).

Delaney, T.A. and Turner, R.J.W.
1994: A preliminary directory of trace element databases available in the Vancouver map area; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 299–316.

Hungr, O. and Jackson, L.E., Jr.
1992: A debris flow basin and event data base format with an example data set from southwestern British Columbia; Geological Survey of Canada, Open File 2522 (diskette).

Matysek, P.F., Gravel, J.L., Jackaman, W., and Feulgen, S.
1990: British Columbia regional geochemical survey, stream sediment and water geochemical data, Vancouver – NTS 92G; British Columbia Ministry of Energy, Mines and Petroleum Resources, RGS 26, 115 p. (*also* Geological Survey of Canada, Open File 2184).

Monahan, P.A. and Luternauer, J.L.
1994: Greater Vancouver Geotechnical Database (British Columbia): Richmond pilot project; *in* Current Research 1994-E; Geological Survey of Canada, p. 85–91.

Mustard, P.S. and Roddick, J.A.
1992: Vancouver subsurface information data bank for the period 1913 to 1972; A re-release of Open File 382 (1976, J.R. Bélanger and J.E. Harrison) in a DOS database format; Geological Survey of Canada, Open File 2532, 9 p.

Ricketts, B.D. and Dunn, D.
1995: Groundwater database development, Fraser Valley, British Columbia; *in* Current Research 1995-A; Geological Survey of Canada, p. 7–10.

Woodsworth, G.J. and Ricketts, B.D.
1994: A digital database for groundwater data, Fraser Valley, British Columbia; *in* Current Research 1994-A; Geological Survey of Canada, p. 207–210.

CD-roms

Journeay, J.M. and Monger, J.W.H.
1997: Geoscience Library for the Southern Coast and Intermontane Belts, S.W. British Columbia; Geological Survey of Canada, Open File 3276, 1 CD-ROM.

Journeay, J.M. and Williams, S.P.
1995: GIS Map Library: A Window on Cordilleran Geology; Geological Survey of Canada, Open File 2948 (v. 1.0), 1 CD-ROM.

Web sites and the internet

Geological Survey of Canada web site: www.nrcan.gc.ca/gsc

Geological Survey Branch, B.C. Ministry of Energy and Mines web site: http://www.em.gov.bc.ca/Mining/Geolsurv/default.htm

Climatological setting of the Fraser River delta and its urban estuary

Peter L. Jackson[1]

Jackson, P.L., 2004: Climatological setting of the Fraser River delta and its urban estuary; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 23–34.*

Abstract: "Lotus land" or "Canada's banana belt" are names used by both locals and other Canadians to vividly convey that southwestern British Columbia has a relatively benign climate. The climate can be characterized as warm and wet all year with dry spells during the summer. The temperature regime of the region is moderate, especially by Canadian standards; summers are warm but seldom hot or humid, and winters are cool but seldom cold. Annual precipitation, occurring mostly in the form of rain, is high, although summers usually have little precipitation. Winds are generally light. One only needs to venture a few kilometres north or east into the mountains, however, for the climate to change dramatically; annual precipitation can triple, occurring mostly as snow, and temperatures can decrease by several degrees. The physiographic setting accounts to a great extent for the region's climate as well as its large spatial variation.

Résumé : Le « pays du lotus », la « ceinture bananière du Canada » : c'est par ces surnoms colorés que les gens du lieu et le reste des Canadiens expriment le fait que le sud-ouest de la Colombie-Britannique jouit d'un climat relativement doux. On peut caractériser ce climat comme étant assez chaud et pluvieux à l'année longue, avec des périodes sèches pendant l'été. Le régime de température de la région est modéré, surtout si on le compare au reste du Canada; l'été, bien qu'assez chaud, est rarement chaud ou humide, et l'hiver est frais, mais rarement froid. La précipitation annuelle, qui s'accumule surtout sous forme de pluie, est abondante, bien qu'il y ait peu d'accumulation en été. Les vents sont généralement légers. Il suffit pourtant de s'engager dans les montagnes à quelques kilomètres au nord ou à l'est pour que le climat change considérablement; dans ces régions, la précipitation annuelle peut être trois fois plus abondante et s'accumuler principalement sous forme de neige, et la température peut être moindre de plusieurs degrés. La topographie explique en grande partie le climat de la région ainsi que sa grande variabilité spatiale.

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PLACE AND CLIMATE

How the geographic setting affects local conditions

Introduction

Climate is determined by the interaction between major weather systems and the local setting, which dramatically alters those weather systems. The physiographic features which are most important in modulating the weather and climate are discussed below, ranging from large-scale to small-scale effects.

Effects of location on the western edge of a continent

The combination of the land-sea contrast and the mountains of western North America results in preferential positions for surface high- and low-pressure systems (*see* Fig. 1, 2) and sets the stage for the local climate (*see* further discussion in the section 'Large-scale climatology of the region'). With storms and winds typically coming from the west or southwest, this means that the air blowing into the Fraser Lowland region acquires most of its characteristics from the Pacific Ocean. Because the Pacific Ocean changes temperature relatively little during the course of a year, this proximity to water moderates the region's temperatures, giving comparatively

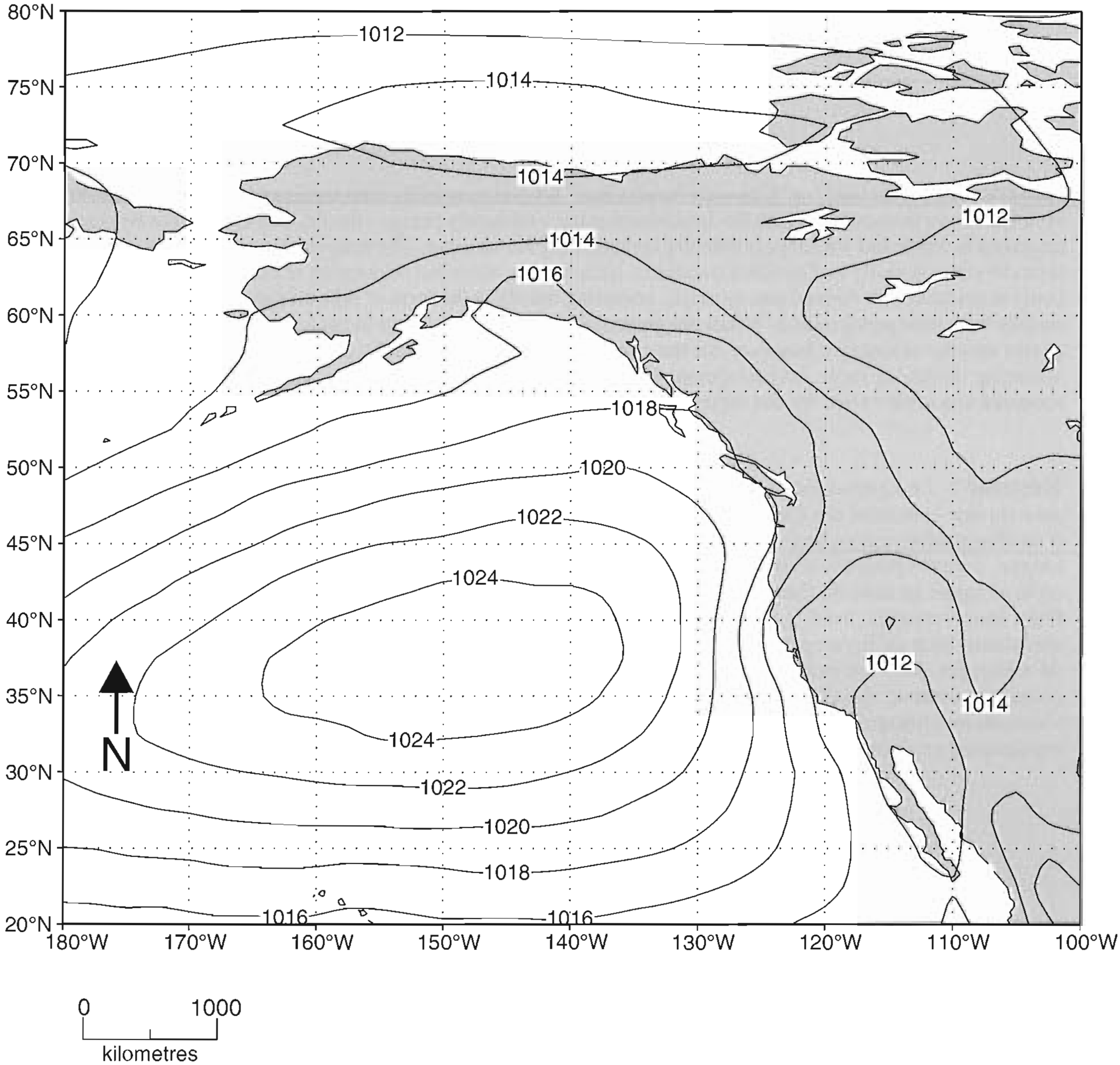

Figure 1. Mean sea-level pressure field (1982–1994) for July (contour values are in hectopascals).

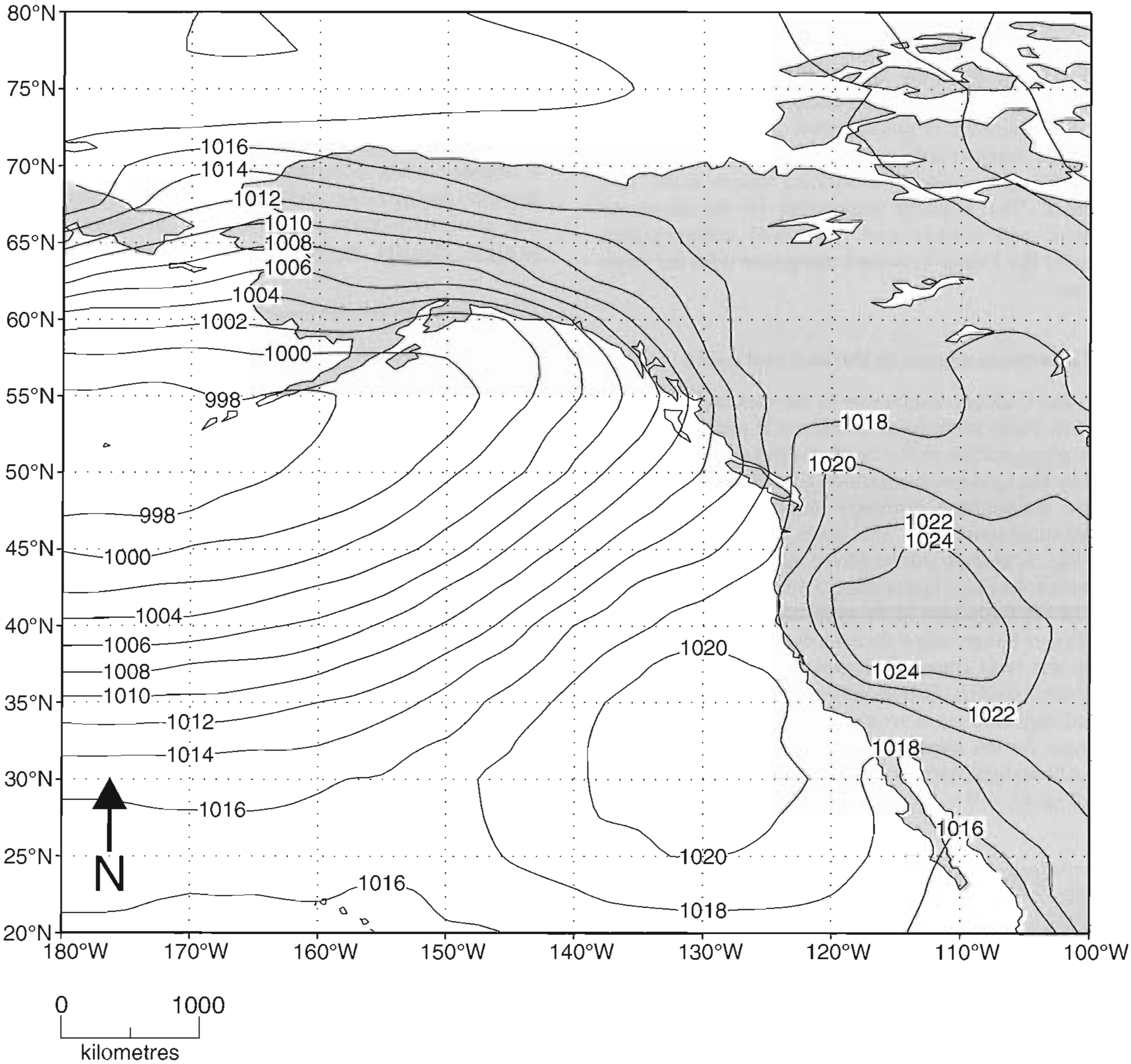

Figure 2. Mean sea-level pressure field (1982–1994) for January (contour values are in hectopascals).

warm winters and cool summers. The over-water trajectory of air reaching the region moistens the air and helps account for the frequent cloudy conditions and high precipitation. The low precipitation observed in the summer is also due in part to the region's proximity to the Pacific Ocean, where air at levels less than a few hundred metres from the surface is kept cool by the ocean. This cool marine layer is capped by an inversion, a region where the temperature increases with elevation and separates the layer of cool marine air from the rest of the atmosphere. This configuration of cool, dense air underlying warmer, less dense air is inherently stable and, therefore, resistant to upward and downward motions. Consequently, the frequency of convective clouds and showers generated by the sun warming the ground, such as thunderstorms, is reduced and helps to account for dry summers.

Effects of significant mountain ranges immediately to the west

Because weather systems typically come from the west or southwest, they must cross the mountains of Vancouver Island or the Olympic Peninsula before reaching the Fraser Lowland. In crossing mountains, air is forced to rise. As air rises, it encounters lower pressure and expands. The work required for the expansion comes from the internal energy of the air, so that the rising air must cool. This is called adiabatic cooling and amounts to about a 10°C change with every 1000 m increase in elevation for unsaturated air. As the rising air cools, it approaches saturation, resulting in the water vapour condensing to form clouds and precipitation along the upwind side of the mountains. When water vapour condenses, it releases latent heat and warms the air. Precipitation along the seaward slopes removes water from the air. When the air descends back to sea level, it moves towards higher pressure, is compressed and warms adiabatically by 10°C with every 1000 m decrease in elevation; however, it may have gained additional heat if condensation occurred and it may have lost moisture if precipitation occurred. This can result in drier, warmer air over the Fraser Lowland than existed over the open ocean — something known as the 'rain shadow effect'. This is partly responsible for the decreased precipitation and clouds and increased temperatures observed over the Fraser Lowland compared with the outer coastal areas.

Effects of mountain ranges to the east and north

The Coast and Cascade mountains to the east and southeast and the north shore mountains to the north account for the increase in precipitation in the northern and eastern parts of the region by the upslope mechanism described above. With atmospheric temperature normally decreasing with elevation, the mountainous areas also have greater amounts of snow (*see* Fig. 3) as they will be above the freezing elevation level (i.e. below freezing temperature) for a greater portion of the year. The configuration of the mountains on either side of the lower Fraser River valley forms a confluence to the east. Wind from the west causes horizontal convergence of air, creating upward motion. Enhanced upward motion can result in increased moisture condensation and precipitation, helping to account for the increase in precipitation up the valley (compare Abbotsford Airport with Vancouver International Airport in Fig. 4).

Effects of location at a coastline

A seashore location has a large effect on regional variations in wind and temperature, especially during the summer months when conditions are calm and clear. Because ocean temperature fluctuates only slightly between day and night (tenths of a degree) when compared to land temperature (tens of degrees) during clear conditions, there is typically a temperature gradient between land and ocean that reverses from day to night. Usually, the land is warmer than the ocean by day

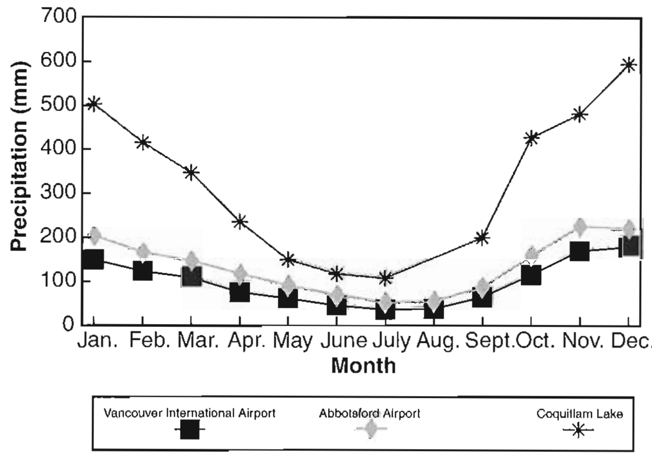

Figure 4. *Monthly average precipitation (1961–1990) at Vancouver International Airport, Abbotsford Airport, and Coquitlam Lake.*

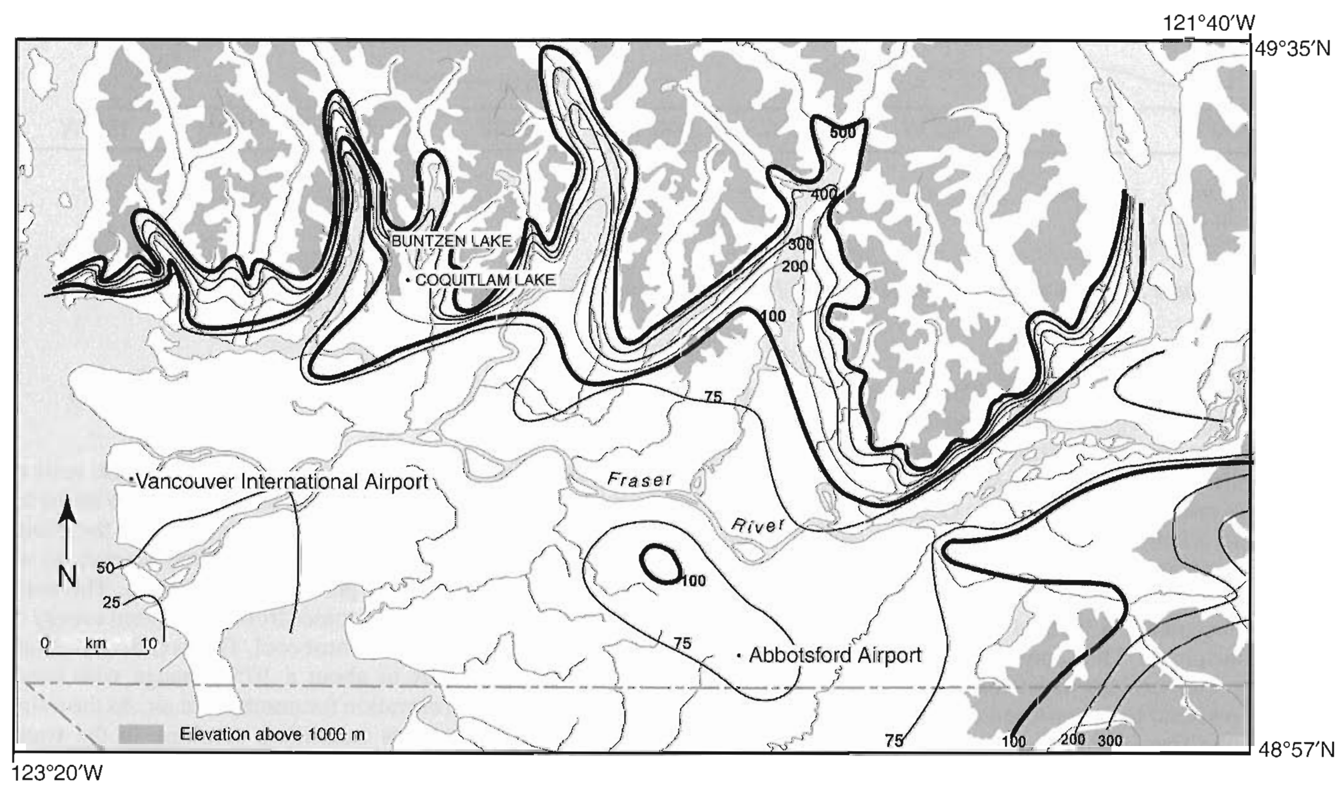

Figure 3. *Spatial variation in annual snowfall. Data are annual averages based on the 1961–1990 period (contour values are in centimetres).*

and is often cooler than the ocean by night. This temperature difference causes differential expansion of the air, resulting in relatively low pressure at the surface over the land by day and often lower pressure over water by night. Because air tends to flow towards low pressure, the change in pressure due to differential thermal regimes forces the well-known summertime circulations with sea-breeze by day and land-breeze by night (schematically shown in Fig. 5). As the cool marine air is moved inland by the sea breeze on sunny days, it is warmed by the underlying ground surface, causing daytime maximum temperatures to increase inland from the coastline (*see* Fig. 6 and compare Vancouver International and Abbotsford airports during the nonwinter months).

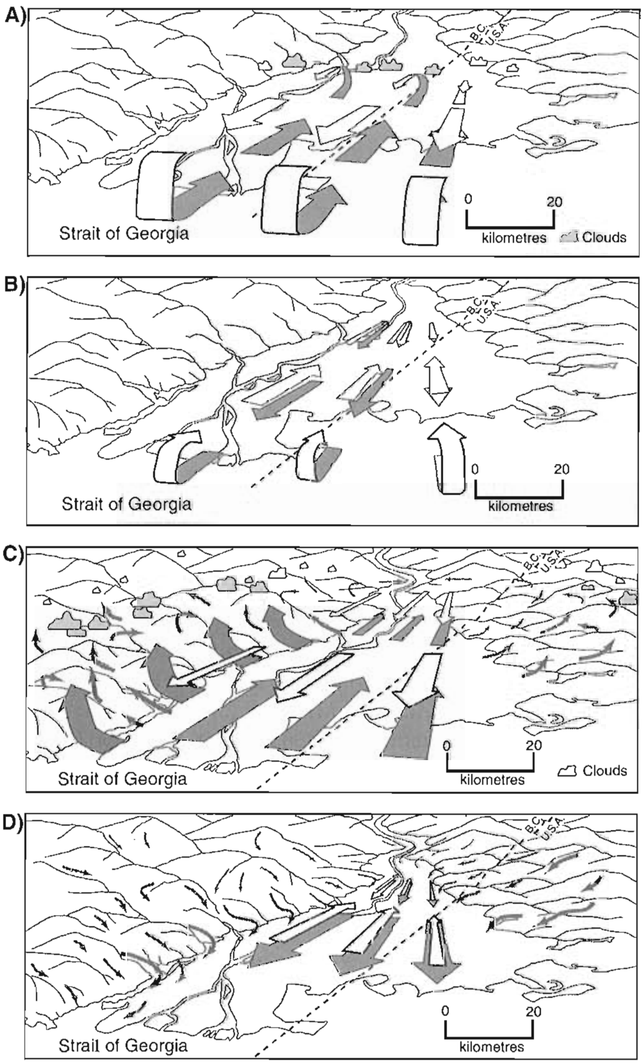

Figure 5. *Schematic depiction of wind circulations over the Fraser Lowland which can occur under calm, clear conditions:* ***A)*** *sea breeze by day,* ***B)*** *land breeze at night,* ***C)*** *upslope (anabatic) flows by day, and* ***D)*** *downslope (katabatic) flows by night.* Modified from *Oke and Hay (1994, Fig. 32).*

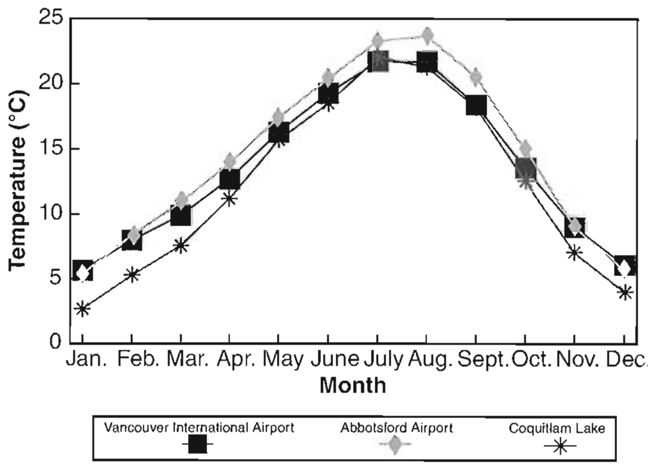

Figure 6. *Monthly average daily maximum temperatures (1961–1990) at Vancouver International Airport, Abbotsford Airport, and Coquitlam Lake.*

Effects of fiords and valleys

The configuration of a valley modifies the distribution of wind directions, with winds tending to align with the valley orientation (*see* Fig. 7, 8). The valleys and fiords dissecting the surrounding mountains affect the local wind flows during summer and winter. On summer days, because of differential heating by the sun of air near the ground on a hillside, compared to air above the ground but at the same elevation in the main valley, the air tends to flow upslope and upvalley — these are called 'anabatic' and 'valley' winds. By night, the reverse occurs, and cool air tends to flow downslope and downvalley — called 'katabatic' and 'mountain' winds (*see* Fig. 5). During the winter months, the presence of fiords and valleys, including the Fraser River valley, can have a more dramatic effect on the local weather (Jackson, 1996). At these times, cold continental arctic air can form over Alaska and Yukon Territory and move southward onto the central British Columbia plateau. The shallow cold 'pool' of dense air is partially contained by the coastal mountains; however, the air does flow out at low elevation through the valleys and fiords, and penetrates through the coastal mountain barrier. These bitterly cold winds from the east and northeast that bring arctic air to the coast are called 'Squamish' or 'outflow' winds. They often result in snow and are associated with the coldest extreme temperatures on record in the region. The Squamish winds have been observed to flow out of Howe Sound and the Fraser River valley as well as some of the secondary valleys such as Harrison and Stave lakes.

Effects of urbanization

The urbanization of the Fraser Lowland and its surroundings has impacted on the local climate. Perhaps the best known impact of urbanization on climate is the 'urban heat island' effect, which occurs mostly on calm, clear nights, when temperatures are warmer over urban areas than over their rural

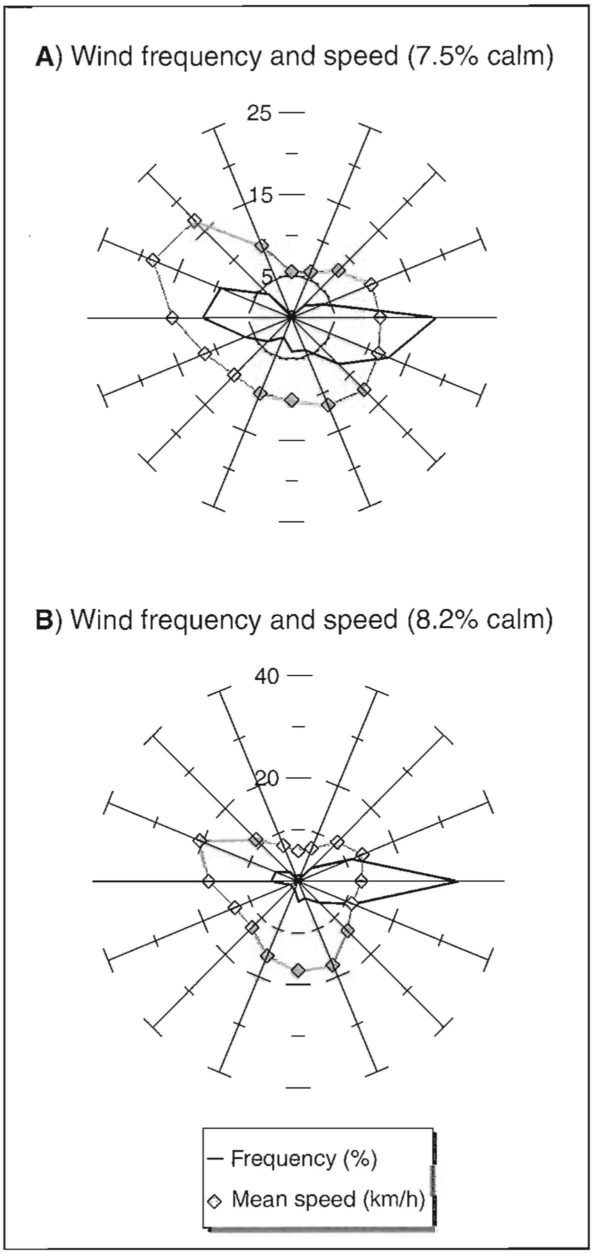

*Figure 7. Wind rose diagrams for Vancouver International Airport (1951–1980) in **A)** July and **B)** January. Direction (north at top) is the direction from which the wind is blowing. Radius is frequency (%) and speed (km/h).*

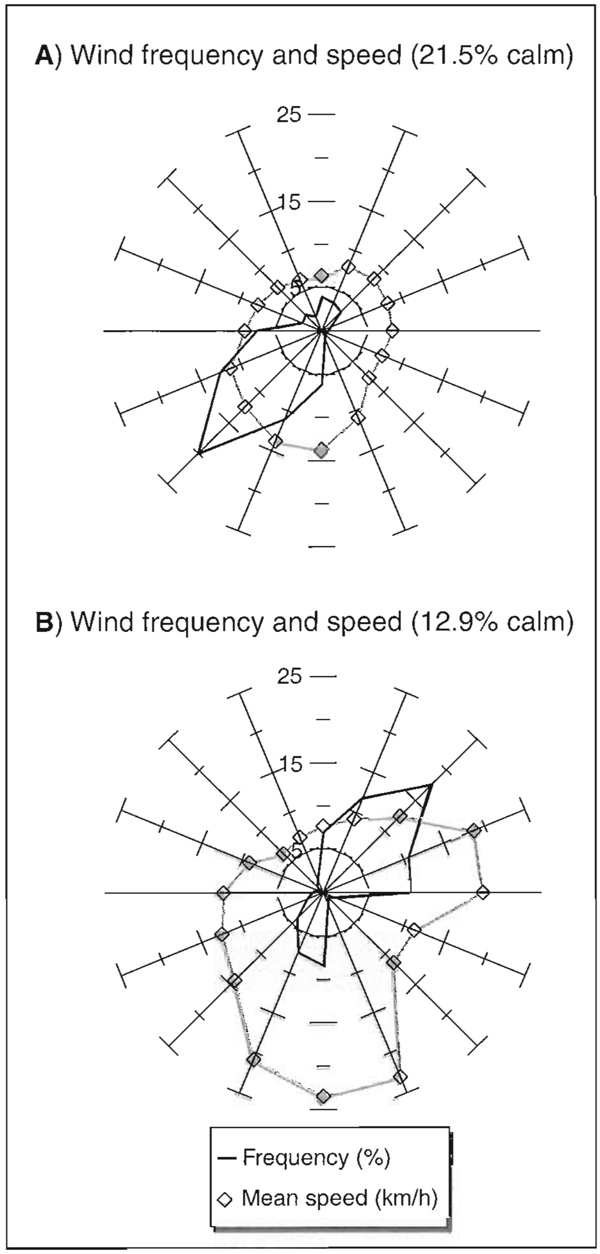

*Figure 8. Wind rose diagrams for Abbotsford Airport (1951–1980) in **A)** July and **B)** January. Direction (north at top) is the direction from which the wind is blowing. Radius is frequency (%) and speed (km/h).*

surroundings. Temperature observations depicting the urban heat island in Vancouver are shown in Figure 9 and illustrate an urban warming of 7°C compared with rural areas.

Paving of natural surfaces dramatically alters the hydrology of an urban area. Runoff is increased, especially during storms, and natural watercourses are removed or changed during urbanization. Other effects of urbanization related to pollutant emission are discussed in Jackson (2004).

Effects of local surface variations on microclimates

Microscale variations in climate over the region will occur wherever there are variations in elevation or surface type. Surface-type changes that particularly affect the microclimate of a site include variations in solar reflectivity (albedo) controlling the amount of heat from the sun absorbed at a site; variations in surface moisture that determine the partitioning of energy available at a site between evaporation and heating; slope and aspect that also affect the solar radiation regime at a location; and variations in surface aerodynamic roughness that

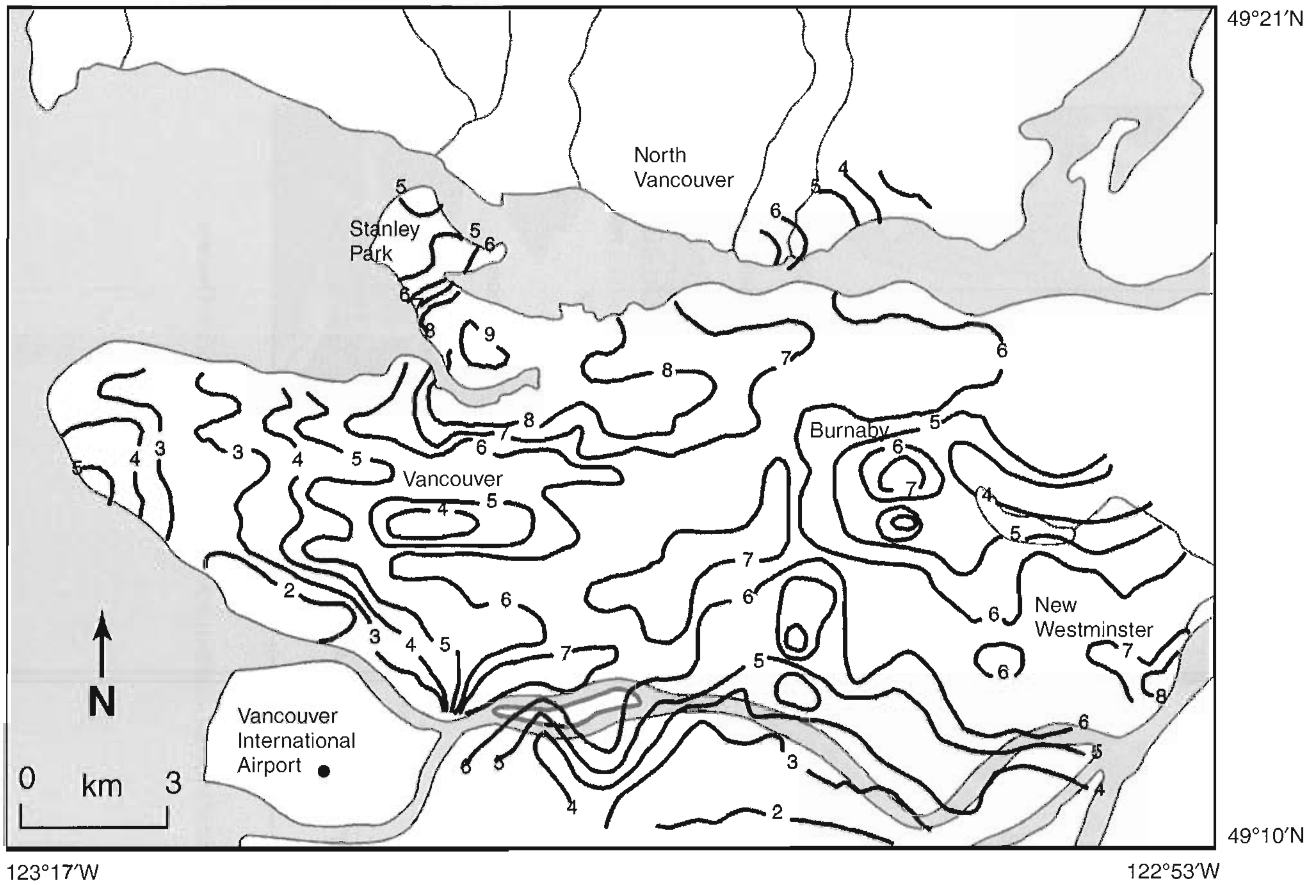

Figure 9. Vancouver's nocturnal urban heat island on a spring evening. Contours are of potential temperature (°C) observed at 1.5 m above ground. Modified from *Oke and Hay (1994, Fig. 30).*

affect the wind field. These surface variations result from the vegetation and land-use differences across the landscape. Human developments such as buildings and roads that have climatological characteristics much different from most natural surface types will have a dramatic effect on the microclimate of a site.

LARGE-SCALE CLIMATOLOGY OF THE REGION

The large-scale climatology, or average weather conditions, sets the framework within which the local modifications discussed above can act. The mean positions of these large-scale weather patterns are determined by latitude as well as by the global positions of oceans, continents, and major mountain barriers.

Synoptic conditions during the dry season

The 1982–1994 average sea-level pressure map for July (Fig. 1) depicts a high-pressure centre over the Pacific Ocean near 150°W, 38°N with a ridge of high pressure extending northeastward across the central British Columbia coast. Winds blow nearly parallel to the contours of equal pressure (isobars), inclined slightly towards low pressure, with low pressure to the left of the wind direction. The position of this ridge is favourable for winds from the northwest and dry

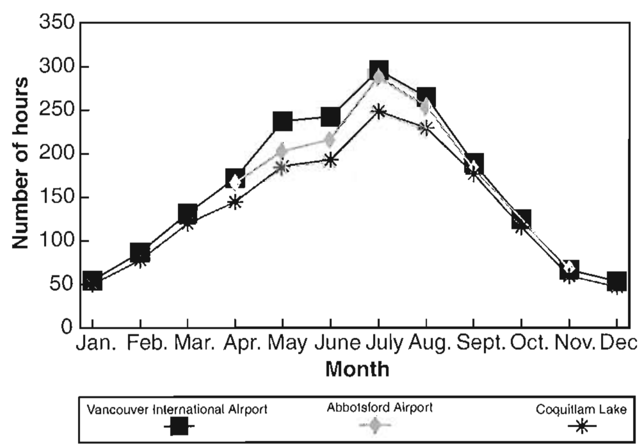

Figure 10. Monthly average of bright sunshine hours (1961–1990) at Vancouver International Airport, Abbotsford Airport, and Coquitlam Lake.

sunny conditions (*see* the wind distribution for Vancouver, shown in Figure 7, which indicates a high frequency of winds from the west in July, and the sunshine-hour and precipitation data in Figure 10 and Figure 4 that indicate dry, sunny conditions during the summer months). The surface high-pressure ridge is associated with a stable ridge at higher elevations.

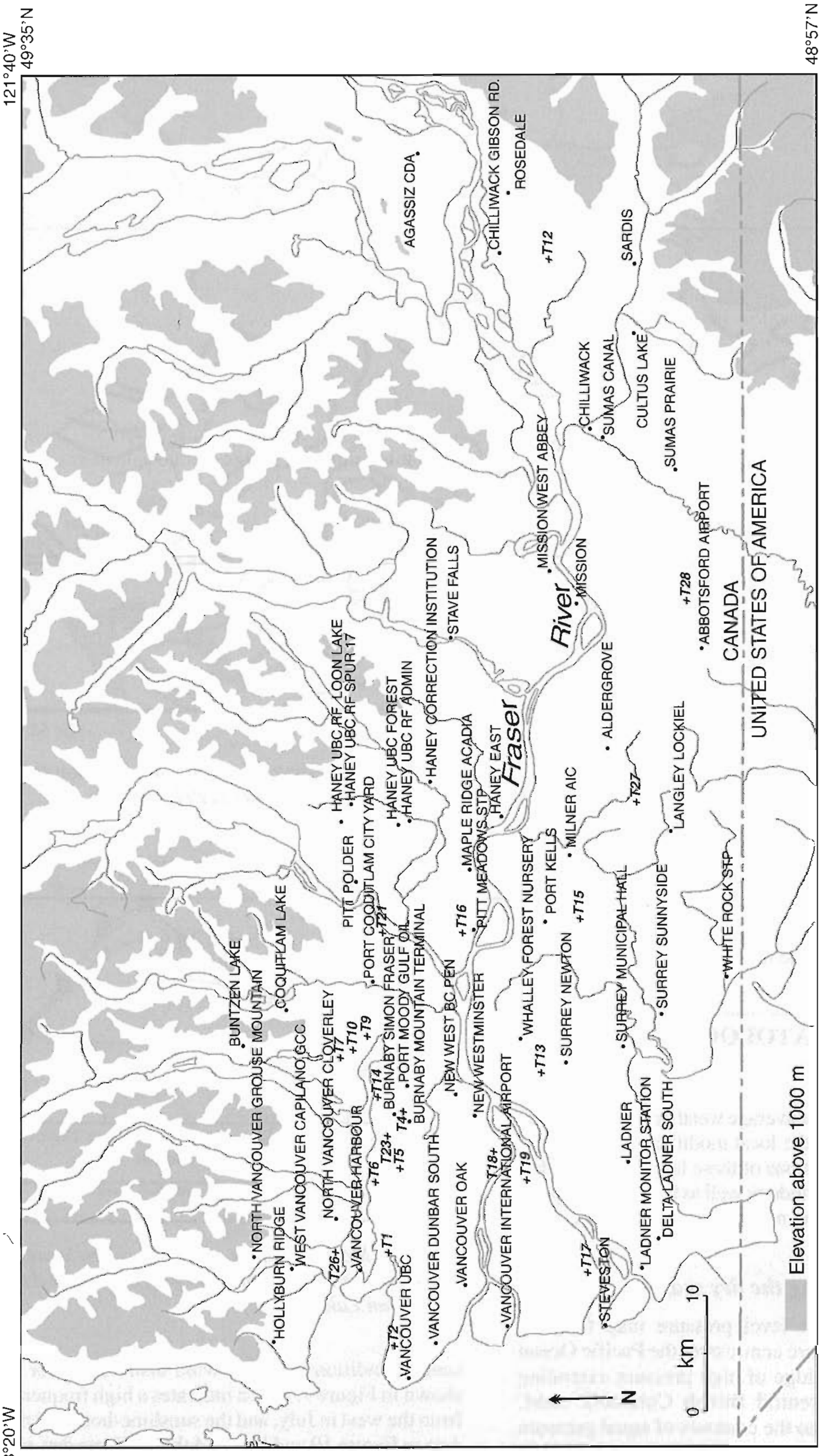

***Figure 11.** Map showing topography and stations used in climatological analysis. Stations with prefix "T" are part of the Greater Vancouver Regional District air monitoring network.*

The effect of the quasi-stationary 'blocking high' both at the surface and aloft is to deflect storms to the north, away from the region. Under these conditions, the sea-breeze–land-breeze circulation discussed in the section 'Effects of location at a coastline' can dominate the weather pattern over the area. This normal condition during the dry season can be interrupted by low-pressure systems which bring cloudiness and precipitation. Often during the summer months, extended periods of dry, sunny conditions are interrupted by low clouds, fog, and the invasion of the region by cool marine air from the outer coast. These phenomena, known as 'stratus surges', are linked to small-scale coastal systems called "coastal trapped disturbances" (Reason and Dunkley, 1993), which reverse the northwesterly winds and bring low clouds and fog northward from California along the outer west coast. This shallow layer of cool, cloudy air can move in through Juan de Fuca Strait and cover the region with low clouds and occasional fog, although precipitation seldom occurs. The weather conditions preceding the dry season, during April, May, and June, can be governed by 'cold lows' — deep cold systems that move slowly and somewhat erratically, resulting in unstable weather conditions with highly variable cloudiness and showers.

Synoptic conditions during the wet season

Figure 2 shows the 1982–1994 average sea-level pressure pattern for January. The pattern is in many ways the reverse of that shown in Figure 1 for the dry season — the high pressure of July is replaced by a large area of low pressure near the Aleutian Islands, called the 'Aleutian Low'. The orientation of the isobars indicates winds blowing typically from the south. When these large-scale southerly winds are modified by the configuration of the valley, the result is frequent winds from the east at Vancouver International Airport (Fig. 7) and Abbotsford Airport (Fig. 8). The overall pattern suggests cloudiness and precipitation but, with winds from the south and east, relatively mild temperatures. Low-pressure systems will typically propagate through the region every few days, bringing clouds and precipitation. This pattern can be interrupted by northeasterly Squamish winds bringing cold arctic air and snow, as discussed in the section 'Effects of fiords and valleys'.

DETAILED CLIMATOLOGY OF THE FRASER RIVER DELTA

The summaries presented here are selected from the Atmospheric Environment Service 1961–1990 climate normals (Atmospheric Environment Service, 1993), except the wind rose diagrams, which use the 1951–1980 normals. Data for three stations representative of the region will be displayed: Vancouver International Airport (3 m elevation) located on the western edge of the delta, Abbotsford Airport (54 m elevation) located inland but on the flat delta, and Coquitlam Lake (161 m elevation) located near the north shore mountains. Spatial variations are found using all available data from the stations shown in Figure 11.

Temperature

Temperature does not vary much across the domain. Figure 6 and Figure 12 show the annual variations of monthly average daily maximum and minimum temperatures, respectively. Average daily maximum temperatures tend to be warmer inland than in coastal areas, whereas average daily minimum temperatures tend to be cooler. During the winter months, however, daily maximum temperatures are higher at Vancouver International Airport than at Abbotsford Airport. These trends can be attributed to distance from the ocean, which has a moderating influence both diurnally and annually. On a diurnal timescale, ocean proximity reduces daytime maximum temperatures and increases nocturnal minimum temperatures. On an annual timescale, the ocean increases the daytime maximum at Vancouver International Airport during the winter and decreases it during the summer.

Bright sunshine hours

Figure 10 shows the monthly average number of sunshine hours for each station. As expected, the plots for all three stations peak in the summer months. Coquitlam Lake, because of cloudiness resulting from its proximity to the mountains, has fewer sunshine hours than either Abbotsford or Vancouver International airports. Abbotsford Airport has fewer sunshine hours than Vancouver International Airport, probably because its location further away from the coastline allows more convective cloud formation and because confluence of the valley could result in enhanced upward motion and cloud formation. This is consistent with the increased precipitation shown in Figure 4.

Precipitation

Precipitation shows remarkable variation across the region — a threefold increase from Tsawwassen in the south to Buntzen Lake in the north (*see* Fig. 13). As the north shore

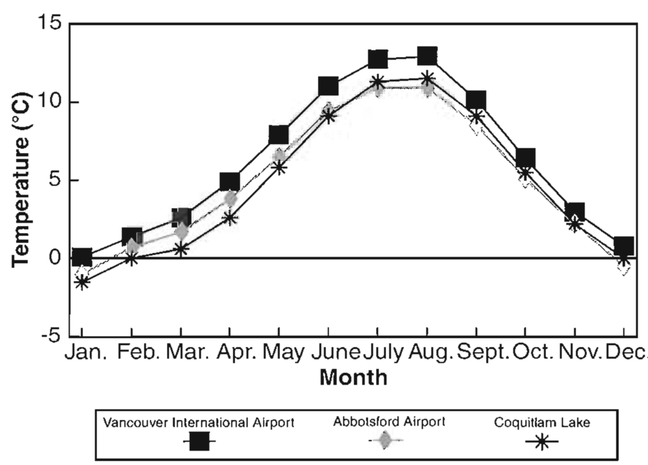

Figure 12. *Monthly average daily minimum temperatures (1961–1990) at Vancouver International Airport, Abbotsford Airport, and Coquitlam Lake.*

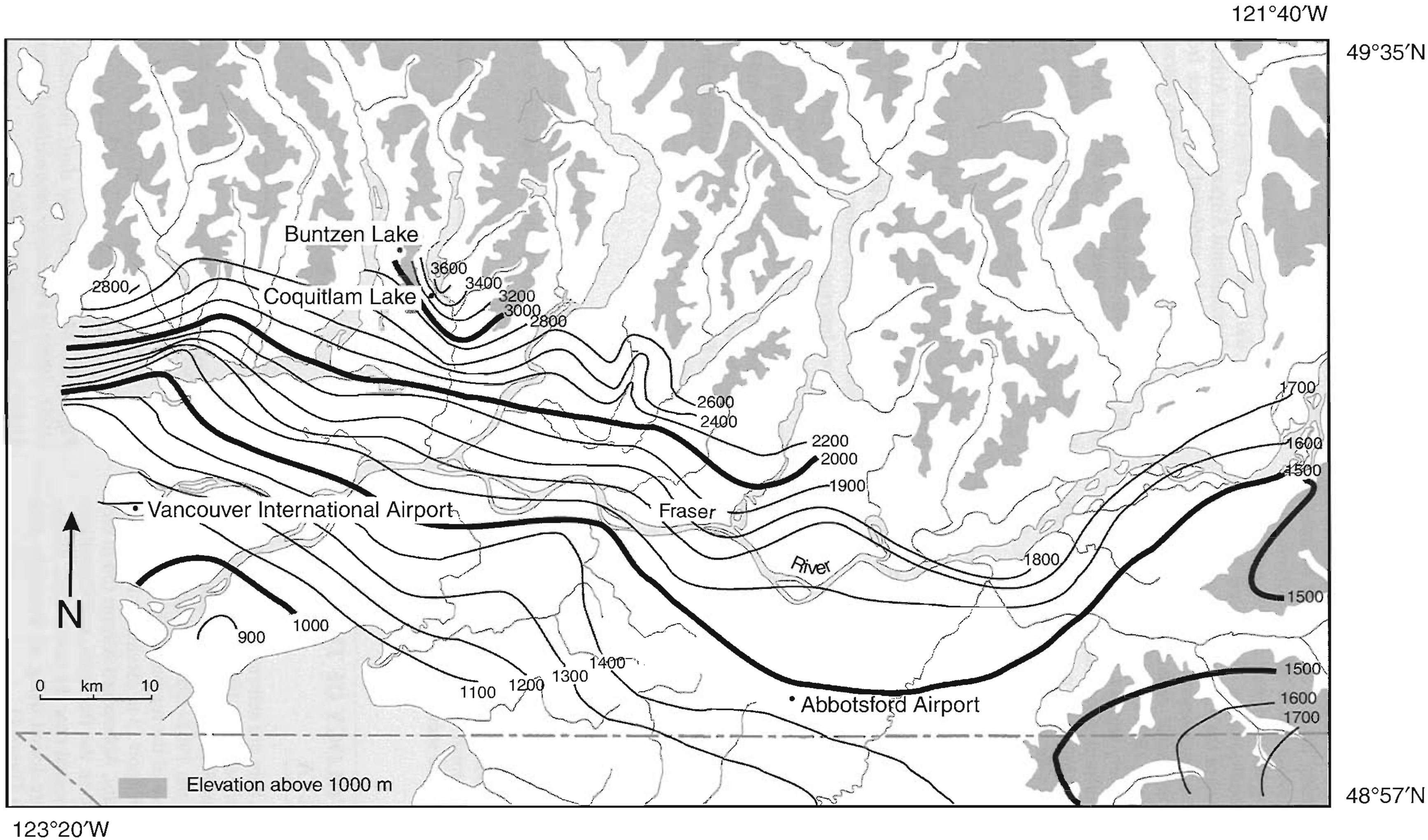

Figure 13. Spatial variation in annual precipitation. Data are annual averages based on the 1961–1990 period (contour values are in millimetres).

mountains are at higher elevation, much of the precipitation in the winter months falls there as snow (*see* Fig. 3). Figure 4, showing the total monthly average precipitation for the three stations, illustrates the summer dry season and winter wet season. The amount of precipitation in all months generally increases to the east and, especially, towards the mountains in the north.

Fog

Fog can occur at a location by two mechanisms, nocturnal radiation cooling and horizontal movement or advection of moist air into a region. Radiation fog forms overnight under calm, clear conditions when the surface air cools to its saturation point and fog forms in a shallow layer from the ground up. Monthly average days with fog for Vancouver International Airport and Abbotsford Airport are shown in Figure 14. The data for both stations are similar, with no fog days on average in April, May, and June. This is most likely because these months are characterized by unstable weather, such as the 'cold low' scenario discussed in the section 'Synoptic conditions during the dry season'. Vancouver International Airport has a higher average occurrence of fog during the winter than Abbotsford Airport, possibly due to advection fog from Georgia Strait. Abbotsford Airport has more fog days than Vancouver International Airport during the summer, probably because the conditions are better inland (more calm winds at night: 21.5% for Abbotsford Airport compared with 7.5% for Vancouver International Airport) for the formation of radiation fog.

Water balance

The monthly average water-balance components for Vancouver International Airport (Hare and Thomas, 1979) are shown in Figure 15. The surplus of precipitation in the winter (December through April) is removed from the system as runoff. After April, evaporation exceeds precipitation, with the difference coming from soil-water storage. By June, the soil water has been depleted, so that the actual evaporation rate falls below the potential evaporation rate (this is the rate of evaporation if water were freely available). By July the actual evaporation decreases due to insufficient available water, even though the potential evaporation is still increasing. In September the precipitation has once again caught up with the potential evaporation rate, and in early fall the excess precipitation is used to recharge the depleted soil water storage. During November, the soil is once again at capacity and surplus precipitation is again removed from the system as runoff.

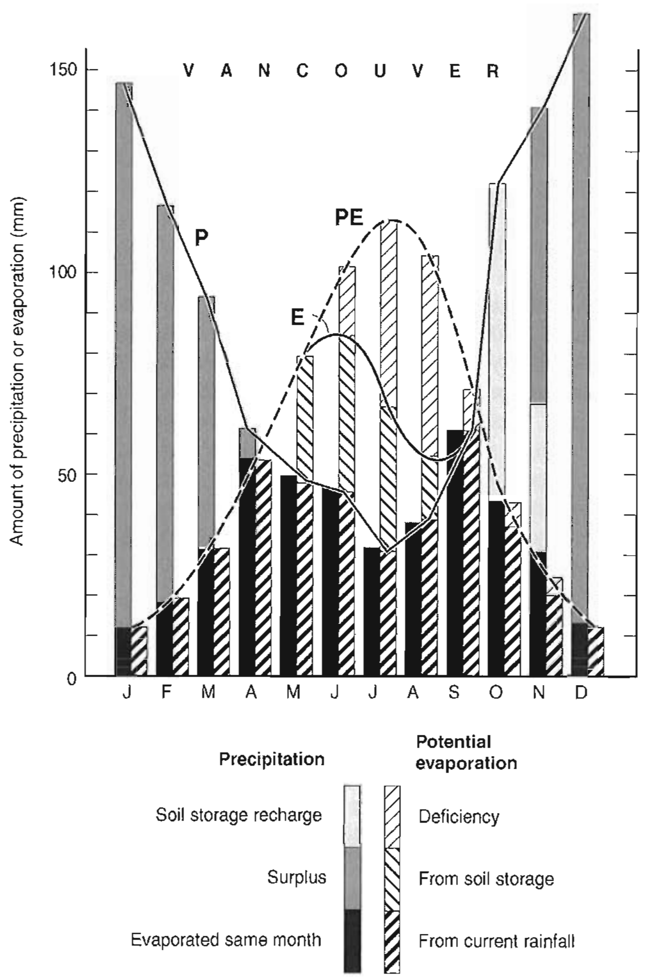

*Figure 15. Water balance components for Vancouver (*after *Hare and Thomas, 1979, Fig. 3.15). P = precipitation, E = evaporation, PE = potential evaporation — the evaporation which would occur if there were an unlimited moisture supply.*

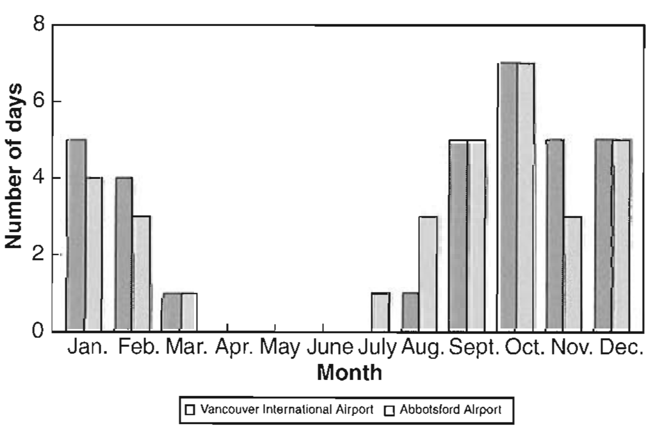

***Figure 14.** Monthly average number of days with fog (1961–1990) at Vancouver International Airport and Abbotsford Airport.*

Wind

The most common wind direction at Vancouver International Airport is easterly, whereas at Abbotsford Airport northeasterly winds dominate during the winter and southwesterlies dominate for the rest of the year. Figures 7 and 8 show wind rose diagrams during July and January for Vancouver International Airport and Abbotsford Airport. In these diagrams, the radial dimension is frequency and mean speed, and the direction represents the direction from which the wind is blowing. Channelling by the valley configuration results in the preferred directions. The effects of local wind flows such as sea and land breezes (Vancouver International Airport) in summer and Squamish winds (Abbotsford Airport) in winter are evidenced by the high frequency of westerly and northwesterly winds at Vancouver International Airport during July, and the high frequency of northeasterly winds at Abbotsford Airport during January. Sea breezes occur an average of 86 days each year at Vancouver International Airport and 48 days each year at Abbotsford Airport. August has the most sea breezes (10 days) with durations of about nine hours and speeds of about 10 km/h (Steyn and Faulkner, 1986). Winds are generally stronger at Vancouver International Airport than at Abbotsford Airport, because it is in a more 'exposed' location: closer to Georgia Strait, which has a low aerodynamic roughness, and in a broader part of the valley less constrained by surrounding mountains.

CONCLUSIONS

The weather and climate of the Fraser Lowland are profoundly influenced by its physiographic setting. The presence of ocean, mountains, valleys, and urbanization all act to create the uniqueness in what is arguably the region's most talked-about feature — its climate. Across the delta, there are significant variations in all climatic variables — precipitation, sunshine, wind, and temperature. These variations, combined with spatial variations in ground materials, have a significant influence on the ecology of the region.

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REFERENCES

Atmospheric Environment Service
1993: Canadian Climate Normals, 1961-90, British Columbia; Environment Canada, Ottawa, Ontario, 134 p.

Hare, F.K. and Thomas, M.K.
1979: Climate Canada; (second edition), John Wiley and Sons, Toronto, Ontario, 230 p.

Jackson, P.L.
1996: Surface winds during an intense outbreak of arctic air in southeastern British Columbia; Atmosphere-Ocean, v. 34, p. 285–311.

Jackson, P.L.
2004: Atmospheric impacts of urbanization; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Oke, T. and Hay, J.
1994: The Climate of Vancouver; (second edition), B.C. Geographical Series, Number 50, Vancouver, British Columbia, 50 p.

Reason, C.J.C. and Dunkley, R.
1993: Coastally trapped stratus events in British Columbia; Atmosphere-Ocean, v. 31, p. 235–258.

Steyn, D.G. and Faulkner, D.A.
1986: The climatology of sea-breezes in the Lower Fraser Valley, B.C.; Climatological Bulletin, v. 20, no. 3, p. 21–39.

Ecological setting of the Fraser River delta and its urban estuary

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Abstract: The Fraser River delta is rich with marshes, old fields, bogs, and agricultural land. All of the natural elements of the delta are interdependent with each other. Similarly, the delta is interconnected with surrounding marine ecosystems of Burrard Inlet and Boundary Bay and the urban forests of the Burrard Peninsula and the Surrey uplands.

The delta is of global significance in its role as a major stopover point for migrating birds along the Pacific Flyway and in its vital contribution to supporting the salmon runs of the Fraser River. It also has an international role in maintaining biodiversity.

Natural ecosystems of the delta have been significantly degraded and continue to be threatened by urbanization and population growth, but major short- and long-term programs are in place to restore and manage several of the affected areas.

Résumé : Le delta du Fraser regorge de marais, de vieux champs, de tourbières et de terres agricoles. Tous ses éléments naturels sont interdépendants; de plus, le delta a des liens avec les écosystèmes marins environnants de l'inlet Burrard et de la baie Boundary et avec les forêts urbaines de la péninsule Burrard et des hautes terres de Surrey.

Le delta revêt une importance mondiale en tant que halte pour les oiseaux migrateurs qui empruntent la voie migratoire du Pacifique, ainsi qu'en raison du soutien vital qu'il apporte aux migrations des saumons sur le Fraser. Il joue également un rôle à l'échelle mondiale dans le maintien de la biodiversité.

Les écosystèmes naturels du delta se sont sensiblement dégradés et sont toujours menacés par l'urbanisation et la croissance démographique, mais de grands projets de restauration et de gestion à court ou long terme sont en place dans plusieurs des zones touchées.

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INTRODUCTION

This paper examines the ecosystems of the Fraser Lowland and their regional and global importance. In addition to describing the major ecosystems, the more common species — those that give the delta its unique ecological characteristic — also are identified. Examples are given of various aquatic and terrestrial ecosystems that maintain the natural value of the delta. The paper concludes with a brief description of the major efforts to restore and manage the delta.

In its natural state prior to European settlement, the lands of the Fraser River delta consisted of estuarine marshes with bands of vegetation extending landward parallel to the advancing edge of river deposits. Grassland communities established themselves where the land was not flooded daily. On even less flooded land some shrub communities developed; behind these, close to the uplands, was a forest of Sitka spruce (Butler and Campbell, 1987).

The delta looks very different today. Most of the original wet meadows, grasslands, and shrubs are gone, converted to agricultural and urban uses by hundreds of kilometres of dykes. Agriculture has become a dominant feature of the landscape. Urban sprawl has directly destroyed vast areas of natural habitat and indirectly altered much of the rest. Our population and lifestyles already require the productivity of 8 100 000 ha of land to support, even though only 400 000 ha are available locally, causing us to place great demands on the delta for human needs while also appropriating the additional required productivity from other parts of the world (Rees and Wackernagel, 1994). With the population of the Greater Vancouver Regional District expected to double over the next 25 years, natural ecosystems of the Fraser River delta are in great danger.

Even though the delta has been dramatically changed over the last 100 years, it still remains one of the most valuable natural areas in Canada. There is more plant and animal diversity in British Columbia than in any other province of Canada, and the Fraser River delta enjoys a share of the biodiversity found in the province. Several highly productive and varied ecosystems converge at the delta; this diversity (Appendix A) is reflected in a richness of biological activity.

Many urban streams of the upland forests immediately adjacent to the delta support their own salmon runs which, although much reduced in contrast to historical numbers, are still significant and the focus of a large community effort to ensure their maintenance. All five species of salmon use the Fraser River delta. The Fraser River also supports a large spring migration of millions of eulachon. Boundary Bay attracts spawning Pacific herring. The eulachon and herring link the marine environment with other ecosystems of the Fraser River delta because these fish are pursued by thousands of ducks and gulls and marine mammals such as the Steller's sea lion (Butler and Campbell, 1987).

Knowledge of the historical vegetation of the delta is based on surveys done by Royal Engineers from 1858 to 1880 (Table 1). They did not survey beyond the landward edge of the marsh, intertidal areas, or the outer margins of bogs because they were not suitable for settlement, the main reason for the survey. At that time the delta consisted mostly of wet meadow and bog habitat. By 1985, wet meadows had been largely replaced by cultivated farmland and urban and/or industrial areas. The tree and shrub habitat has been reduced to one-third of its original area.

Table 1. Historical changes from 1880 to 1985 in the areal extent of habitat types in the Fraser River delta, based on Butler and Campbell (1987).

	Area of delta cover (%)	
Habitat	1880	1985
Seasonal wet meadows	43	<1
Bog	26	1
Trees and shrubs	31	10
Cultivated farmland	0	37
Urban/industrial/miscellaneous	0	52

The productivity of the Fraser River delta supports bird populations from three continents (Butler and Campbell, 1987). The delta is the major stopover point along the Pacific Flyway for millions of birds migrating from Canada's Arctic and the eastern tip of Russia to wintering grounds in Central and South America. It is a vital link in a chain that includes the Copper River delta in Alaska and wetlands in California. Many experts believe that part of the delta should be designated a Ramsar Site by the United Nations to recognize its international importance to bird life; Boundary Bay has already been designated a Ramsar Site.

BIODIVERSITY IN THE FRASER RIVER DELTA

There are a variety of habitats in and around the Fraser River delta. This diversity of habitat type includes mature forests adjacent to the delta; the freshwater of the Fraser, Nicomekl, and Serpentine rivers; the salt marsh (Tsawwassen) and brackish marshes of Roberts and Sturgeon banks; and the marine environments of Boundary Bay and the Strait of Georgia (and nearby Burrard Inlet). These collectively support a high number of species, most of which will at least pass through the delta and usually use it for feeding or nesting. This biodiversity is perhaps most conspicuously reflected in the bird life. There are over 250 species of birds that can be seen on an annual basis, and there are 360 species of birds that have been seen here at least once (Vancouver Natural History Society, 1993).

The ability of the region to support its once-rich plant and animal life is being dramatically reduced, however, by human population growth. The current population of 2.0 million people is expected to increase by 600 000 over the next 20 years. The habitat destruction and environmental degradation that inevitably have occurred with population growth are reflected in the region's biodiversity. Native bird species which no longer breed in the area are the burrowing owl, Western bluebird, yellow-billed cuckoo, horned lark, and purple martin (purple martin returned to nearby Maplewood flats on Burrard Inlet to nest in 1995). Some of the animals currently at risk provincially or uncommon regionally which are found in the delta are listed in Appendix B. Rare vascular plants are listed in Appendix C.

In addition to the large areas of natural ecosystems, urban environments are also a major part of the Fraser River delta. Richmond, and parts of Surrey, Delta, and White Rock are a part of this rich habitat. Urban environments are synonymous with a loss of biodiversity and, without question, the natural ecosystems they have displaced are totally gone; however, cities are not biological deserts. They frequently contain fragments of the original ecosystems in the area, and backyard habitats and parks can help to maintain connections between islands of natural habitat, thereby enhancing their role in the greater ecosystem.

MAJOR ECOSYSTEMS

There are two major types of ecosystems in the Fraser River delta — the aquatic ecosystems of the Fraser River estuary and the terrestrial ecosystems created by the floodplain and dykes. The estuary has extensive brackish and freshwater marshes and rich freshwater aquatic life in the river. The delta itself has fields of lowland habitat, bogs, and floodplain forests with a perimeter of upland forest along the Burrard peninsula and the Surrey uplands.

Aquatic ecosystems

Marshes and tidal flats

Freshwater and brackish marshes are considered together because they are sometimes difficult to distinguish. The Canadian Wildlife Survey estimates that there are 2814 ha of marsh habitat in the Fraser River estuary. At certain times of the year, salt water can move up the Fraser River as far as Annacis Island and Queensborough in New Westminster, and during the spring freshet freshwater can extend far outwards onto Sturgeon and Roberts banks (Carefoot, 1977).

The coastal vegetation of Sturgeon Bank marsh (649 ha), Roberts Bank marsh (1042 ha), the area from Steveston to Deas Island (606 ha), and the Pitt River (447 ha) are extremely productive ecosystems (G.L. Williams, unpub. report, 1986; R. Kistritz, unpub. report, 1989). The extensive eelgrass beds of the tidal flats and the marshes of cattails, Lyngby sedge, bulrushes (soft-stemmed bulrush, seacoast bulrush, and the three-square bulrush), and Pacific silverweed support a large biomass of shellfish, fish, and wildlife. They annually receive about 12 700 000 m^3 of sediment and 450 000 t of organic matter from the Fraser River, which help to support this high level of biological activity (Greater Vancouver Regional District, 1992).

The large amount of detritus created by dying marsh plants forms the basis of the food chain in the brackish marshes. Numerous crabs, clams, juvenile and adult salmon, Pacific herring, and birds flourish here. The seeds and rhizomes of Lyngby sedge and the three species of bulrushes found here are eaten by dabbling ducks, snow geese, and trumpeter and tundra swans. The marsh wren and red-winged blackbird are common nesting birds here.

Tidal flats are found in the intertidal zone seaward of the marshes on Boundary Bay and Roberts and Sturgeon banks. When covered with water, they are home to the Pacific staghorn sculpin, starry flounder, and Dungeness crab, food sources for the great blue heron and diving ducks such as greater scaup and surf scoter.

When exposed at low tide, the tidal flats are the feeding grounds of gulls (75% of all gulls on the delta are glaucous-winged gulls) and the Northwestern crow. The tidal flats also are invaded by sandpipers, plovers, yellowlegs, and other shorebirds looking for amphipods, ghost shrimp, mud shrimp, lugworms, other polychaete worms, and other soft-bodied invertebrates buried in the sediments. Also found here are clams such as the Pacific littleneck, heart cockle, soft-shelled and butter clam, the edible blue mussel, snails such as the screw shell, and whelks.

Shorebird species (the Western sandpiper is the most abundant) are specialized for preying upon selected invertebrates. For example, the curlew and long-billed dowitcher feed on burrowing worms which are deeper in the sediments, while dunlin feed on burrowing shrimp which are not as deep; sanderling and black-bellied plover feed on soft-shelled clams which are just below the surface and the black turnstone favour screw shell snails and edible blue mussels on the surface (Kistritz, 1992).

Harbour seals and sea lions that feed in the Strait of Georgia and the estuary will frequently use the sandbars and tidal flats of the delta to nest.

Fraser River and its tributaries

In the broader region of the Lower Mainland surrounding the Fraser River estuary, the river is joined by many significant urban streams and rivers including: Brunette River (Still Creek–Burnaby Lake–Deer Lake systems), Pitt River (and Widgeon Creek), Coquitlam River (and Scott and Hoy creeks), Salmon River, and creeks of Burnaby's south slope (such as Byrne Creek). Although most of the urban streams have been culverted and covered over by development (Harris, 1989), most of these existing tributaries of the Fraser River have active salmon runs or are part of programs to re-establish salmon runs. Other important fish in the Fraser River delta are noted in Appendix D.

The Fraser River splits into the north and south arms at New Westminster, at the head of the delta. About 85% of the water of the Fraser River flows into the south arm. The foreshore marshes along the banks of the Fraser River support a rich life of invertebrates such as chironomids, *Daphnia* sp., harpaticoid copepods, and amphipods that are the food for juvenile salmon, sculpins, flounder, and stickleback (Greater Vancouver Regional District, 1992). These marshes are foraging and nesting habitats for great blue herons and bald eagles.

At the mouth of the south arm of the Fraser River are the south arm and Ladner marshes, Deas Slough, and several lowland islands. The marsh system and muddy side channels are used by many fish and dabbling ducks (Greater Vancouver Regional District, 1992).

The Serpentine and Nicomekl rivers drain into Boundary Bay. They are usually of low velocity and have considerable marsh habitat. They support a wide variety of aquatic wildlife besides fish such as muskrat, beaver, mink, American water shrew, herons, American bittern, and Virginia rail.

Inland marshes

Small inland marshes are usually destroyed by urbanization; however, one important inland freshwater marsh on the delta, which was destroyed on Sea Island because of the expansion of the Vancouver International Airport, was recreated on Iona Island. Its inhabitants include the yellow-headed blackbird, which is rare in the Lower Mainland. This species successfully changed its nesting habitat to the new site.

Bogs

Burns Bog is the largest urban green space in Greater Vancouver, with an area of 4000 ha. It is a raised dome peat bog and bog forest containing the solid waste landfill of the Greater Vancouver Regional District in its southwest corner. The 60 ha forested Delta Nature Park is on its northeast corner.

Burns Bog is used by 160 species of birds, 24 species of mammals, and 199 species of plants (Appendix E). Black bear, black-tailed deer, and coyote are found here. In addition to serving as an important refuge for shorebirds and waterfowl during storms, the bog acts as a large reservoir for groundwater recharge to maintain other aquatic habitats nearby.

Occasional fires may help to prevent the bog from becoming overgrown with trees and shrubs. Instead of destroying a significant part of Burns Bog, the large fire of 1996 in the bog may have helped to conserve this valuable area.

Terrestrial ecosystems

Farmland and old field habitat

The terrestrial life in the area occupies the lowland habitat created by the floodplain and dyked lands of the delta and the surrounding uplands of glacial till and outwash along the perimeter. Much of the floodplain consists of farmland and old field communities, with their associated hedgerows of hawthorn (these hedgerows help to maintain a high diversity of bird life and small mammals). These terrestrial communities occur on islands such as Sea Island (which had some valuable habitat destroyed by the recent expansion of Vancouver International Airport on the island), Iona Island (with its sewage lagoons of the Iona Island sewage treatment plant, which are suitable shorebird habitats), Lulu Island and Westham Island (with the Reifel bird sanctuary and Alaksen National Wildlife Area of the Canadian Wildlife Service).

These habitats support large populations of the Townsend's vole and Oregon vole, the base of the food chain for the many raptors (hawks, owls, and eagles) that use the Fraser River delta for breeding and especially as overwintering grounds. The Northern harrier, red-tailed hawk, rough-legged hawk, common barn-owl, and short-eared owl, in particular, are commonly seen feeding in this area. The great blue heron also feeds on these rodents.

Farmland and old field habitat also are used as feeding and nesting grounds for many waterfowl. The tens of thousands of snow geese that come to the delta every fall, in particular, rely on this habitat, highlighting the interdependence between the terrestrial and aquatic ecosystems in maintaining the importance of the Fraser River delta as a major stopover point along the Pacific Flyway during migration.

Forests

The remaining or remnant floodplain forests on the delta consist primarily of black cottonwood. Upland forests surrounding the delta play a vital role in maintaining the water quality of the many urban streams that are spawning grounds for coho and chinook salmon. The forests reduce water temperatures, increase dissolved oxygen levels, and provide food in the form of insect life for the growing fry. The importance of the Fraser River delta and estuary as salmon habitat in various stages of their life depends in part on the contribution of the forests.

The upland forests adjacent to the Fraser River delta are part of the boreal forest biome. Around the Fraser River the normally cold biome is relatively warm because of the maritime climate of the Pacific Ocean, whereas the mountains contribute to higher rainfall and create the conditions of a temperate rain forest.

Within the temperate rain forest of the coast, the Fraser River delta and estuary are part of the 'Western Hemlock Biogeoclimatic Zone', a classification used by the British Columbia Ministry of Forests (according to Ministry of Environment classification, the delta and estuary are part of the 'Georgia Depression Ecoprovince', an area that includes southeastern Vancouver Island and northwestern Washington State; they are more specifically part of the 'Fraser Lowland Ecosection'). Western hemlock and western red cedar form the climax community in the forests on the Burrard peninsula and the Surrey uplands. Prior to the climax community, however, we typically see broad-leaved communities of red alder and bigleaf maple, eventually replaced by Douglas fir, which could dominate the forests for hundreds of years until they are in turn replaced by the cedar and hemlock. Typical shrubs in the forest community are red huckleberry, red elderberry, dull Oregon grape, and salal.

Urban habitat

There are many urban wildlife habitats within or bordering the delta. Figure 1 is a map illustrating environmentally sensitive areas identified by each municipality in the region or by other sources.

Foreshore marshes along the river and at its mouth were not included, because maps of these habitats were previously compiled by the Fraser River Estuary Management Program (in their foreshore habitat inventory) and the Fraser River Estuary Study (Fraser River Estuary Study Steering Committee, unpub. report, 1978).

It is clear that although the delta is within urban boundaries, it is prime wildlife habitat. Although we tend to dismiss the importance of urban environments as natural ecosystems, they are in fact more important than most people imagine. One reason for this is that cities are often located in areas that are not only important strategically from a trade or defense perspective, but are also important in biological productivity. The fertility of floodplains and the strategic location of a river mouth make estuaries preferred urban settings. Estuaries have primary productivities that range from 12.5 to 25 t/ha; this is more productive than intensively cultivated agricultural land (Kistritz, 1992). A small bit of city land which destroys an estuarine habitat causes a greater loss of productivity than if it instead destroyed larger forested areas.

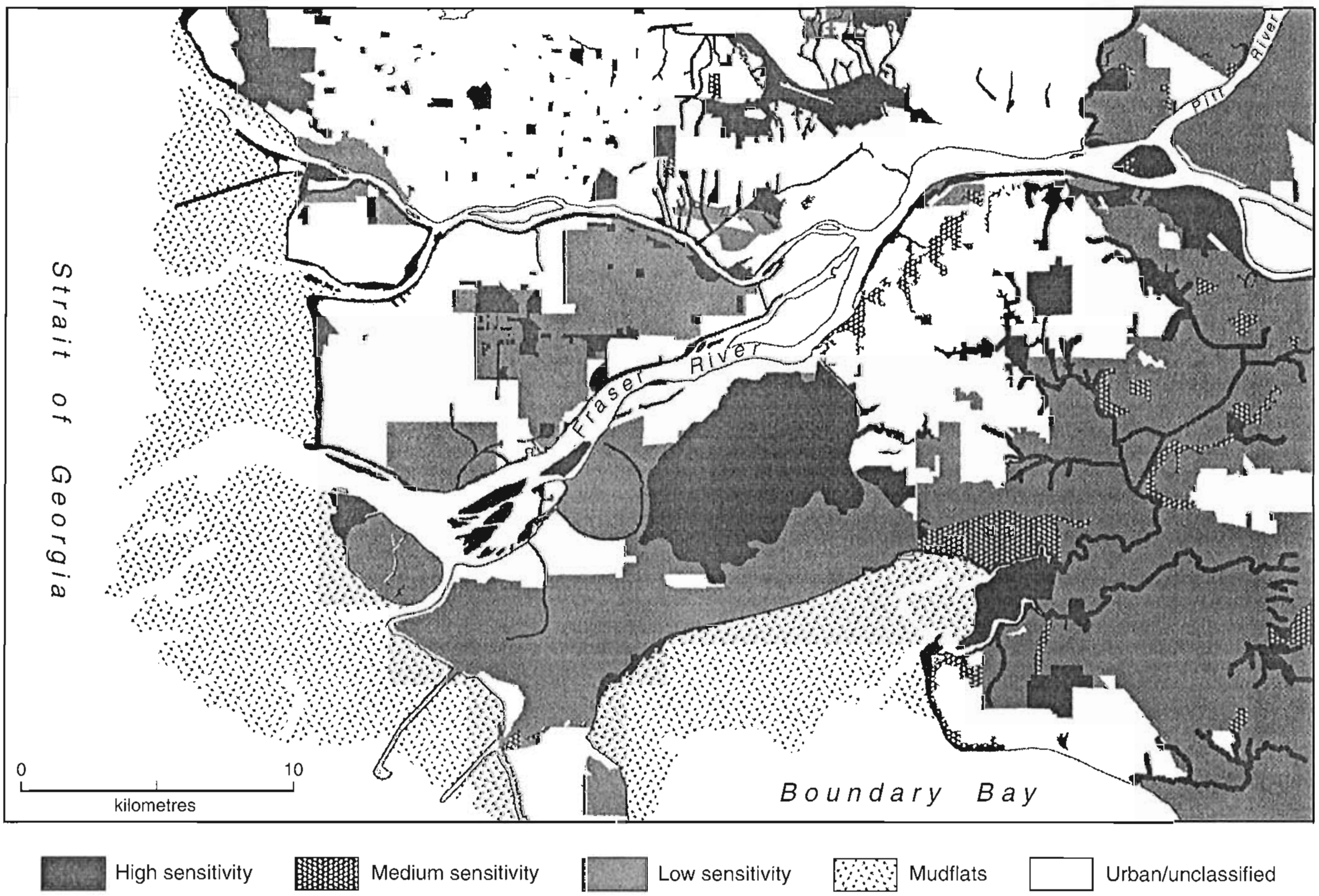

Figure 1. A composite map of environmentally sensitive areas (ESAs) and important wildlife habitat in the Fraser River delta. It is based on ESA reports produced by the municipalities, a study done by the Land for Nature Project, an inventory of urban ravines done by the Douglas College Institute of Urban Ecology, the Greater Vancouver Regional District's Green Zone, and the City of Vancouver's remnant woodlands report (all are listed in Appendix H). The foreshore marshes and mudflats were not included in the maps produced from these reports. The ratings are: high - greatest number of ecologically significant features and processes; medium - areas with several important ecological features and processes; low - at least one feature. All stream and foreshore areas have a high rating.

A second reason why urban habitats should not be overlooked from an ecological perspective is that the small fragments of urban habitat collectively may represent a significant amount of natural habitat. Urban ravines in the Lower Mainland, for example, cover an area of 10.5 km^2 with a linear distance of 98 km (Schaefer, 1994). That is a large amount of riparian (river- and/or stream-side) habitat scattered throughout residential and commercial development. There is a total of 193.2 km of riparian habitat in the Fraser River estuary (G.L. Williams, unpub. report, 1986; R. Kistritz, unpub. report, 1989).

HABITAT RESTORATION AND MANAGEMENT

The lower Fraser River basin has numerous wildlife conservation areas. In 1990 these included: federal migratory bird sanctuaries and wildlife areas (737 ha), provincial ecological reserves (616 ha), wildlife management areas (3833 ha), and crown map reserves and notations of interest (10 808 ha), for a total of 15 994 ha (Environment Canada and the B.C. Ministry of Environment, Lands and Parks, 1991); however, this is less than 3% of the area of the Fraser River delta. Only 13% of the vital foreshore marshes are legislated as wildlife areas (Butler and Campbell, 1987).

More land is being protected each year, with several sites added recently through the provincial government's Lower Mainland Natural Heritage Program. An additional 31 130 ha are in the Agricultural Land Reserve in the Greater Vancouver Regional District (B.C. Agricultural Land Commission, quoted *in* Environment Canada (1991)).

Nevertheless, much of the natural habitat in the area has been destroyed. Maps of prime salmon foreshore habitat along the Fraser River indicate that less than half is still suitable for salmon; it is likely that virtually all of the foreshore would have been used historically.

A number of programs currently underway aim to preserve more land and to improve the quality of existing sites. A few of these are briefly reviewed below because the topic is covered in more detail by Dorcey (2004).

Salmonid enhancement and stream stewardship

The Salmonid Enhancement Program, together with its more recent community voluntary action program, Stream Stewardship, has been responsible for fostering the maintenance and enhancement of riparian habitat throughout the Fraser River estuary. It has focused on improving the salmon habitat in urban streams by planting native vegetation, establishing spawning channels, and cleaning up streams. The Salmonid Enhancement Program also has raised public awareness of the impact of urban runoff pollution through storm drains on salmon-bearing streams. Federal hatcheries and salmon-rearing programs in public schools have greatly improved water quality and riparian habitat in the region.

Recent activities of stream stewardship have expanded to include promoting all fish stocks, not just salmonids, and have highlighted the value of urban streams in natural ecosystems. *See* Appendix G for contact information on this program.

Fraser River Estuary Management Program

The Fraser River Estuary Management Program, formed in 1977, is a co-operative agreement to co-ordinate planning and decision-making in the Fraser River estuary. It is managed jointly by Environment Canada; Fisheries and Oceans Canada; the B.C. Ministry of Water, Land and Air Protection; the North Fraser Port Authority; the Fraser River Port Authority; and the Greater Vancouver Regional District. Since 1985, the Fraser River Estuary Management Program has enabled more effective control of pollution discharges and minimized habitat loss, in addition to improving recreation on the Fraser River and providing greater economic certainty for development (Fraser River Estuary Management Program, unpub. report, 1996).

Some of the activities of the Fraser River Estuary Management Program which have increased or improved habitat in the estuary include: removing garbage and wood debris from degraded foreshore habitats in red-coded zones (the most valuable habitat for fish and wildlife); establishing guidelines and objectives for water quality; monitoring water quality; maintaining a database on habitat compensation, restoration, and development projects; and developing a management plan for the estuary, entitled *A Living Working River*. *See* Appendix G for contact information on this program.

Fraser River Action Plan

The Fraser River Action Plan was a partnership of First Nations, governmental, and nongovernmental organizations dedicated to increasing the productivity of the Fraser River by enhancing fish and wildlife habitat, rebuilding salmon stocks, and managing the natural environment. Its activities included transplanting marsh in the estuary, cleaning up intertidal habitat, building channels and ponds as salmon spawning and rearing habitat, and monitoring populations of crabs and white sturgeon. The Fraser River Action Plan's mandate ended in 1997.

Fraser Basin Council

A joint initiative of First Nations, federal, provincial, and local governments, the Fraser Basin Council covers the entire British Columbia Fraser River basin, not just the Lower Mainland which was the focus of the Fraser River Estuary Management Program. Directed by a management board (replaced by the Fraser Basin Management Council in 1997) of representatives from senior governmental and nongovernmental organizations, the Fraser Basin Council promotes sustainable development in the Fraser River basin with a balance of social, economic, and environmental values.

By co-ordinating government programs and initiatives and by auditing progress towards achieving sustainability in the basin, the Fraser Basin Management Program helps to maintain and improve the quality of habitat in the delta. In addition to sponsoring workshops and community round tables, the Fraser Basin Management Program also directly supports projects to improve habitat and water quality in the Fraser basin (Fraser Basin Management Program, unpub. report, 1994). *See* Appendix G for contact information on this program.

Public stewardship programs

Over the years it has become increasingly evident that a holistic approach to watershed conservation is necessary. Public stewardship programs seek to improve habitat in the watershed by encouraging the community to improve urban streams as fish habitat, clean up refuse, plant native vegetation, and provide food for butterflies and birds. *Streamkeepers, Water Stewardship, Naturescapes* (Pincott and Campbell, 1995a, b, c), and *Greenways*, for example, are all stewardship programs sponsored by the B.C. Ministry of Water, Air and Land Protection (formerly B.C. Environment, Lands and Parks) and other organizations to encourage the public to increase wildlife habitat and to become stewards of public lands.

CONCLUSIONS

The Fraser River delta has highly productive and varied ecosystems. Their richness is important in maintaining biological communities throughout the region. The diversity of plant and animal life is a direct result of the varied landforms and environmental conditions that characterize the Lower Mainland. The ecosystems are all interdependent — adjacent forests are essential in maintaining the suitability of streams for salmon; birds feeding on the tidal flats rest and breed in surrounding fields; and marine mammals feed on fish that congregate in the delta to spawn (Appendix F).

The delta's habitats are too important an area to be lost to the haphazard development and pollution associated with urbanization. Urbanization typically results in 25% of the land being paved. The particulates, ozone and acidity from air pollution can significantly reduce the productivity of plants, depressing the normal functioning of entire ecosystems (*see* MacKenzie and Mohamed, 1989).

As the delta is urbanized, remaining habitat is becoming increasingly fragmented. If a habitat is not totally destroyed in the process, it will probably suffer significant losses in productivity and biodiversity. Even those areas currently located in wildlife management areas and parks are threatened by fragmentation.

The ecosystems of the Fraser River delta exist in a rapidly changing environment. A great deal depends on our success at meeting the challenge of ensuring that the delta is a home for both nature and people.

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REFERENCES

Butler, R.W. and Campbell, R.W.
1987: The birds of the Fraser River delta: populations, ecology and international significance; Canadian Wildlife Service Occasional Paper, Delta, British Columbia, no. 65, 73 p.

Carefoot, T.
1977: Pacific Seashores; J.J. Douglas Ltd., Vancouver, British Columbia, 208 p.

Dorcey, A.H.J.
2004: Evolution of estuarine governance in a metropolitan region: collaborating for sustainability in the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Environment Canada
1991: State of the Environment Report; Supply and Services, Ottawa, Ontario, EN21-54/1991E, 671 p.

Environment Canada and the B.C. Ministry of Environment, Lands and Parks
1991: State of the Environment for the Lower Fraser River Basin; Supply and Services Canada, Ottawa, Ontario, EN1-11/92-1E, 79 p.

Greater Vancouver Regional District
1992: Greater Vancouver's Ecology, Vol. 1, Summary Report; Vol. 2, Technical Report; Prepared by Gartner Lee Ltd. Development Services Department, Greater Vancouver Regional District, Burnaby, British Columbia, 114 p.

Harris, G.
1989: Vancouver's Old Streams; Vancouver Public Aquarium Association, Vancouver, British Columbia, 32 p. (reprint of the Journal of the Vancouver Aquarium, v. 3, no. 1, 1978).

Kistritz, R.
1992: Discover Your Estuary; Environment Canada, Pacific and Yukon Region; North Vancouver, British Columbia, EN 37-98/1992E, 120 p.

MacKenzie, J.J. and Mohamed, T. E-A. (ed.)
1989: Air Pollution's Toll on Forests and Crops; Yale University Press, New Haven, Connecticut, 375 p.

Pincott, S. and Campbell, S.
1995a: Naturescapes; B.C. Environment, Lands and Parks Stewardship Series, Victoria, British Columbia, v. 1, 52 p.
1995b: Naturescapes; B.C. Environment, Lands and Parks Stewardship Series, Victoria, British Columbia, v. 2, 60 p.
1995c: Naturescapes; B.C. Environment, Lands and Parks Stewardship Series, Victoria, British Columbia, v. 3, 30 p.

Rees, W. and Wackernagel, M.
1994: Ecological footprints and appropriated carrying capacity: measuring the natural capital requirements for the human economy; *in* Investing in Natural Capital, (ed.) C. Folke, M. Hammer, A.M. Jannson, and R. Constanza, R. Island Press, Washington, D.C., 160 p.

Schaefer, V.
1994: Urban biodiversity; *in* Biodiversity in British Columbia, (ed.) L. Harding and E. McCullum; Environment Canada, Ottawa, Ontario, p. 307–318.

Vancouver Natural History Society
1993: A Bird Watching Guide to the Vancouver Area, British Columbia; Cavendish Books, North Vancouver, British Columbia, 147 p.

Appendix A

The Fraser River delta as an ecosystem at a glance

Biodiversity

British Columbia has 2850 species of vascular plants of the 4150 found in Canada. There are 448 species of birds, 148 species of mammals, 19 species of reptiles, 20 species of amphibians, and 458 species of fish (365 marine, 71 freshwater, 22 both fresh and salt water). The coastal waters are rich with most of the 639 species of marine algae found in the Pacific northwest, and 6555 species of marine invertebrates (Harding and McCullum, 1994).

The numbers of species found in the waters of the lower Fraser River include 73 fish, 88 aquatic birds, and 11 aquatic mammals (Northcote, 1974). About 360 species of birds have been seen here.

Wetland habitat

There are five classes of wetland habitat in the Fraser River delta, comprising a total area of 26 155 ha. Some 21 581 ha (82%) of this is shallow water tidal flats. There are 2814 ha (11%) of marsh, 1567 ha (6%) of bog, 165 ha (0.5%) of swamp (floodplain forest), and 28 ha (0.1%) of fen (Ward, 1992).

Importance to fish

The Fraser River has a drainage area of 233 000 km^2. By the time it reaches the delta, the Fraser River has already travelled 1375 km, with headwaters reaching Jasper National Park, and with watersheds draining 25% of the entire province. These watersheds support the largest salmon run in the world, and the Fraser River estuary is the gateway. Some 66% of the province's sockeye salmon catch and 60% of the pink salmon catch are supported by the Fraser River basin (Fraser River Action Plan, 1995). About 4 million adult salmon and trout migrate through the area, and it is a major feeding ground for salmon fry and smelts. The estuary plays an important role as a refuge while the metabolisms of these anadromous fish change from saltwater to freshwater in the adults and vice versa in the smelts.

Importance to birds

The average monthly population of birds using the estuary is 500 000 individuals, and during peak migration periods there can be as many as 1.4 million birds. About 1.2 million shorebirds use the delta each year. There are about 135 000 waterbirds using the delta in winter. The density of wintering waterfowl, shorebirds, and raptors is the highest in all of Canada (Butler and Campbell, 1987).

References

Butler, R.W. and Campbell, R.W.
1987: The birds of the Fraser River delta: populations, ecology and international significance; Canadian Wildlife Service Occasional Paper 65, Delta, British Columbia, 73 p.

Fraser River Action Plan
1995: The Fraser River Action Plan: Mid-Term Report 1991-1994; FRAP, Environment Canada, North Vancouver, British Columbia, 39 p.

Harding, L. and McCullum, E. (ed.)
1994: Biodiversity in British Columbia: Our Changing Environment; Environment Canada, Canadian Wildlife Service, Ottawa, Ontario, 426 p.

Northcote, T.G.
1974: Biology of the Lower Fraser River: A Review; Westwater Research Centre: Technical Report 3; University of British Columbia, Vancouver, British Columbia, 94 p.

Ward, P.
1992: Wetlands of the Fraser Lowland, 1989: Summary Report; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series No. 156, 36 p.

Appendix B

Wildlife species at risk which use the Fraser River delta

These are blue-listed (threatened or endangered) by the B.C. Ministry of the Environment (based on Greater Vancouver Regional District, 1992a, b)

Common name	Scientific name
Bald eagle	Haliaeetus leucocephalus
Black-crowned night heron	Nycticorax nycticorax
Common barn-owl	Tyto alba
Great blue heron	Ardea herodias
Green-backed heron	Butorides striatus
Peale's peregrine falcon	Falco peregrinus pealei
Vaux's swift	Chaetura vauxi
Shrew mole	Neurotrichus gibbsi

References

Greater Vancouver Regional District

1992a: Greater Vancouver's Ecology, Volume 1, Summary Report; Prepared by Gartner Lee Ltd. Development Services Department, Greater Vancouver Regional District, Burnaby, British Columbia, 57 p.

1992b: Greater Vancouver's Ecology, Volume 2, Technical Report; Prepared by Gartner Lee Ltd. Development Services Department, Greater Vancouver Regional District, Burnaby, British Columbia, 114 p.

Appendix C

Rare vascular plants of the Fraser River delta

(Based on Greater Vancouver Regional District, 1992a, b)

Common name	Scientific name	Location
Dune bent grass	Agrostis pallens	Lulu Island
Pale spring beauty	Claytonia spathulata	Boundary Bay
Joe-pye weed	Eupatorium maculatum bruneri	Sea Island, Delta
Bolander's rush	Juncus bolanderi	Lulu Island
Pointed rush	Juncus oxymeris	New Westminster
Howells blue grass	Poa howellii	Fraser Lowland
Common reed	Phragmites australis	Fraser Lowland
Geyer's willow	Salix geyeriana	Vancouver
River bulrush	Scirpus fluviatilis	Vancouver

References

Greater Vancouver Regional District

1992a: Greater Vancouver's Ecology, Volume 1, Summary Report; Prepared by Gartner Lee Ltd. Development Services Department, Greater Vancouver Regional District, Burnaby, British Columbia, 57 p.

1992b: Greater Vancouver's Ecology, Volume 2, Technical Report; Prepared by Gartner Lee Ltd. Development Services Department, Greater Vancouver Regional District, Burnaby, British Columbia, 114 p.

Appendix D

Fish of the Fraser River delta

In addition to salmonids, the Fraser River estuary is home to many other species of fish such as white sturgeon, spiny dogfish shark, Pacific cod, walleye pollock, and dolly varden (Williams et al., 1989). There are 29 species of fish with residential populations in the lower region of the Fraser River (Northcote and Burwash, 1991).

References

Northcote, T.G. and Burwash, M.D.
1991: Fish and fish habitats of the Fraser River Basin; *in* Water in Sustainable Development: Exploring Our Common Future in the Fraser River Basin, (ed.) A.H.J Dorcey and J.R. Griggs; Westwater Research Centre, Vancouver, British Columbia, 310 p.

Williams, G.L., Johnson, J.E., Hendrickson, D.A., Contreras-Baldaras, S., Williams, J.D., Navarro-Mendoza, M., McAllister, D.E., and Deacon, J.E.
1989: Fishes of North America: Endangered, Threatened, or of Special Concern; Fisheries, v. 14, no. 6, p. 2–20.

Appendix E

Bog plants of the Fraser River delta

The dominant plant is sphagnum moss. Some plants in Burns Bog are considered to be remnants of the last ice age; cloudberry, crowberry, and velvet-leaf blueberry are examples. In areas where the succession of the bog has advanced to form a bog forest, there is shore (lodgepole) pine and paper birch.

Another bog on the delta is in the Richmond Nature Park on Lulu Island. This raised peat bog contains many of the common bog plants also found in Burns Bog, such as sphagnum mosses, bog laurel, Labrador tea, bog cranberry, sundew, and velvet-leaf blueberry.

Appendix F
Scientific names of biota mentioned in the text

PLANTS

Aquatics (marsh and bog)

Sphagnum moss (*Sphagnum* spp.)
American glasswort (*Salicornia virginica*)
Desert saltgrass (*Distichlis stricta*)
Eelgrass (*Zostera marinus*)
Cattail (*Typha latifolia*)
Lyngby sedge (*Carex lyngbyei*)
Softstem bulrush (*Scirpus validus*)
Seacoast bulrush (*Scirpus maritimus*)
American bulrush (*Scirpus americanus)*
Pacific silverweed (*Potentilla pacifica*)
Cloudberry (*Rubus chamaemorus*)
Crowberry (*Empetrum nigrum*)
Velvet-leaf blueberry (*Vaccinium myrtilloides*)
Bog laurel (*Kalmia microphylla*)
Labrador tea (*Ledum groenlandicum*)
Bog cranberry (*Oxycoccus oxycoccos*)
Sundew (*Drosera rotundifolia*)

Shrubs

Red huckleberry (*Vaccinium parvifolium*)
Red elderberry (*Sambucus racemosa*)
Dull Oregon grape (*Mahonia nervosa*)
Salal (*Gaultheria shallon*)

Trees

Shore (lodgepole) pine (*Pinus contorta*)
Sitka spruce (*Picea sitchensis*)
Western hemlock (*Tsuga heterophylla*)
Western red cedar (*Thuja plicata*)
Douglas fir (*Pseudotsuga menziesii*)
Paper birch (*Betula papyrifera*)
Red alder (*Alnus rubra*)
Bigleaf maple (*Acer macrophyllum*)
Black cottonwood (*Populus balsamifera*)

Birds

American bittern (*Botaurus lentiginosus*)
Great blue heron (*Ardea herodias*)
Tundra swan (*Cygnus columbianus)*
Trumpeter swan (*Cygnus buccinator*)
Snow goose (*Chen caerulescens*)
Greater scaup (*Aythya affinis*)
Surf scoter (*Melanitta perspicillata*)
Virginia rail (*Rallus limicola*)
Plovers (*Charadrius* spp.)
Black-bellied plover (*Pluvialis squatarola)*
Curlew (*Numenius* spp.)
Yellowleg (*Tringa* spp.)
Western sandpiper (*Calidris mauri*)
Sandpiper (*Calidris* spp.)
Long-billed dowitcher (*Limnodromous scolopaceus*)
Black turnstone (*Arenaria melanocephala*)
Dunlin (*Calidris alpina*)
Glaucous-winged gull (*Larus glaucescens*)
Sanderling (*Calidris alba*)
Gull (*Larus* spp.)
Bald eagle (*Haliaeetus leucocephalus*)
Northern harrier (*Circus cyaneus*)
Red-tailed hawk (*Buteo jamaicensis*)
Rough-legged hawk (*Buteo lagopus*)
Yellow-billed cuckoo (*Coccyzus americanus)*
Common barn-owl (*Tyto alba*)
Short-eared owl (*Asio flammeus*)
Burrowing owl (*Athene cunicularia*)
Horned lark (*Eremophila alpestris*)
Purple martin (*Progne subis*)
Northwestern crow (*Corvus caurinus*)
Marsh wren (*Cistothorus palustris*)

Western bluebird (*Sialia mexicana*)

Yellow-headed blackbird (*Xanthocephalus xanthocephalus*)

Red-winged blackbird (*Agelaius phoeniceus*)

Mammals

American water shrew (*Sorex bendirei*)

Black bear (*Ursus americanus*)

Mink (*Mustela vison*)

Coyote (*Canis latrans*)

Steller's sea lion (*Eumetopias jubata*)

Harbour seal (*Phoca vitulina*)

Beaver (*Castor canadensis*)

Townsend's vole (*Microtus townsendii*)

Oregon vole (*Microtus oregoni*)

Muskrat (*Ondatra zibethica*)

Black-tailed deer (*Odocoileus hemionus*)

Fish

Spiny dogfish shark (*Squalus acanthias*)

White sturgeon (*Acipenser transmontanus*)

Pacific herring (*Clupea harengus*)

Pink salmon (*Oncorchynchus gorbuscha*)

Sockeye salmon (*Oncorhynchus nerka*)

Dolly varden (*Salvelinus malma*)

Eulachon (*Thaleichthys pacificus*)

Pacific cod (*Gadus macrocephalus*)

Walleye pollock (*Theragra chalogramma*)

Threespine stickleback (*Gasterosteus aculeatus*)

Pacific staghorn sculpin (*Leptocottus armatus*)

Starry flounder (*Platichthys stellatus*)

Invertebrates

Lugworm (*Abarenicola pacifica*)

Polychaete worm (*Nereis vexillosa*)

Littleneck clam (*Protothaca staminea*)

Soft-shelled clam (*Mya arenaria*)

Butter clam (*Saxidomus giganteus*)

Edible blue mussel (*Mytilus edulis*)

Heart cockle (*Clinocardium nuttalli*)

Screw shell (*Batillaria attramentaria*)

Whelk (*Nassarius* spp.)

Amphipod (*Corophium* spp.)

Dungeness crab (*Cancer magister*)

Mud shrimp (*Upogebia pugettensis*)

Ghost shrimp (*Callianassa californiensis*)

Appendix G
Contact information for programs

Program	Contact
Salmonid Enhancement Program (SEP)	Fisheries and Oceans Salmonid Enhancement Program 610 Derwent Way, New Westminster, B.C. V3M 5P8 Telephone: (604) 666-8266.
Fraser River Estuary Management Program (FREMP)	Fraser River Estuary Management Program #501 - 5945 Kathleen Avenue, Burnaby, B.C. V5H 4J7 Telephone: (604) 775-5756.
Fraser Basin Council	Fraser Basin Council 1st Floor, 470 Granville Street Vancouver, B.C. V6C 1V5

Appendix H
Selected bibliography

Abs, S., Berris, C., Ferguson, A., and Groves, S.
1990: Finding the balance: environmentally sensitive areas in Surrey; Planning Department, Surrey, British Columbia, 66 p.

City of Richmond
1994: Environmentally sensitive areas (map); Planning Department, Richmond, British Columbia.

Cook, K., Mooney, P., Hall, K., Healey, M., Watts, D., Brown, S., and Shrier, H.
1993a: An evaluation of environmentally sensitive areas in the Township of Langley, Volume 1, ESA Analysis; Westwater Research Centre, University of British Columbia, Vancouver, British Columbia, v. 1, 153 p.
1993b: An evaluation of environmentally sensitive areas in the Township of Langley, Volume 2, ESA Summary Sheets; Westwater Research Centre, University of British Columbia, Vancouver, British Columbia, v. 2, 214 p.

Dunster, K. and Dunster, J.
1992: The Nature of Burnaby: an Environmentally Sensitive Areas Strategy; City of Burnaby, British Columbia, 128 p.

Federation of British Columbia Naturalists
1992: Environmentally Important Sites in the Greater Vancouver Regional District; Land For Nature Project, Federation of British Columbia Naturalists, Vancouver, British Columbia, 25 p.

Gartner Lee Ltd.
1992: Environmental Assessment of Port Coquitlam; City of Port Coquitlam, British Columbia, 76 p.

Greater Vancouver Regional District
1993: Creating Greater Vancouver's Green Zone; Strategic Planning Department/Parks Department, Greater Vancouver Regional District, Burnaby, British Columbia, 59 p.

Kistritz Consultants Ltd.
1994: Environmental Overview of Ladner; Planning Department, Corporation of Delta, Delta, British Columbia, 95 p.
1992: Environmental Overview of the North Delta Area; Planning Department, Corporation of Delta, Delta, British Columbia, 138 p.

Norecol, Dames, and Moore
1994: Our Legacy for Future Generations: Delta Rural Land Use Study, Vol. 2, Full Report with All Background Information; Corporation of Delta, Delta, British Columbia, 163 p.

Schaefer, V., Aston, M., Bergstresser, N., Gray, J., and Malacarne, P.
1992: Urban Ravines, Volume 2, B.C. Lower Mainland Ravines Inventory; Douglas College Institute of Urban Ecology, New Westminster, British Columbia, 248 p.

Stewart and Ewing Associates Ltd.
1992: Preliminary Evaluation of Remnant Woodlands in Vancouver; Vancouver Parks Board, Vancouver, British Columbia, 104 p.

First towns of the Fraser estuary: a brief history of Fraser valley Halkomelem society

Michael Kew[1]

Kew, M., 2004: First towns of the Fraser estuary: a brief history of Fraser valley Halkomelem society; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 49–55.*

Abstract: Human settlement and town-centred living in the Fraser River delta preceded the arrival of Europeans by thousands of years; however, Euro-Canadian colonizers and their descendants have continued to think of the land as having been unsettled and unused when they arrived. Such thinking facilitated settlement and pushed aside the original people. Reappraising First Nations history is an important step in rethinking human relationships to the delta. It informs us of alternative forms of social organization, different ideas about human relationships to resources, and other ways of using resources. Re-examining First Nations history in the delta is an important way to begin to enlarge our view of alternatives for the future. Their long history of stable and bountiful use of the land may not provide a model to be re-created, but it can serve as an example to focus thinking about the underpinning concepts of 'sustainability'.

Résumé : Le peuplement et l'établissement de villages dans le delta du Fraser ont précédé de plusieurs millénaires l'arrivée des Européens; cependant, les colons euro-canadiens et leurs descendants ont toujours fait comme si personne n'avait occupé ou utilisé le territoire avant leur arrivée. Cette façon de penser a facilité la colonisation et mené à l'éviction des premiers occupants. La réévaluation de l'histoire des Premières nations est une étape importante vers une nouvelle façon de concevoir les relations entre les humains et le delta. Elle nous fait connaître d'autres formes d'organisation sociale, des idées différentes sur les relations entre les humains et les ressources naturelles, ainsi que d'autres façons d'utiliser ces ressources. Le réexamen de l'histoire des Premières nations dans le delta est une façon importante de commencer à élargir notre perspective sur les solutions d'avenir. La longue histoire de l'utilisation durable d'une terre généreuse par ces nations n'offre peut-être pas de modèle à reproduire, mais elle peut servir d'exemple pour aider à réfléchir aux concepts fondamentaux de la durabilité.

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ARRIVAL OF EUROPEANS

Canadians have long held the idea that the land is a vast reservoir of treasures, unowned and empty of people. In this mythic, idealized view, the land is conceived of as 'natural', waiting to be tamed with its lakes and rivers to be named and its land free for settlement, and simply awaiting the surveyor's transit and the farmer's plough. This myth served British Columbia's European settlers and immigrants by making it easier to set aside any concern for indigenous people and, in fact, to ignore Canadian policies and aboriginal rights protected by British common law and legislation. From 1871 to 1990, successive governments of British Columbia denied aboriginal title in the province. This was done in the face of British Colonial policy and established practice of the government of Canada and in the face of First Peoples' living presence and their vigorous but polite objections. The widespread acceptance of the myth of an empty land helped successive waves of immigrants view themselves as pioneers and developers rather than pillagers and trespassers.

This paper is not intended to be a lesson in morality, although ignoring the moral side of any activity is done with peril. Rather, it is a reminder that we urgently need to examine easily accepted assumptions on which knowledge and sciences are based. We certainly must abandon the myth that history began with the coming of Europeans and recognize that human interdependence with resources — humans as integral components of ecological systems — began long before Europeans arrived. And so when we set out to examine urban settlement in the Fraser River delta, let us begin by noting its long history and reminding ourselves that urban settlement in this region is not new. Sedentary, town-centred living began at least two thousand years ago among the ancestors of the Halkomelem-speaking people of the Fraser Lowland. Speakers of Halkomelem, along with speakers of Squamish, Nooksack, Straits Salish, and Clallam, comprise a single cultural group known as 'Central Coast Salish'. Their territories are contiguous (*see* Fig. 1) and they share essentially the same cultural system (*see* Suttles (1990) for a concise summary description). The full story of human history in the area and of the varied roles that human society has played in shaping the Fraser Lowland ecological systems has scarcely been touched. We in the fields of anthropology and related sciences have just begun to ask the questions that need to be answered, and we are far from realizing a full understanding of what human resource use has been in this area and of what the effect of human use has been, for example, on the spread, scope, and dynamic character of salmon resources. Not only have humans been living in the delta area for a long time; they have used resources from all parts of the area, from the sea and river channels to the tops of mountains, and they built and lived in flourishing communities.

Let me take you back in time to share a few actual observations by the first European visitors to the populous Fraser River delta. The journal of North West Company fur trader Simon Fraser provides some of the most detailed descriptions. On June 28, 1808, upon reaching the territory of Halkomelem-speaking people in the vicinity of Yale, he recorded details of:

> ...an excellent house 46 by 23 feet, and constructed like an American frame house. The planks are 3 or 4 inches thick, each passing the adjoining one a couple of inches. The posts, which are very strong, and rudely carved, receive the beams across. The walls are 11 feet high, and covered with a slanting roof. On the opposite side of the river, there is a considerable village with houses similar to the one upon this side.
>
> — Lamb, 1960, p. 99

Three days later he was received hospitably at a village, probably in the vicinity of Matsqui, and recorded this account:

> The number of Indians at this place is about 200....
>
> Their houses are built of cedar planks, and in shape [are] similar to the one already described. The whole range, which is 640 feet long by 60 broad, is under one roof. The front is 18 feet high, and the covering is slanting. All the apartments which are separated in portions, are square, excepting the chief's which is 90 feet long. In this room the posts or pillars are nearly 3 feet [in] diameter at the base, and diminish gradually to the top. In one of these posts is an oval opening answering the purpose of a door, thro' which to crawl in and out. Above on the outside are carved a human figure large as life, and there are other figures in imitation of birds and beasts. These buildings have no flooring. The fires are in the centre and the smoke goes out an opening at [the] top.
>
> — Lamb, 1960, p. 103–104

Reaching the sea on July 2, 1808, Fraser was again careful to note the size of the town through which he made a brief tour:

> At last we came in sight of a gulph or bay of the sea....On the right shore we noticed a village called by the Natives Misquiame [Musqueam];....The fort is 1500 feet in length and 90 feet in breadth. The houses, which are constructed as those mentioned in other places, are in rows; besides some that are detached.
>
> — Lamb, 1960, p. 105–106

Another large community was recorded in the journal of James MacMillan, a Hudson's Bay Company trader sent to establish Fort Langley. On entering the main channel of the Fraser River aboard the schooner *Cadboro* on July 23, 1827, he wrote, "At 3 P.M. a breeze springing up from the South West, sail was set, and we passed the Cowitchen Villages Saumni [?] Pinellahutz & Quomitzen about 6 O'clock, and anchored about a mile above....The population of the Cowitchen Villages may be at a rough guess 1500 souls."

Thirty years earlier, Peter Puget, with Vancouver's expedition in 1792, was impressed by the size of the village at Point Roberts: "The Body of the Village consists of three Rows of Houses each Row divided by a Narrow Lane & partitioned off into four or Six Square houses and every one large and capacious." (quoted *in* Lamb, 1984, footnote p. 578).

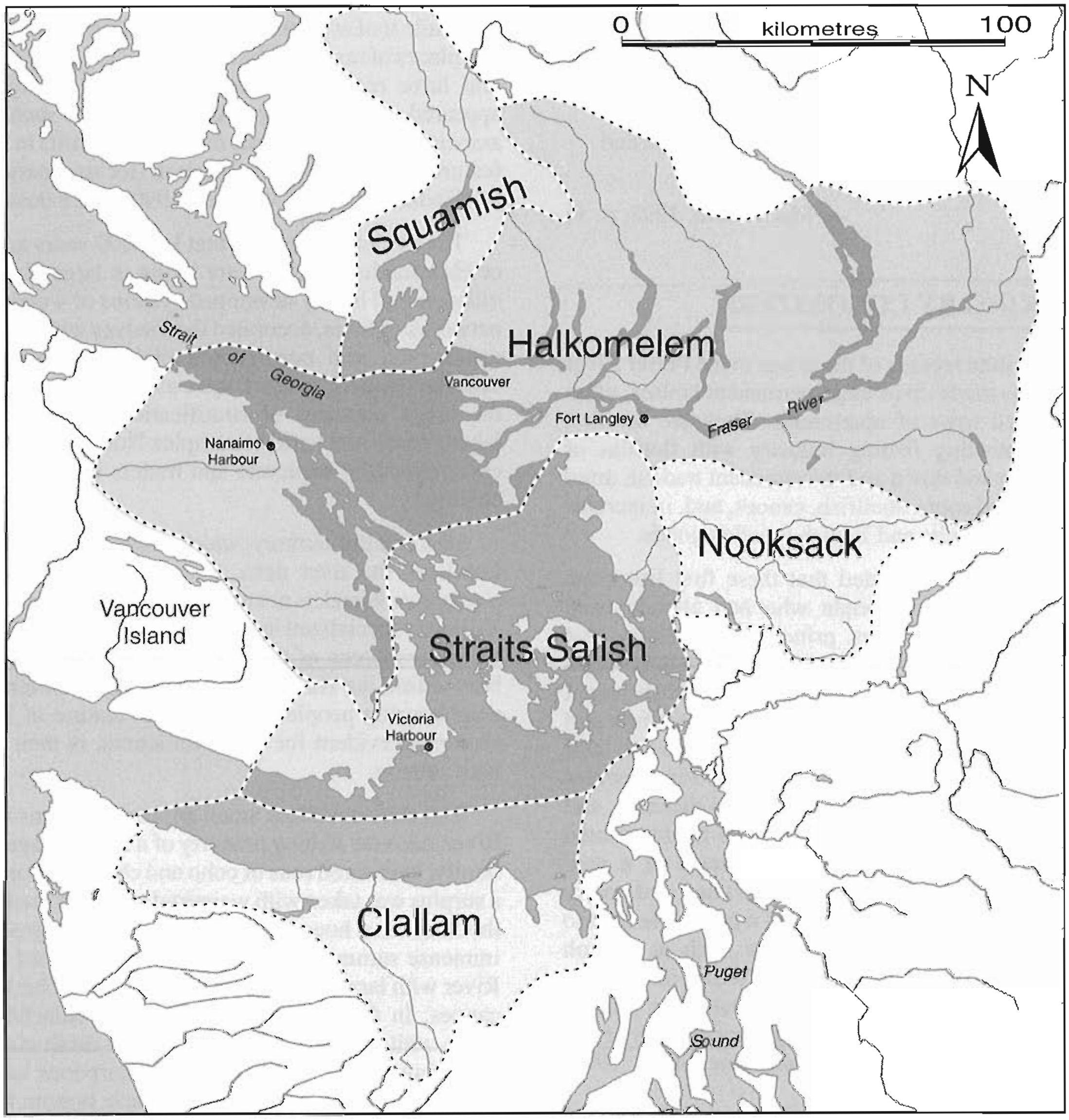

Figure 1. *Geographic areas of Central Coast Salish cultures* (modified from *Suttles, 1990, Fig. 1*).

Not only were large villages and towns established throughout the Fraser Valley, but the river itself served as a busy artery for transportation. Hudson's Bay Company traders at Fort Langley in the 1820s witnessed the traffic of traders and fishing families passing up and down the river as various fishing seasons went by. Here is a sample of their observations:

Friday 28th. [September, 1827] "Nearly 100 Canoes and Rafts of the Homes [Squamish] Tribe passed today, on their way down the River." (Maclachlan, 1998, p. 39);

Saturday 3rd. [May, 1828] "...50 Canoes of Musquiams Came to the wharf, with their families." (Maclachlan, 1998, p. 61);

Sunday 20th. [July, 1828] "Fine day — Indians passing by the Hundreds." (Maclachlan, 1998, p. 69);

Monday 22nd. [September, 1828] "...150 Cowitchens families Stop[p]ed at the wharf to trade....There are 245 canoes of Cowitchens already passed...." (Maclachlan, 1998, p. 75);

Thursday 25th. [September, 1828] "200 Canoes of Whooms [Squamish] stopped along Side of the wharf — they are on their way to Burrards Canal for the winter...."(Maclachlan, 1998, p. 75).

An entry for August 25, 1827, elaborates on the mode of heavy transportation with canoes:

> Families for the Sanch [Saanich] Village at Point Roberts have been passing in continued succession during the day all bound for the Salmon fishery. Their luggage as well as that of the other tribes is transported up and down the River on Rafts, which are formed by laying Boards across two or more Canoes Kept 8, 10,

or 12 feet asunder. They have also among them large War canoes procured from Indians to the northward, which are used by them as Luggage Boats, and which contain a great Bulk of Furniture and Baggage. The Size of some of these craft is fully 50 feet in length and 6 to 7 ft. across the middle.

— Maclachlan, 1998, p. 34

MYTH-MAKING BY COLONIZERS

These earliest written records of the towns in the Fraser River delta tell of towns made up of large permanent houses, often built as connected rows of apartments. They are the first records of the bustling fishing industry with flotillas of canoes moving up and down and the attendant trade in dried fish, dried bulbs and roots, shellfish, canoes, and, in increasing amounts, beaver pelts and British woollen goods.

We also should be reminded that these first European observers were meeting a people who had already been affected by introduced diseases, principally smallpox, that one modern assessment concludes reduced their population by at least 30% (Boyd, 1994, p. 29). Despite such recent decline, the early traders were respectful of the numbers and strength of Halkomelem people and did not challenge their property rights. Within decades they and other First Peoples were to suffer further losses from introduced diseases, and within fifty years their own presence was to be discounted and their characters diminished by proponents of a new mythology — the myth that land was unowned and empty (*see* Tennant, 1990, p. 40–41). This was a profitable idea to promote and found powerful advocates such as Joseph Trutch, Chief Commissioner of Lands and Works in the colonial government, who reported in 1867 that "The Indians really have no right to the lands they claim, nor are they of any actual value or utility to them..." (quoted *in* Fisher, 1971, p. 11).

Unfortunately, echoes of such views may still be heard among British Columbians, a fact plain to readers of Chief Justice McEachern's 1990 trial judgment in *Delgamuukw* as he found the homelands of the Gitksan and Wet'suwet'en to be "...a vast almost empty area..." (Supreme Court of British Columbia, 1990, p. 11), and their forebears to be people lacking "...many of the badges of civilization, as we of European culture understand that term..." (Supreme Court of British Columbia, 1990, p. 31).

WHAT DO ARCHAEOLOGY AND ETHNOLOGY REVEAL?

Over the last 30 years, research has confirmed what First Nations people have been saying for a long time about living in their homelands from the beginning of time. Radiocarbon dating in Halkomelem territory has established human presence at the Milliken site near Yale 9000 years before present (Carlson, 1990, p. 63), and for all practical purposes, that may be as good a measure of 'beginning of time' as most of us need.

While tool assemblages have changed over that long time and places of residence have shifted, uses of resources in general have remained remarkably stable. Until Europeans appeared, there were no dramatic changes such as are often associated with large-scale migration or shifts in fundamental features of economic organization (for summary discussions *see* Fladmark (1986), Mitchell (1990), and Rousseau (1993)).

The evidence suggests that by 2000 years ago, ancestors of Halkomelem people were living in large plank houses in villages, had highly developed systems of woodworking and networks of trade, decorated themselves with costly personal ornaments, and constructed elaborate tombs for their deceased leaders. In short, there already existed a society with the major elements of stratification and specialization of labour consistent with the complex Northwest Coast societies encountered by explorers and traders in the late eighteenth century.

Halkomelem territory, which extends throughout the Fraser Lowland, the river delta, and across to adjacent parts of Vancouver Island, is not uniform in environment or resources. Villagers specialized in using a wide range of distinctive and varied resources of their local areas, and exchanged them both within the Halkomelem-speaking community and with neighbouring peoples. But a major feature of Halkomelem economy, evident for many millennia, is their relationship with salmon.

The once countless small tributary streams to the Fraser River, each the fishing property of a local village or extended family, harboured runs of coho and chum salmon from which a surplus was taken with weirs and traps and then dried within the communal houses for use in winter. Spring salmon and the immense summer runs of sockeye were fished in the Fraser River with large pursing trawl nets operated between pairs of canoes. In their seasons sturgeon and eulachon were also taken with similar nets of appropriate mesh sizes. Sturgeon also were captured with ingenious harpoons having jointed shafts that enabled a fisher to reach bottom-lying fish in depths of more than fifty feet (*see* Stewart (1977) for illustrations).

The large, open waterways of the main river, directly accessible to fishers from local villages, also were fished by people whose villages were located across Georgia Strait and in Howe Sound. The Fraser River was a fishing and transportation corridor along which people speaking several different languages met and congregated by the hundreds in regularly used seasonal villages. As the first fur traders observed it, the Fraser River delta was even then a cosmopolitan centre of industry and trade (Boxberger, 1989).

WHAT KIND OF SOCIETY DID HALKOMELEM HAVE?

If Halkomelem society had been structured along more familiar lines of political organization, such as a tribal system with a centralized chiefship or kingship, Europeans may have understood it better. But it actually consisted of large independent household groups connected to one another by far-reaching kinship ties. Each household unit was formed around a central core of bilaterally related kin; that is, persons sharing a line of descent traced without distinction as to the gender of connecting kin. These bilateral or cognatic kin groups shared ownership of important real property such as house sites and resource-use sites like fish-trap locations, berry and root harvesting grounds, and on the salt water, shellfish beds. The locus of their identity was the communal family house site in a named village. Skilled and experienced individuals owning valuable personal capital goods like canoes, wood-working equipment, and tools acted as stewards of bilateral kin property and leaders of the house groups. These were composed of the core of related blood kin, plus affinal kin and slaves. Because many of the houses consisted of a number of different screened or partitioned sections under the same roof, and each section could contain one or more nuclear family units, it is difficult and would be misleading to attempt an estimate of the average number of occupants per house. In discussing the 640 foot long house described by Fraser (*see* above), Suttles has written that accepting Fraser's figures, "...implies an average of 20 persons in each of the ten apartments. It seems reasonable to suppose that each apartment housed two to four families,..."(Suttles, 1992, footnote 5, p. 221). This was a large house, but some houses and villages were smaller, each house likely equivalent in number of occupants to one of the apartments in the large house. We may conclude, therefore, that occupants of houses ranged in numbers from 20 to several hundred people. These house groups formed the large towns observed by early visitors, but neither these house groups nor the towns recognized an office of chief or a formal governing council.

To describe the mechanisms of governance in this political system, we must examine the way in which the networks of kinship and economic obligations were established and maintained. Rules of marriage prohibited alliances between blood kin and, therefore, required alliances between different extended families, usually outside the household and village and often with distant groups. Thus, people throughout the whole region were connected through countless networks of marriage ties and, because of the rule of bilateral descent, by blood ties as well.

To these links must be added the factor of class. Halkomelem society, like all Northwest Coast indigenous societies, was hierarchical. There were named categories of people from high-born to low or worthless, with every gradation from top to bottom, and finally, at the lowest level, slaves (*see* Suttles, 1958, 1990). Slaves were people from outside the local district who were purchased or captured in raids upon others and whose kin were unable to defend them or recover them through payment of goods. They were without ordinary rights in the house and valued for their labour (*see* Donald, 1990, p. 145–168). Marriages, as well as being exogamous to the village, were also class-linked, so that the bonds and linkages of kinship connecting household to household and village to village were reinforced by shared class values between powerful families of different villages.

Trade by barter was a common practice, but another major mechanism of distribution was the system of gift and service exchange known as the potlatch. Local surpluses of foods were given as gifts to in-laws in distant villages where visiting donors were thanked in return with their local goods; later, reciprocal visits reversed the direction of giving. These systems of exchange created and maintained amicable relations between kin groups outside the local town and district. They provided means for establishing social connections, enjoining support when needed and thus creating overlapping networks of alliance over a wide area and beyond boundaries of dialect and language. They also provided means for resolving disputes and redistributing wealth (*see* Elmendorf (1960), Suttles (1987), and Kennedy (1995) for discussions of networks of marriage alliances).

The Fraser River valley Halkomelem population, like the wider Central Coast Salish culture of which it was part, was further united by a shared religious ideology. This is found in their view of the world, humans, and the place of humans in the world. Humans are subordinate to nonhuman powers embodied in and associated with other life forms. Humans maintain their place and obtain their strength through delicately balanced reciprocal exchanges with nonhuman powers. These relationships are still celebrated in modern Halkomelem towns and villages through personal and community ritual. This philosophical system does not separate but fully integrates the 'spiritual' and the 'practical' in such a way that 'religious' specialists also may be economic specialists, curers, seers, and community leaders.

To summarize, governance of this society was achieved by networks of interdependent, intermarrying families in separate towns throughout the region, linked and bound together by a shared ideology, kinship, and class affiliation — all made tangible by reciprocal exchanges of foods and goods which redistributed the regionally specific wealth throughout the whole region. This society was not without conflict and occasional violence — even warfare. These are attested to by oral history and the observations of traders in the early years of the nineteenth century. Nevertheless, without a centralized apparatus of government, armies, police forces, and agriculture, this society produced a flourishing population and abundant living with highly developed music, sculptural art, and philosophy. Their long history of stable settlement without evidence of substantial immigration or disruption surely provides an example of 'sustainable resource use'. It ought to set us thinking much more critically about the social underpinnings of 'sustainability' (*see* Kew and Griggs, 1991).

HALKOMELEM SOCIETY TODAY

In the Fraser River valley Halkomelem area today there are about 6000 registered Indians affiliated with 29 bands, the present legal designation of Indian communities. They live scattered through the valley on small parcels of Indian reserve land associated with age-old village sites. Despite more than a century of cultural oppression — policies deliberately intended to eradicate indigenous culture — Halkomelem people retain a distinctive identity, maintain age-old systems of intervillage alliances through kinship and exchange, and also maintain their ancient religious system. Furthermore, they are developing impressive new structures of governance and building upon tradition, and also borrowing and adapting introduced forms to create new institutions suited to contemporary needs (for recent and continuing outlines of such efforts *see Sto:lo Nation Newsletter, Sqwelqwel to Sto:lo,* v. 1, no. 2, 1995; Carlson (1997)). Today, band offices and tribal councils are full of experienced, highly trained, and highly motivated new leaders.

The place of First Nations in the settlement and human shaping of the Fraser River valley has been neglected or dismissed by Europeans. Up to now this omission has served the interests of immigrant society and its privileged sectors. But it will no longer suffice, for recent court decisions and First Nations peoples have forced governments and public agencies to revisit the issue of land rights.

The 1973 Supreme Court decision in Calder led to the formulation of Canada's modern procedure of Indian Treaty Negotiation (*see* Tennant, 1990; British Columbia Claims Task Force, unpub. report, 1991). In 1990, the Sparrow decision was crucial in redirecting Department of Fisheries policy. This decision concerned a Musqueam man's aboriginal right to fish in Canoe Passage, a short branch of the south arm of the Fraser River. The Supreme Court of Canada concluded that his aboriginal rights had not been extinguished and were pre-eminent over those of other users of the resource. In the same year, the Province of British Columbia finally relinquished the position taken more than 100 years ago by Joseph Trutch speaking as Commissioner of Lands and Works in the Colony of British Columbia, and began to participate in treaty negotiations. Several Fraser River valley Halkomelem bands and the Sto:lo Nation (a political association of 21 bands, centred around Chilliwack, who have grouped together to create a new form of local governance, administering many of their own services and working as one group in treaty negotiation) have registered their intent and are busily preparing to negotiate treaties.

Aboriginal rights are all those rights of land occupancy and resource use which aboriginal peoples formerly exercised and which were the means of maintaining their societies. If recently concluded aboriginal treaties elsewhere in Canada are a guide, British Columbia treaties will include financial compensations to First Nations, new allocations of lands, agreements about sharing resource revenues, and agreements which will guarantee access to portions of such resources as fish as well as negotiated and guaranteed participation in resource and land-use planning. Treaty negotiations are about property rights, about negotiating control of lands and resources — that is to say, wealth — within the fabric of society, and they promise to return property rights which have long been denied. If nothing else, this will mean that First Nations everywhere will be negotiating new roles for themselves as participants in land-use planning and local development.

CONCLUSIONS

It is more important than ever before in applied sciences and especially in resource management that we cast off our old conceptions of indigenous cultures and reshape our thinking about them. If we wish to know more about the natural history and dynamics of the five different species of salmon still making the Fraser River the greatest salmon-producing waterway in the world, we should start by understanding them as part of a ten-thousand-year-old system in which humans have played key roles as predators and protectors. We have much to learn from understanding First Nations peoples, their history, and their ways of understanding and living successfully in this place.

Also, it is time that those of us who are directly or indirectly involved in applied research or program development recognize that First Nations are now major players in the whole process of planning and governing resource use. This means including them in planning and decision-making institutions, and recognizing and studying with them their role and interest in the entire human and natural history of the region.

REFERENCES

Boxberger, D.
1989: To Fish in Common: the Ethnohistory of Lummi Indian Salmon Fishing; University of Nebraska Press, Lincoln, Nebraska, 212 p.

Boyd, R.
1994: Smallpox in the Pacific Northwest: the first epidemics; *in* BC Studies, no. 101, University of British Columbia Press, Vancouver, British Columbia, p. 5–40.

Carlson, K.T. (ed.)
1997: You are asked to witness: the Sto:lo in Canada's Pacific Coast history; Sto:lo Heritage Trust, Chilliwack, British Columbia, 208 p.

Carlson, R.
1990: Cultural antecedents; *in* Handbook of North American Indians: Northwest Coast; Smithsonian Institution, Washington, D.C., v. 7, p. 60–69.

Donald, L.
1990: Liberty, equality, fraternity: was the Indian really egalitarian?; *in* The Invented Indian, (ed.) J. Clifton; Transaction, New York, New York, p. 145–168.

Elmendorf, W.W.
1960: The structure of Twana culture; Washington State University Research Studies, v. 23, no. 3, Monographic Supplement 2, Pullman, Washington, 306 p.

Fisher, R.
1971: Joseph Trutch and Indian Land Policy; *in* BC Studies, no. 12, University of British Columbia Press, Vancouver, British Columbia, p. 3–33.

Fladmark, K.
1986: British Columbia Prehistory; National Museum of Man, Ottawa, Ontario, 150 p.

Kennedy, D.I.
1995: Looking for tribes in all the wrong places: an examination of the central coast Salish social network; M.A. thesis, Department of Anthropology, University of Victoria, British Columbia, 164 p.

Kew, M. and Griggs, J.
1991: Native Indians of the Fraser Basin: towards a model of sustainable resource use; *in* Perspective on Sustainable Development in Water Management: Towards Agreement in the Fraser River Basin, (ed.) A. Dorcey; Westwater Research Centre, University of British Columbia, Vancouver, British Columbia, p. 17–47.

Lamb, W.K. (ed.)
1960: The Letters and Journals of Simon Fraser, 1806-1808; Macmillan, Toronto, Ontario, 292 p.

Lamb, W.K. (ed.) (cont.)
1984: A Voyage of Discovery to the North Pacific Ocean and Round the World, 1791-1795 by George Vancouver; four volumes; Hakluyt Society, London, United Kingdom, 1752 p.

Maclachlan, M. (ed.)
1998: The Fort Langley Journals, 1927–30; UBC Press, Vancouver, British Columbia, 279 p.

Mitchell, D.H.
1990: Prehistory of the coast of southern British Columbia and northern Washington; *in* Northwest Coast, Handbook of North American Indians, v. 7; Smithsonian Institution, Washington, D.C., p. 340–358.

Rousseau, M.K.
1993: Early prehistoric occupation of south-central British Columbia; *in* BC Studies, no. 99, University of British Columbia Press, Vancouver, British Columbia, p. 140–183.

Sqwelqwel to Sto:lo
1995: Sqwelqwel to Sto:lo, Sto:lo Nation Newsletter; Sto:lo Nation, Chilliwack, British Columbia, 181 p.

Stewart, H.
1977: Indian Fishing: Early Methods on the Northwest Coast; J.J. Douglas, Vancouver, British Columbia, 181 p.

Supreme Court of British Columbia
1990: Reasons for Judgement in Delgamuukw, et al. and Her Majesty the Queen in Right of the Province of B.C. and the Attorney General of Canada, Smithers Registry No. 0843.

Suttles, W.
1958: Private knowledge, morality, and social classes among the Coast Salish; *in* American Anthropologist, v. 60, no. 3, p. 497–507.
1987: Cultural diversity within the Coast Salish continuum; *in* Ethnicity and Culture, (ed.) R. Auger, M. Glass, S. MacEachern, and P. McCartney; Archaeological Association, University of Calgary, Calgary, Alberta, p. 243–249.
1990: Central Coast Salish; *in* Northwest Coast, Handbook of North American Indians, v. 7; Smithsonian Institution, Washington, D.C., p. 453–475.
1992: The Shed-Roof House; *in* A Time of Gathering: Native Heritage in Washington State; (ed.) R.K. Wright; Burke Museum, University of Washington Press, Seattle, Washington, p. 212–222.

Tennant, P.
1990: Aboriginal People and Politics: the Indian Land Question in British Columbia, 1849-1989; University of British Columbia Press, Vancouver, British Columbia, 305 p.

Metropolitan Vancouver: an economic gateway to the Pacific Rim

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Davis, H.C. and Hutton, T.A., 2004: Metropolitan Vancouver: an economic gateway to the Pacific Rim; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 57–66.*

Abstract: During the twentieth century, the metropolitan Vancouver economy has undergone a substantial transformation from a centre of administrative, distributive, and commercial services for the province to its present position as a gateway to the increasingly integrated network of urban economies on the Pacific Rim. Two related phenomena have been central to this transformation and are expected to continue well into this century: a restructuring of the metropolitan economy and a reorientation of the economy's export markets. The restructuring of the Vancouver economy has resulted primarily from a shift of the region's employment from the extractive and manufacturing activities to service activities. This shift has resulted in the rise to dominance of producer services, those professional and technical services that are information-intensive and require a highly skilled labour force. As producer services become increasingly valued in global markets, their export from the region continues to expand.

Résumé : Au cours du vingtième siècle, l'économie de la région de Vancouver a subi une transformation importante qui l'a fait passer d'un rôle de centre provincial de services administratifs, de services commerciaux et de services de distribution à sa situation actuelle de point d'accès au réseau de plus en plus intégré des économies urbaines du littoral du Pacifique. Deux phénomènes connexes, qui devraient se poursuivre pendant une bonne partie du nouveau siècle, sont au cœur de cette transformation : la restructuration de l'économie du Grand Vancouver et la réorientation des marchés d'exportation. La restructuration de l'économie vancouvéroise résulte principalement d'un déplacement d'emplois dans la région depuis des activités d'extraction et de fabrication vers des activités de service. Ce déplacement a eu pour effet la domination progressive des services à la production, soit les services professionnels et techniques à forte composante d'information qui nécessitent une main-d'œuvre hautement qualifiée. Comme les services à la production acquièrent de plus en plus de valeur sur les marchés mondiaux, leur exportation à partir de la région poursuit sa croissance.

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INTRODUCTION

During the first half of the twentieth century, metropolitan Vancouver's development was shaped largely by the resource sector of the province's interior. This linkage occurred primarily through its resource-processing activities, manufacturing facilities, and the flow of commodity exports due to Vancouver's position as Canada's western rail terminus and largest port. Although Vancouver never attained the status of a classic 'industrial metropolis' similar to Toronto, Montreal, and Hamilton, these resource-related activities constituted a significant industrial sector within the economy.

The second half of the twentieth century saw an important expansion of Vancouver's linkages with the provincial resources sector, characterized by the rapid growth of service activities. To a considerable extent, these new activities represented a maturation of Vancouver's economy and its specialized position within a large and expanding provincial economy.

The principal components of the linkage of Vancouver's service sector with the resource sector reflected the city's 'command and control' functions characteristic of a metropolitan 'core' operating within the resource-dependent 'periphery' (Hutton, 1997). Vancouver's specialized services sector included head-office operations of principal resource corporations, notably in the forestry and mining sectors; related banking and financial industries, including the Vancouver Stock Exchange; and a growing complex of interrelated commercial services.

These resource-related industries clearly remain of considerable importance to Vancouver's economy (Davis, 1993). For example, the port of Vancouver continues to export in excess of 50 million tonnes of resource commodities annually (increasingly to Pacific Rim markets), and forest industry operations such as mills, pulp production, and end-product manufacturing are still in operation, particularly along the Fraser River. At the same time, Vancouver has unequivocally entered a new phase of economic development, characterized at the broadest level by continuing economic restructuring — the shift of shares of the region's employment from primary (extractive) and secondary (manufacturing) activities to the tertiary (services) sector. At the core of this transformation have been the so-called 'producer services', those information-intensive services that are high–value-added and require a highly skilled, white-collar labour force. Such services include professional, commercial, and technical services such as computer services, engineering services, management consulting, accounting, legal services, advertising, finance, and telecommunications. Concomitant with the rapid growth of these services has been their increasing export to markets within the Pacific Rim, especially the expanding markets of the Asia–Pacific region.

In the following sections, we first consider evidence of the restructuring of the Vancouver economy and provide some of the underlying reasons for this phenomenon. Based on three major empirical surveys of the metropolitan economy over the two decades 1971–1991 (Davis, 1976; Ley and Hutton, 1987; Davis and Hutton, 1991), the increasing tendency of the region to export its specialized high-order services is documented. Particular attention is given to the reorientation of the economy toward the Pacific Rim during this period. In this latter context, the principal functions that comprise Vancouver's expanding role as a gateway to the Asia–Pacific region are considered.

ECONOMIC RESTRUCTURING OF THE VANCOUVER ECONOMY

In the late 1940s, approximately 60% of the Canadian labour force was in the goods-producing sector: the extractive industries (agriculture, forestry, fishing, and mining), construction, and manufacturing. By the early 1990s, this sector accounted for less than 30% of the work force. This shift of the labour force to the service sector is a familiar one in economically developed nations. During the 1980s and well into the 1990s, virtually all of the increase in net employment creation was in the service (non-goods) sector.

Restructuring has been an ongoing process over the past several decades in the metropolitan Vancouver economy. During the twenty-year period 1971–1991, the service sector more than doubled, growing at a rate which exceeded twice the rate of the primary sector and four and a half times the rate of manufacturing (*see* Table 1). By 1991, service activities accounted for nearly four-fifths of the region's labour force.

A number of factors underlying this shift have been suggested by Greenfield (1966), Spengler (1967), Tucker (1977), Economic Council of Canada (1978, 1990), Davis and Hutton (1981), Knight (1982), McCrae (1985), and Browne (1986). These factors include:

1. Disproportionate increases in labour productivity: labour productivity increases have occurred disproportionately in the goods-producing industries, thus skewing the labour force toward the service sector.
2. Differential income elasticities: empirical evidence supports the hypothesis of a slightly greater income elasticity of service activities compared to goods, which results in a shift to the purchases of services as incomes rise.
3. Increasing female employment: the dramatic increase in female labour force participation rates over the past four decades has resulted in a significant transfer of service activities formerly performed within the household into the monetized portion of the economy.
4. Contracting out for specialized services: a tendency among firms to contract for specialized services that were formerly done in-house also has contributed to the shift toward service activities.
5. Production processes: the production of goods in advanced economies has become increasingly dependent on services as inputs to the resource extraction and manufacturing processes, reflecting in large part recent technological innovations in areas such as computer technology and telecommunications.

Table 1. Metropolitan Vancouver labour force and growth rates by industry, 1971–1991.

	1991 Labour force	Growth rates (%)		
		1971–1981	1981–1991	1971–1991
All industries	883120	42.4	30.6	86.1
Extractive	21375	31.8	18.2	55.7
Agriculture	11575	43.8	48.2	113.2
Fishing and trapping	2865	46.0	24.6	81.9
Logging and forestry	4085	32.2	-7.9	21.8
Mining, quarrying and oil wells	2850	5.2	-19.6	-15.4
Construction	64340	43.5	39.9	100.8
Manufacturing	98675	25.7	-0.3	25.3
Food, beverages and tobacco	14805	23.3	-4.8	17.3
Rubber and plastics products	3790	97.8	114.1	323.5
Leather and textiles	2025	26.3	11.0	40.1
Clothing	5545	65.3	44.6	139.0
Wood products	11585	10.7	-36.3	-29.4
Furniture and fixtures	3085	27.7	5.3	34.4
Paper and allied products	4510	7.8	-9.7	-2.7
Printing and publishing	12255	15.9	58.0	83.2
Primary metals	2260	10.4	-16.3	-7.6
Fabricated metal products	10340	27.3	-8.5	16.4
Machinery	3950	100.6	-37.0	26.4
Transportation equipment	5165	35.4	-23.1	4.1
Electrical and electronic products	6465	26.0	59.6	101.1
Non-metallic mineral products	2595	6.7	-16.7	-11.1
Petroleum and coal	1395	79.5	-6.4	68.1
Chemicals	3525	22.5	20.9	48.1
Other manufacturing	5380	50.5	50.5	126.5
Services	689465	63.3	35.1	120.7
Transportation	44805	37.6	0.9	38.8
Storage and warehousing	2320	59.6	3.1	64.5
Communication	24845	56.3	39.7	118.2
Other utilities	7445	52.2	-0.3	51.8
Wholesale trade	52775	50.3	21.1	82.0
Retail trade	113065	53.0	30.3	99.4
Finance	30150	79.5	17.6	111.1
Insurance	11630	41.0	125.6	218.2
Real estate operations and insurance agencies	24630	75.9	36.8	140.5
Business service	70080	129.6	62.3	272.6
Government – federal	18175	40.4	26.6	77.7
Government – provincial and territorial	10145	149.5	-15.5	110.9
Government – local and other	16730	72.8	32.7	129.3
Education	55340	52.7	31.7	101.0
Health and social services	76530	77.5	42.4	152.7
Accommodation, food and beverage	66540	94.9	52.8	197.9
Amusement and recreation	17145	49.7	96.7	194.6
Personal and household	21415	-6.3	117.2	103.6
Other services	25700	76.5	34.0	136.5

This shift in the labour force has been accompanied by a general tendency for service activities, particularly producer services, to concentrate in metropolitan areas. Empirical evidence of this centralizing tendency has been presented for Canada (Coffey and Polèse, 1987, 1988; Hutton and Ley, 1991), the United States (Noyelle and Stanback, 1984; W.B. Beyers, paper presented at the Annual Conference of the Association of American Geographers, Phoenix, Arizona, 1988), the United Kingdom (Marshall, 1985; Howell and Green, 1986), Australia (O'Connor and Edgington, 1991), and other developed countries (Browne, 1986; Daniels, 1985, 1987, 1990).

As is the case with the continuing shift to the services, a variety of reasons have been offered to explain this centralizing tendency of services. Coffey and Polèse (1989), for example, argue that while the location of consumer services will approximate that of the economy's population pattern, producer services will locate disproportionately in areas of population concentrations. Their model of the location of producer services emphasizes the importance of a pool of highly skilled labour, the availability of complementary economic activities (largely office-related activities), the costs of providing the particular service to market, and the role of the metropolitan environment (broadly defined to include social, cultural, political, and physical elements) as an attractive force.

Complementary conclusions were reached by Wheeler (1988) in his study of the location patterns of United States corporate headquarters and subsidiaries. Wheeler found a strong rank correlation between population size and the number of corporations and subsidiaries. From his analysis of the 30 largest metropolitan areas, he concluded, in accordance with the earlier studies of Pred (1977) and Noyelle and Stanback (1984), that producer service employment will continue to expand rapidly in major urban diversified economies and proximate population centres. The primary determinants of this spatial concentration of service activity are the availability of specialized information, complementary service activity, and intermetropolitan accessibility.

EVOLUTIONARY REORIENTATION OF VANCOUVER TOWARD THE PACIFIC RIM

Vancouver was established in the late nineteenth century as the western terminus of the national rail system and as Canada's premier Pacific port. During the first half of the present century, Vancouver developed as the principal resource-processing centre for British Columbia's staple sector, and its strategic position as a centre for resource exportation was largely consolidated. With the general rapid growth of the provincial economy over the past five decades, Vancouver's commercial functions have expanded substantially, with the city acting as head office, business service, and financial centre for the provincial economy.

Based on existing surveys of the metropolitan Vancouver economy over the twenty-year period from the early 1970s to the 1990s, this section of the paper will develop a sense of how the region has further evolved from its principal function as the provincial higher-order service centre to a place in the network of increasingly interdependent metropolitan economies of the Pacific Rim.

The early 1970s

An integral part of Vancouver's economic growth has been the development of a dense network of service linkages between Vancouver and the resource-dominated hinterland. The general dimensions of these linkages that developed during the first quarter-century of the postwar period in British Columbia were revealed in an input-output study of the metropolitan Vancouver economy (Davis, 1976). The resulting interindustry model was constructed using data from survey returns that accounted for 25% of total employment in the region. Table 2 depicts the geographical distribution of exports from the Vancouver economy in 1971 for seven service-industry categories. Several significant observations regarding the role of Vancouver as a service centre emerge. First, it is apparent that while a preponderance of services originating in metropolitan Vancouver (especially those catering predominantly to final, rather than intermediate, demand) were consumed within Vancouver, a significant volume was destined for markets in British Columbia outside the metropolitan region.

According to Table 2, 'business services' (which would correspond roughly to the producer-services designation employed in contemporary analyses) were extensively engaged in such exports. Indeed, the volumes of Vancouver's business services destined for the local (i.e. metropolitan) and hinterland economies were almost identical: 44.7% and 44.2%, respectively. Other Vancouver service sectors catering at least in part to intermediate demand also were substantially engaged in British Columbia's hinterland economy, underlining the pre-eminence of Vancouver as a higher-order service centre for British Columbia.

The input-output study of the metropolitan Vancouver economy also revealed a relatively low volume of service exports to the national market and an almost negligible level of service sales to the United States and other international markets. None of the service activities exported more than 13% of its sales to Canadian markets outside British Columbia, nor more than 4% of its sales to the United States or to the rest of the world. These figures emphasize the tight bonding of Vancouver at the time with the local and provincial markets for services.

The mid-1980s

In the decade following the input-output study of the metropolitan economy, Vancouver's producer services experienced considerable growth as measured by the expansion both of firms and employment. The number of firms classified as engaged in business and professional services within the downtown virtually doubled, from 1800 in 1971 to 3500 in 1980, while employment in the business-services sector within the metropolitan area quadrupled during the period 1961–1982 (Ley and Hutton, 1987). As a consequence, service activities led employment growth both in terms of

Table 2. Per cent geographic distribution of service exports from the Vancouver economy, 1971 (*modified from* Davis, 1976).

	Vancouver	Rest of province	Rest of Canada	USA	Rest of world
Communications	58.0	29.4	12.6	0.0	0.0
Utilities	75.5	24.5	0.0	0.0	0.0
FIRE	80.1	14.4	2.6	2.0	0.9
Health and welfare	95.1	4.8	0.1	0.0	0.0
Education	87.4	3.9	8.1	0.3	0.3
Business services	44.7	44.2	7.2	1.5	2.4
Other services	73.5	9.4	12.8	3.9	0.5

FIRE = Finance, insurance, real estate

occupational and industrial measures during the 1970s, and (coupled with relatively slow growth or even decline among the manufacturing industries and occupations) consequently underpinned the restructuring of the metropolitan economy.

The early 1980s were characterized by the most severe recession in British Columbia since the 1930s. Particularly sharp commodity price shocks in the early years of the decade were followed by a protracted period of very low demand for the province's resources in the United States and other export markets, severely depressing the key forestry and mining sectors. While no sector or region of British Columbia was immune from the effects of this sustained downturn, the province's resource and manufacturing sectors were particularly affected and, indeed, some resource-dependent regions experienced no significant recovery until well into the second half of the 1980s.

Against this backdrop of a protracted recession, a major survey of Vancouver's producer-services sector was conducted in 1984 (Ley and Hutton, 1987). While the sample of firms in this survey was smaller than that of the 1971 input-output study of the metropolitan Vancouver economy and was confined mainly to downtown firms, the broad findings appear to suggest a significant, if not fundamental, change in the market orientation of Vancouver's producer-service sector.

Table 3 depicts the distribution of market areas for the 626 producer-service firms in the 1984 sample, encompassing thirteen industry groups, as well as a 'miscellaneous' category. As with the findings from the 1971 metropolitan Vancouver input-output study, the local (metropolitan) market accounts for a high proportion of sales, both for the sample of all firms as a whole and for most individual producer-service industry groups, whereas the 'rest of the province' remains an important market for many.

Relative to the findings of the 1971 input-output study, however, it appears that by the mid-1980s national and international markets had become significantly more important for Vancouver producer-service firms. Some 17% of sales for the sample firms were made to markets outside British Columbia — the national market outside the province accounting for 10% and international exports for 7%. As might be expected, smaller firms were disproportionately tied to the local and provincial markets, whereas larger firms were more extensively involved in national and international markets, although the export threshold for the producer firms appeared to be lower than is common among manufacturing firms.

The 1984 study also disclosed that among the thirteen producer-service industry groups, those most active in the provincial hinterland included management consultants, geological and engineering consultants, and insurance services, whereas groups active at the national level included geological and engineering consultants, management consultants, securities and commodities firms, and real estate, as well as firms in the miscellaneous services category. Producer-service firms with a significant international market involvement included geological and engineering consultants, real estate, and financial services.

Responses from a number of firms selected for interview indicated that in the broadest terms, motivation for export marketing included both 'push' and 'pull' factors. The latter included notably the opportunities in large and growing markets in the United States and the Asia–Pacific region, where firms that had matured serving the demands of the provincial resource economy could successfully bid for contracts. At the same time, other firms cited the limitations of the local and provincial markets as an incentive for exporting. Additionally, the severe impact of the 1982–1985 recession, which

Table 3. Market areas of Metropolitan Vancouver producer services, 1984–1985 (*after* Ley and Hutton, 1987, **T**able 5, p. 421).

	Percentage of sales for principal market areas			
	Vancouver >75%	Other British Columbia >25%	Other Canada >10%	Rest of world >10%
	Percentage of firms in each category			
All firms	51.4	20.4	20.9	13.3
Printing	96.9	0.0	0.0	0.0
Banking	65.6	15.6	7.8	10.9
Securities, commodities	47.4	9.1	29.5	27.3
Insurance	42.0	33.0	17.9	7.9
Real estate	38.5	23.1	26.9	30.8
Personnel	65.0	15.0	20.0	0.0
Data processing	57.6	21.2	18.2	15.2
Accounting	68.2	4.5	13.6	4.5
Advertising	69.6	6.5	15.2	4.3
Architectural planning	45.0	22.5	15.0	10.0
Geology and engineering	26.5	38.2	44.1	32.4
Legal services	63.2	21.1	5.3	10.5
Management consultants	31.8	31.8	31.8	9.1
Miscellaneous services	41.9	20.9	34.9	15.1

affected both resource- and supporting producer-service activities, obliged many producer-service firms to seek more resilient (i.e. national and international) markets.

The early 1990s

The context for service-sector growth and export development changed very significantly in the period following the 1984 study. With respect to the general economic environment, the severe recession of the early and even mid-1980s was followed by a sustained period of high growth, particularly in metropolitan Vancouver, where British Columbia's high-growth producer services are concentrated (Davis and Hutton, 1989). At the same time, a series of public-policy initiatives and regulatory changes, designed wholly or in part to enhance the export of services, were introduced. First, in 1983, the City of Vancouver approved an economic strategy that identified international banking, producer services, and tourism as key, propulsive sectors, and included a series of supporting programs. Second, the governments of Canada and British Columbia signed a 'memorandum of understanding' in 1986, which for the first time emphasized the role of services (specifically exportable producer services) as a leading sector for Vancouver and British Columbia. Third, the governments of Canada and the United States concluded a new 'Free Trade Agreement' in 1988, designed to remove or at least reduce barriers to bilateral trade (including trade in services) over the 1990s.

In the fall of 1990, a questionnaire survey of selected sectors of the Vancouver economy was undertaken jointly by the City of Vancouver Economic Development Office and the University of British Columbia School of Community and Regional Planning (Davis and Hutton, 1991, 1994). The survey was of several hundred firms, principally producer services and technology-intensive manufacturing. The results reported here focus on the 251 responses from the producer services, with emphasis on market orientation, geographic destination of sales, and expected future markets.

Market orientation

In the survey, each firm was asked to designate the percentage distribution of its sales among the business, household, and government sectors. The results, shown in Table 4, indicate what would be expected of producer services: the primary market of the activities is predominantly the business sector. Eighty-seven per cent of the firms surveyed sold at least half of their output to other producers.

A principal focus of the survey was engineering services, a sector of the economy that has not received much attention in studies of restructuring compared with other producer services such as finance, real estate and insurance, legal services, advertising, accounting, and management consulting. Like the other producer-service activities, however, engineering services are experiencing economic globalization and are increasingly exported (Rimmer, 1991).

Geographic distribution of sales

Survey respondents were asked to estimate the approximate percentages of current sales to clients located in metropolitan Vancouver, Victoria, the remainder of British Columbia, the rest of Canada, the United States, the United Kingdom and Western Europe, the Asia–Pacific region, and elsewhere. The responses of the surveyed firms, shown in Table 5, indicate the extent of the export orientation of the producer-service firms in the Vancouver economy. The ratio of exports to total sales ranges from 24% for advertising services to 84% for computer services.

In contrast with the 1984 survey results shown in Table 3, the 1990 findings in Table 5 show less of a dependence on the local market and a greater proportion of international sales (with the exception of advertising). While this difference perhaps indicates to some degree a greater orientation to external markets, particularly those abroad, it is likely explainable in large part by the focus on engineering and management-consulting firms in the present survey in comparison with a much broader selection of producer firms in the earlier study.

Table 4. Market orientation of firms surveyed (*data from* Davis and Hutton, 1994).

			Primary market			
Service activity	**SIC number**	**No. of firms**	**Business**	**Business and government**	**Government**	**Total**
Engineering	7752	155	117 (75.5%)	24 (15.5)	14 (9.0)	(100.0)
Advertising	774	50	48 (96.0%)	1 (2.0)	1 (2.0)	(100.0)
Management consulting	7771	38	28 (73.7%)	6 (15.8)	4 (10.5)	(100.0)
Computer	7721	8	7 (87.5%)	1 (12.5)	0 (---)	(100.0)
Total		251	200	32	19	

SIC = Standard Industrial Classification (Statistics Canada, 1980)

A second point is perhaps less dependent on the composition of the survey respondents. In addition to the results displayed in Table 3, the 1984 survey revealed that 32% of the responding firms reported exports to the United States, followed by Europe (15%) and east and southeast Asia (11%). This relative importance of Europe and Asia is quite distinctly reversed in the results of the 1990 survey shown in Table 5, which very much reflect Vancouver's continuing economic reorientation toward the Pacific Rim countries (Davis and Hutton, 1991).

The 1990 results are particularly striking when compared with the geographic distribution of exports for service activities in the metropolitan Vancouver economy two decades earlier. Tables 2 and 5 provide strong evidence of the changing function of the metropolitan region's economy over the period 1971–1991. In the early 1970s, producer services were predominantly oriented toward the facilitation and administration of natural resource activity in the provincial economy. Exports of producer services were thus overwhelmingly to the rest of the province. By 1990, a complex of interdependent corporate services was beginning to merge, which weakened, relatively if not absolutely, the traditional tie between the Vancouver economy and that of the remainder of the province. Stronger links with the United States and the Asia–Pacific region had evolved; the direct exports of producer services to these regions has formed a critical part of these new ties.

Future markets

Firms surveyed were asked in which regions they expected to register their greatest sales increase over the next five to ten years. Table 6 shows the number of firms that listed each geographical market in which a significant increase in sales is foreseen. Several firms listed more than one region.

What is striking about these figures in the context of the present paper is the strong export expectations of each of the four sectors. This is in sharp contrast with the 1984 survey of 88 producer-service firms in which 68% of the firms indicated metropolitan Vancouver as the major growth area for sales.

In the engineering sector, more firms listed the United States than Vancouver as the major growth area. Vancouver was listed by only one more firm than was Asia. Perhaps reflecting the incipient talks regarding the North American Free Trade Agreement, six engineering firms indicated Mexico as the prime growth area for sales (included as "other" in Table 6), equal to the number that looked to Europe. Overall,

Table 5. Geographical distribution of sales by service activity, 1990 (*data from* Davis and Hutton, 1994).

Service activity	No. of firms	(Per cent) Vancouver CMA	Victoria CMA	Rest of B.C.	Rest of Canada	U.S.	Europe	Asia	Other	Total
Engineering	148	42.5	5.4	22.4	10.1	10.5	0.8	4.3	4.0	100.0
Advertising	49	76.3	6.6	5.2	6.0	4.0	0.3	1.0	0.6	100.0
Management consulting	35	54.2	2.5	11.8	21.3	5.6	0.8	3.6	0.2	100.0
Computer	8	16.3	1.9	25.9	16.9	19.0	5.0	15.0	0.0	100.0
Total	240									

CMA = Census Metropolitan Area

Table 6. Area of expected major increase in sales over the next five to ten years, 1995–2000, by service activity (number of firms) (*data from* Davis and Hutton, 1994).

Service activity	No. of firms	Vancouver CMA	Victoria CMA	Rest of B.C.	Rest of Canada	U.S.	Europe	Asia	Other
Engineering	155	33	1	30	25	39	6	32	17
Advertising	50	23	4	12	8	16	0	4	0
Management consulting	38	11	1	10	12	13	2	7	1
Computer	8	0	1	0	1	5	2	3	0
Total	251	67	7	52	46	73	10	46	18

CMA = Census Metropolitan Area.

from the row of total responses in the table, it is clear that the growing importance of the Asian market, particularly in relation to the European market, can be expected to continue.

VANCOUVER AS A GATEWAY TO THE PACIFIC RIM

The economic restructuring of the metropolitan Vancouver economy and the resultant expansion of service exports is but one aspect of increasing trade links between Vancouver and the Asia–Pacific region. The port of Vancouver, by far the largest port in Canada and one of the major deep-sea ports of the Pacific Rim, annually handles 60 to 70 million tonnes of commodity exports, much of it destined for Asia–Pacific markets. While the exchange of goods and services is perhaps the major gateway function performed by the Vancouver region, it is not the only link that the region provides to the Pacific Rim.

A second function performed by the metropolitan region is the facilitation of travel and tourism. Air travel is the most dynamic component of this gateway function, and the frequency of direct flights to major business centres is often regarded as a measure of a city's 'connectivity' within international markets. For travel and tourism between the Asia–Pacific region and metropolitan Vancouver, it is the critical link. Over the past two decades, air traffic through the Vancouver International Airport has expanded to the point that the airport ranks second only to Toronto in Canada, and among west-coast airports it is exceeded only by Los Angeles in terms of international traffic. Vancouver International Airport currently handles about twice as many international travellers as does the SeaTac airport in Seattle, Washington. The growth of Asia–Pacific region passenger traffic through Vancouver International Airport has been particularly rapid, doubling over the 1990–1995 period. This growth has been fuelled by expanding business travel, increases in tourism and immigration, and the increased travel of friends and relatives of newly settled immigrants. In addition to air traffic, tourism through the cruise-line industry has increased exponentially over the past decade.

Immigration itself is a third component of Vancouver's gateway functions. Together with Toronto, Vancouver has accommodated approximately half of the immigrants to Canada in recent years. While Toronto's influx of immigrants has included large numbers of Caribbean and Latin Americans, as well as Asians, the ethnic profile of Vancouver's recent immigrants has been preponderantly Asian–Pacific. In the Vancouver region, Asians now constitute more than a fifth of the metropolitan population. Among Vancouver's Asian immigrants, Chinese have been overwhelmingly the dominant group. In 1991, for example, Chinese accounted for more than half the immigration stream of 331 920 Asian immigrants to Canada.

As the stream of immigration is a significant underpinning of Vancouver's gateway function of facilitating travel and tourism, it also significantly influences a fourth gateway function, that of linking the region with the Asia–Pacific region through flows of finance and investment. In recent years, Vancouver has made substantial gains as a financial intermediary centre. In the private sector, Vancouver's institutional complex in the area of banking and investment includes the Vancouver Stock Exchange, one of North America's principal exchanges for venture capital; major regional offices of Canada's six largest chartered banks; approximately twenty foreign-banking ('Class B') banks; and VanCity savings, which has become one of Canada's largest credit unions. In the public sphere, there have been a number of government initiatives. Vancouver's International Finance Centre, for example, has been created through both federal and provincial legislation to allow international transactions to be undertaken without being subjected to normal Canadian taxation rules. Another example of a major public-sector initiative in this area is the creation in 1991 of the International Maritime Centre–Vancouver, an institution established to encourage and assist the transfer of head operations of foreign shipping lines to Vancouver.

Perhaps the most outstanding example of Vancouver's transformation as a Pacific Rim city and gateway centre in the area of finance and investment is demonstrated by the growth of the region's HSBC Bank Canada (formerly Hong Kong Bank of Canada). In less than two decades, the bank became Canada's seventh largest. HSBC Bank Canada stands out among foreign banks in Canada not only by virtue of its size but also by its links to Asian markets and its association with the Vancouver business community — particularly, but not exclusively, with those of Chinese ethnicity. With its headquarters in Vancouver, the bank now has more than sixty branches across Canada.

In recent years, the Vancouver region has undergone a socio-cultural reorientation that has reinforced its gateway functions and promises to enrich and strengthen them in the future. For example, Vancouver's secondary and tertiary educational institutions increasingly reflect an Asia–Pacific orientation, expressed in research, exchange programs, curriculum, and student representation. The University of British Columbia (UBC) may be regarded as the lead institution with respect to research and teaching in this sphere, as articulated in UBC's *Toward the Pacific Century* 1988 mission statement. The University of British Columbia is also heavily engaged in training programs for educators, planners, and property managers from many Asian societies. Other institutions in the region play key supporting roles. Capilano College's innovative "CANASEAN" program, for example, involves exchanges of professionals, educators, and business people between Vancouver and southeast Asian countries. As a measure of Vancouver's developing educational role in the Pacific realm, the number of Asian students in British Columbia (a large majority of whom reside in Vancouver) tripled during the period 1985–1992 (D.W. Edgington and M.A. Goldberg, unpub. report, 1996).

Vancouver also has come to play increasingly important political-administrative roles in the Pacific domain. There are no fewer than sixty-four consulates in Vancouver, eighteen of which have opened since 1990. In the case of at least one important Asia–Pacific country, Singapore, the Vancouver consulate represents the only official government presence in Canada. These consulates play facilitating roles in trade development between Vancouver, the Asia–Pacific region, and other external economies and markets. As another reflection of Vancouver's political role in the Pacific realm, the city hosted the 1997 conference of the Asia–Pacific Economic Council.

SUMMARY AND CONCLUSIONS

Empirical data suggest that over the two decades 1971–1991, the principal role of the metropolitan Vancouver economy was transformed from that of a provider of administrative, distributive, and commercial services to the rest of the province to its present position as a node in the increasingly integrated network of urban economies on the Pacific Rim. The principal role in this transformation has been played by producer services, the information-intensive, high–value-added service activities that have become dominant in the Vancouver economy and further distinguish it from the remainder of the province.

Over the past two census periods, these services have been the most rapidly growing activities in the Vancouver economy, and there is mounting empirical evidence that their contribution to the region's exports is accelerating. Empirical evidence also shows that the destinations of Vancouver's producer-service exports are increasingly markets in the Pacific Rim, particularly the Asia–Pacific region. It is a trend that we can expect to see continue well into the next century.

The rapid expansion of producer services in the metropolitan Vancouver economy and their increasing exportation to the Asia–Pacific region have added substantially to Vancouver's role as 'Canada's gateway city' to the Asia–Pacific. Other complementary links to Vancouver's growing economic-trade relationships with this part of the world have also been evolving. These links include travel and tourism, immigration, finance and investment, and a growing Asian social and cultural orientation within the metropolitan region. A challenge for the future is the nurturing and shaping of these linkages in a manner that will maintain and expand the resulting benefits and extend these benefits to a maximum number of the region's residents.

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REFERENCES

Browne, L.E.
1986: Taking in each other's laundry — the service economy; New England Economic Review, July/August, p. 20–31.

Coffey, W.J. and Polèse, M.
1987: Trade and location of producer services: a Canadian perspective; Environment and Planning, v. A19, p. 597–611.
1988: Locational shifts in Canadian employment, 1971–1981: decentralization versus congestion; The Canadian Geographer, v. 32, p. 248–256.
1989: Producer services and regional development: a policy-oriented perspective; Papers of the Regional Science Association, v. 67, p. 13–27.

Daniels, P.W.
1985: Service Industries: A Geographical Appraisal; Methuen, London, United Kingdom, 320 p.
1987: The geography of services; Progress in Human Geography, v. 11, p. 433–447.
1990: Services in the international economy; Fulbright Commission Colloquium Proceedings, Cardiff, United Kingdom, p.10–11.

Davis, H.C.
1976: An interindustry study of the Metropolitan Vancouver economy; Urban Land Economics, No. 6, Faculty of Commerce, University of British Columbia, Vancouver, British Columbia, 39 p.
1993: Is the Metropolitan Vancouver economy uncoupling from the rest of British Columbia?; BC Studies, No. 98 (summer), University of British Columbia, Vancouver, British Columbia, p. 3–19.

Davis, H.C. and Hutton, T.A.
1981: Some planning implications of an expanding urban service sector; Plan Canada, v. 21, p. 15–23.
1989: The two economies of British Columbia; BC Studies, No. 82, University of British Columbia, Vancouver, British Columbia, p. 3–15.
1991: An empirical analysis of producer service exports from the Vancouver metropolitan region; Canadian Journal of Regional Science, v. 14, p. 375–394.
1994: Marketing Vancouver's services to the Asia Pacific; The Canadian Geographer, v. 38, no. 1, p. 18–27.

Economic Council of Canada
1978: A Time for Reason; Ministry of Supply and Services, Ottawa, Ontario.
1990: Good Jobs, Bad Jobs; Ministry of Supply and Services, Ottawa, Ontario.

Greenfield, H.I.
1966: Manpower and the Growth of Producer Services; Columbia University Press, New York, New York, 144 p.

Howell, J. and Green, A.E.
1986: Location, technology and industrial organization in U.K. services; Progress in Planning, v. 26, p. 85–183.

Hutton, T.A.
1997: The Innisian core-periphery revisited: Vancouver's changing relationship with British Columbia's staple economy; BC Studies, No. 113, University of British Columbia, Vancouver, British Columbia, p. 69–100.

Hutton, T.A. and Ley, D.
1991: The service sector in metropolitan development in Canada; in Services and Metropolitan Development: International Perspectives, (ed.) P.W. Daniels; Routledge, London, U.K., 368 p.

Knight, R.V.
1982: City development in advanced industrial societies; *in* Cities in the 21st Century, (ed.) G. Gappert and R.V. Knight, Sage, Beverly Hills, California, p. 47–68.

Ley, D.F. and Hutton, T.A.
1987: Vancouver's corporate complex and producer services sector: linkages and divergence within a provincial staple economy; Regional Studies, v. 21, no. 5, p. 413–424.

Marshall, J.N.
1985: Business services, the regions and regional policy; Regional Studies, v. 19, p. 353–363.

McCrae, J.
1985: Can growth in the service sector rescue Western Canada?; Canadian Public Policy, v. 11, p. 351–353.

Noyelle, T. and Stanback, T.
1984: The Economic Transformation of American Cities; Rowman and Allanheld, Totowa, New Jersey, 295 p.

O'Connor, K. and Edgington, D.
1991: Producer services and metropolitan development in Australia; *in* Services and Metropolitan Development: International Perspectives, (ed.) P.W. Daniels; Routledge, London, U.K., p. 204–225.

Pred, A.
1977: City-systems in Advanced Economies: Past Growth, Present Processes, and Future Development; John Wiley and Sons, New York, New York, 256 p.

Rimmer, P.J.
1991: The global intelligence corps and world cities: engineering consultancies on the move; *in* Services and Metropolitan Development: International Perspectives, (ed.) P.W. Daniels; Routledge, London, U.K., p. 66–107.

Spengler, J.J.
1967: Services and the future of the American economy; South Atlantic Quarterly, v. 66, p. 105–115.

Statistics Canada
1980: Standard Industrial Classification, 4th ed.; Statistics Canada, Ottawa, Ontario.

Tucker, K.A.
1977: The nature and size of the service sector; *in* Economics of the Australian Service Sector; (ed.) K.A. Tucker, Beckenham, Croom Helm, Kent, United Kingdom, p. 13–52.

Wheeler, J.O.
1988: The corporate role of large metropolitan areas in the United States; Growth and Change, v. 19, p. 75–86.

Onshore and offshore geohazards of the Fraser River delta

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Abstract: The Greater Vancouver Regional District of southwestern British Columbia is a highly urbanized and industrialized area that lies in Canada's most seismically active region, overlying the Cascadia subduction zone. The Fraser River delta is the most seismically vulnerable area within this region. A significant effort has been made to identify potential geohazards and refine assessments of earthquake ground-surface responses to an earthquake on the delta, both on- and offshore. These studies involve state-of-the-art geological, geophysical, and geotechnical techniques including coring, drilling, geotechnical and geophysical boring, and electromagnetic, seismic reflection, refraction, and shear-wave surveying. This research has led to the identification of numerous failure features, possibly related to past earthquakes, and to the prediction that the top 10 to 20 m of sediment over much of the delta, on- and offshore, are susceptible to seismic liquefaction and possible flowsliding. Ground-surface response modelling should take into account three-dimensional ground-motion-amplification effects.

Résumé : Le District régional de Vancouver est un milieu fortement urbanisé et industrialisé situé dans la région du Canada qui connaît la plus forte activité sismique, c'est-à-dire le sud-ouest de la Colombie-Britannique, qui se trouve au-dessus de la zone de subduction de Cascadia. Le delta du Fraser est la partie de cette région qui est la plus vulnérable aux secousses sismiques. De grands efforts ont été déployés afin de déterminer les dangers géologiques éventuels et de raffiner les évaluations des mouvements du sol liés à un tremblement de terre dans le delta, sur terre comme au large. Ces études mettent à contribution des techniques géologiques, géophysiques et géotechniques de pointe, dont le carottage, le forage, le sondage géotechnique et géophysique, ainsi que les levés électromagnétiques, les levés de sismique-réflexion et de sismique-réfraction, et les levés d'ondes de cisaillement. Ces recherches ont mené à l'identification de nombreux indices de rupture qui pourraient avoir des liens avec des tremblements de terre passés, et à la prévision selon laquelle la couche sédimentaire supérieure de 10 à 20 m d'épaisseur qui recouvre une grande partie du delta, sur terre comme au large, est susceptible de se liquéfier en cas de séisme, ce qui pourrait entraîner des glissements. La modélisation des mouvements du sol devrait prendre en compte les effets tridimensionnels d'amplification de ces mouvements.

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INTRODUCTION

The city of Vancouver and the densely populated Lower Mainland region of southwest British Columbia are situated over an active subduction zone, with the trench axis located about 150 km to the west of Vancouver. This setting makes the region subject to a higher risk of large damaging earthquakes than any other part of Canada (Rogers, 1994). The area encompasses one of the largest deltas in Canada, the Fraser River delta, which is undergoing rapid urban development. The Fraser River delta is a thick accumulation of sand and silt deposited entirely during the last 10 000 years. These soils are considered to be loose or soft in engineering terms, requiring increased factors of safety for earthquake loading under the current National Building Code guidelines (Sy et al., 1991; National Research Council of Canada, 1995, p. 149, Table 4.1.9.1.C). Ground-motion amplification of earthquake shaking and liquefaction of cohesionless, water-saturated soil could occur in such materials.

The Lower Mainland region, including Vancouver, has a population in excess of 2 million people with an annual increase of several per cent. Approximately 250 000 people live on the delta proper, and it is the region receiving most of the recent population increase. In addition to this urbanization, the delta is host to a $74 million per year farming industry, expanding industrial capacity, an international airport handling over 14 million passengers in 1996 (second busiest in Canada and twenty-ninth in the world), a ferry terminal transporting 8.79 million passengers in 1996 (2.79 million vehicles), and the largest bulk shipping facility in Canada (shipping 20 million tonnes of coal per year), recently expanded to include container shipping. The new container port doubles Vancouver's container shipping capacity — the busiest in Canada. The delta also hosts a $260 million per year fishery and a submarine hydroelectric cable corridor which supplies power to Vancouver Island and Victoria, the capital city of the province.

In light of the seismic hazard and the intense urbanization and important economic contribution of the region, the Geological Survey of Canada (GSC), in co-operation with academic, private, and public agencies, has conducted studies in the Fraser River delta to identify the potential geohazards and refine assessments of potential earthquake ground-surface response. These data are intended to assist policy-makers and engineers in making appropriate development and construction decisions to protect lives and property of the citizens of the region.

GEOLOGICAL SETTING

The tectonic setting of southwestern British Columbia is similar to that of the east coast of Japan, the south coast of Alaska, and most of the west coast of Central and South America, all of which have experienced devastating earthquakes within the last several decades. In the case of southwestern British

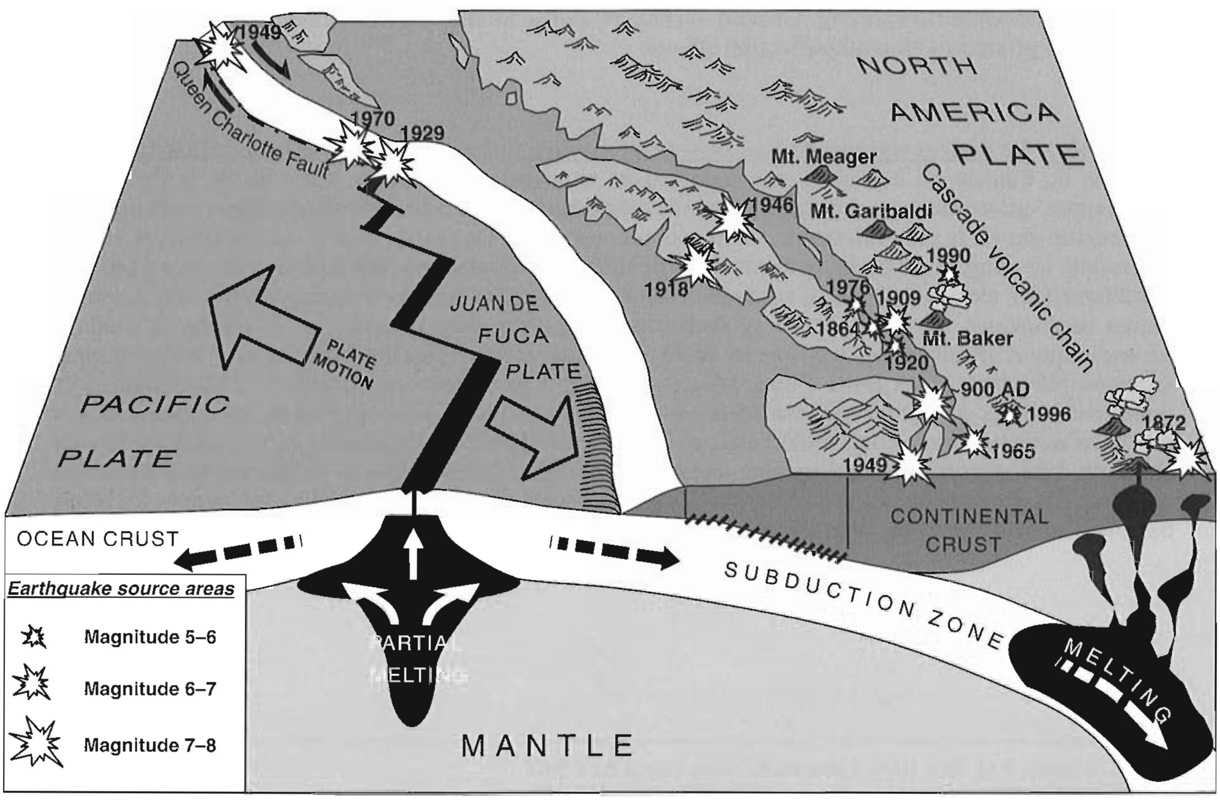

Figure 1. Sketch of the tectonic setting of southwest British Columbia, showing the subduction zone and location of earthquakes.

Columbia, the oceanic Juan de Fuca and Explorer plates are being subducted in a northeast direction beneath the continental North America Plate (Fig. 1).

Earthquakes which may present a hazard to the area occur in three distinct source regions (Rogers, 1994): 1) continental crust earthquakes, which may occur locally at Richter scale magnitudes estimated at up to 7.5; 2) deeper earthquakes within the subducted oceanic plate; these subcrustal earthquakes may be large but are generally in the depth range of 45 to 65 km below the surface; and 3) very large earthquakes on the subduction boundary between lithospheric plates. An average of 300 earthquakes are recorded in southwestern British Columbia each year. The vast majority of these earthquakes are crustal in origin and too small to be felt. The most significant historic event was a crustal earthquake with a magnitude of 7.3 in central Vancouver Island in 1946. Two very shallow crustal events 30 km west of Vancouver in the central Strait of Georgia were felt recently throughout southwestern British Columbia: a magnitude 3.4 event occurred on June 13, 1997 at an epicentre depth of 2 km, and a magnitude 4.6 event occurred on June 24, 1997 at a depth of 4 km. Earthquakes of this type and location probably pose the greatest seismic hazard to the Fraser River delta. The remaining recorded earthquakes are subcrustal, infrequent, and generally occur towards the subduction zone where the oceanic lithosphere of the Juan de Fuca Plate is being forced down and under the North America Plate. They are generally deep, offshore, and not normally felt, but have included damaging earthquakes in southern Puget Sound in 1949 (magnitude 7.0) and 1965 (magnitude 6.5). Subduction boundary earthquakes have not occurred in historic times, but paleoseismic and archeological evidence shows they occur at intervals of centuries, with the last one occurring about 300 years ago (Atwater, 1987; Adams, 1990; Clague and Bobrowsky, 1994; Hyndman, 1995). Analysis of contemporary crustal deformation reveals that strain is accumulating for a future event (Dragert et al., 1995). Evidence of this strain is collected through accurate positioning data of fixed sites on Vancouver Island and the mainland. For example, Victoria is moving about 7 mm/year in an eastward direction relative to a base site at Penticton (300 km inland), and the Cascadia margin is currently being uplifted vertically by about 4 mm/year (Dragert and Hyndman, 1994; Hyndman, 1995). In addition, there is increasing evidence of thrust faulting in areas like the eastern Juan de Fuca Strait (Johnson et al., 1996; Mosher and Johnson, 2001; Johnson et al., 2001), resulting from buildup of compressive stress.

The Fraser River delta lies in the zone of most frequent crustal earthquakes and is categorized as the zone with the highest seismic risk in Canada. Geologically, the delta is located in a structural depression of Late Cretaceous and Tertiary clastic sedimentary rocks near the west margin of the North America Plate. This depression forms what is now the Strait of Georgia. Overlying these basement rocks and underlying the delta sediments are Quaternary deposits resulting from various stages of Pleistocene glaciation.

The Fraser River began to build its delta into the Strait of Georgia about 10 000 years ago (Clague et al., 1983, 1991; Luternauer et al., 1993), after the last glaciation. Under the burden of glacial ice, the land had been isostatically depressed, causing relative sea level at 14 000 years BP (before present) to be over 90 m higher than it is today. With the removal of the weight of the glaciers, the land rebounded, causing relative sea level to fall. It had fallen to more than 12 m below its present position by 8000 years BP (Mathews et al., 1970). By about 5000 years BP, global eustatic sea level rise had brought sea level back to within a few metres of its present position, and sea level has continued to rise a few centimetres per hundred years since that time. At about 5000 years BP, the Fraser River, which previously had flowed southwest into Boundary Bay, began to discharge west into the Strait of Georgia (Clague et al., 1991). During the last 5000 years, the Fraser delta has prograded westward into the deeper water. Considerable channel meandering and anastomosing of channels are known to have occurred, even in historical times, although channel locations have been fixed by dykes and jetties over the last century.

Progradation of the delta into the Strait of Georgia created a 40 km long coastal zone (Fig. 2). Tidal flats extend about 9 km from the dyked edge of the delta to the subtidal slope. The delta has an area in excess of 1000 km^2; the onshore

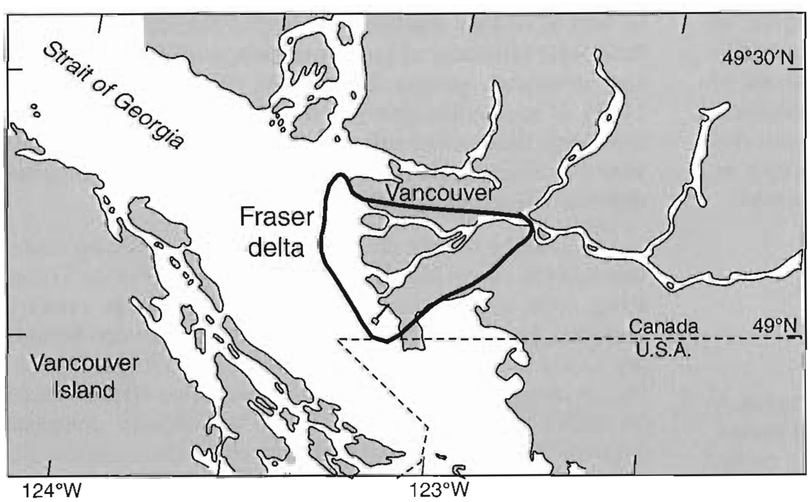

Figure 2.

Map of southwestern British Columbia showing the Fraser River delta. Unconsolidated delta sediments to the 250 m isobath in the offshore are outlined with the dark line.

portion is about 450 km^2, the intertidal region is 215 km^2, and the foreslope is about 350 km^2. A further 3500 km^2 within the Strait of Georgia are affected by sedimentation of material derived from the Fraser River. The slope break, marking the modern transition from the intertidal flats to the foreslope, lies at about the 10 m depth contour. The western delta slope is inclined 1 to 23° (average about 2–3°) towards the marine basin of the Strait of Georgia and terminates at about 300 m water depth, 5 to 10 km seaward of the edge of the tidal flats.

The stratigraphy of the Fraser River delta has been studied through onshore and offshore seismic and drilling programs (Tiffin, 1969; Hamilton, 1991; Clague et al., 1991; Hart et al., 1992a, b, 1993, 1995; Luternauer et al., 1993; Monahan et al., 1993a, b; Christian et al., 1994a, b; Dallimore et al., 1995, 1996; Mosher et al., 1997; Mosher and Hamilton, 1998; Monahan, 1999). Postglacial deltaic sediments vary in thickness between 19 and 305 m (Dallimore et al., 1994, 1996; Luternauer and Hunter, 1996) (*see* Fig. 3); they overlie Late Pleistocene till, stratified proglacial sediments and interglacial deposits (Clague et al., 1991). The deltaic sediments include bottomset, foreset, and topset facies. Clay, silt, and sand, which constitute the bottomset facies of the delta, unconformably overlie Pleistocene glacial and glaciomarine deposits. Sandy and silty foreset beds, dipping up to about 7°, conformably overlie the bottomset facies, or unconformably overlie Pleistocene deposits. Topset deposits are composed of distributary channel sands, channel-fill sand and silt, and intertidal and overbank silt, sand, and peat. These latter deposits thin westward from 40 m at the apex of the delta to 20 m or less at the western margin of the dyked delta plain.

TECHNIQUES

The purpose of this research is to identify potential geohazards and refine assessments of the earthquake ground-surface response on the Fraser River delta, including its on- and offshore portions. A number of technologies have been employed to better understand the sediment constituting the delta. Details of the techniques employed and their application can be found in Appendix A. In brief, these techniques include geological, geophysical, and geotechnical (engineering) methods. Geological and geophysical data provide information on lithological composition and its degree of variability. These data also provide information about sedimentary depositional processes, and may show a record of past catastrophic events such as earthquakes. Geophysical and geotechnical data can yield information on the present-day physical properties of the delta sediments, supporting an evaluation of how they may behave during an earthquake.

RESULTS AND DISCUSSION

Geology

The stratigraphic sequence of the Lower Mainland region of southwestern British Columbia consists of 1) thrusted, folded, and faulted Tertiary and older sedimentary rocks, 2) glacially derived Pleistocene deposits, 3) glaciomarine turbidite sequences from the latest deglaciation, and 4) a modern Fraser River delta sequence which includes all components of delta sedimentation processes (e.g. turbidity currents, channel, levee, levee-overspill, debris flows, river bedload, hemipelagic deposition, tidal reworking) (Fig. 3). The modern delta can be grossly divided into bottomset, foreset, and topset sediments. Over the last 10 000 years, sediment from the Fraser River has been deposited over an area of approximately 4500 km^2 within the Georgia depression, including the Fraser Lowland and the Strait of Georgia.

Some of the more significant surficial morphological elements of the Fraser delta are 1) extensive deltaic plains, underlain almost continuously by channel-fill deposits of sand (Monahan et al., 1993a, b); 2) active river channels, constrained in their locations by dykes and jetties; 3) a 350 km^2 foreslope, ranging in water depth from 10 m to 250 m and with slopes up to 23°, but averaging 2 to 3°; 4) erosive channels, gullies, and sea valleys transecting the foreslope and maintained by sediment mass-flow processes; and 5) an extensive prodelta occupying much of the southern Strait of Georgia. A number of features have been identified from the geological record which are interpreted to represent liquefaction and slope-failure events, including, for example, sand boils, dykes, slumps, and slides (Hamilton and Luternauer, 1983; Hamilton and Wigen, 1987; Pullan et al., 1989, 1998; Clague et al., 1992, 1998; Hart et al., 1992c, 1993; Hart, 1993; Mosher et al., 1994, 1995; Mosher, 1996; Mosher and Law, 1996; Mosher and Hamilton, 1998). Modern delta sediment thicknesses range from 19 m to 305 m and are extremely variable spatially because of the undulating bedrock and Pleistocene topography.

Ground-motion amplification

It has long been known that thick 'soft soil' sites, such as the deltaic sediments of the Fraser River delta, are prone to ground-motion amplification in certain frequency ranges as a result of earthquake shaking (Reiter, 1990). Although the earthquake type (source and magnitude) and the travel path (direction and attenuation) are fundamentally important, site geology also exerts a major influence. Knowledge of the overburden and bedrock shear-wave velocities and densities, as well as of total thickness of overburden, can often yield first-order estimates of ground-motion amplification effects and resonance ground frequencies (Shearer and Orcutt, 1987). It is possible that site resonance effects may result from large shear-wave velocity contrasts within the unconsolidated overburden, such as between the Holocene–Pleistocene deposits (Hunter et al., 1998).

As a rule of thumb, the natural period of a building structure is 0.1N, where N is the number of storeys. For the Fraser River delta, ground resonance periods due to large velocity contrasts associated with the Holocene–Pleistocene boundary would be in the range of multi-storey buildings, depending on overburden thickness. Such resonance effects would be added to amplification caused by velocity contrasts between the ground surface and bedrock (Shearer and Orcutt, 1987).

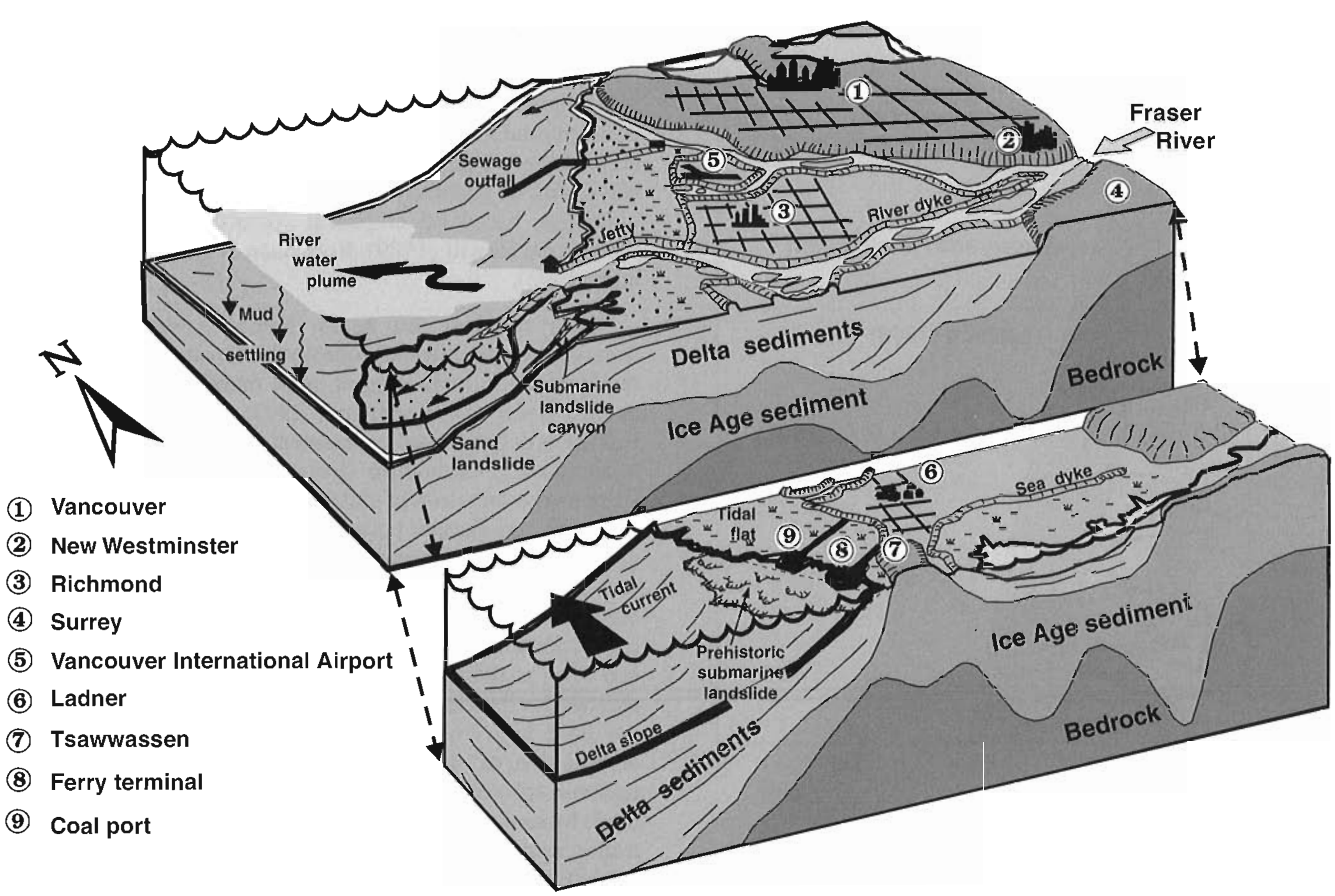

Figure 3. Schematic of Fraser River delta morphology, structure, and stratigraphy (modified from *Turner et al., 1996*).

Recent evidence of ground-motion amplification in the Fraser River delta has come from seismograph recordings made of a moderate earthquake centred in Washington State, south of the survey area (Rogers et al., 1998) (Fig. 4). These data have shown that for thick soil sites, horizontal ground-motion amplification in the range of 0.5 to 4 Hz can be 3 to 5 times that of bedrock, with even larger amplification over limited frequency ranges where Quaternary sediments thin (<50 m) towards the northern edge of the delta or elsewhere within the delta where bedrock and/or Pleistocene deposits come close to the surface.

Liquefaction

If a cohesionless soil is sufficiently loose and the static shear stress is greater than the large-strain undrained shear strength, flow liquefaction is possible. Flow liquefaction can be initiated with either dynamic or static loading and can result in rapid flowslides. If a cohesionless soil is exposed to rapid undrained cyclic loading (i.e. seismic shaking), excess pore pressures can develop, resulting in liquefaction that can lead to ground oscillations, lateral spreading, and flowsliding. The channel-fill sediment facies, which underlies much of the surface of the modern delta, comprises the most liquefiable sediments (Watts et al., 1992; Christian, 1998; Monahan, 1999).

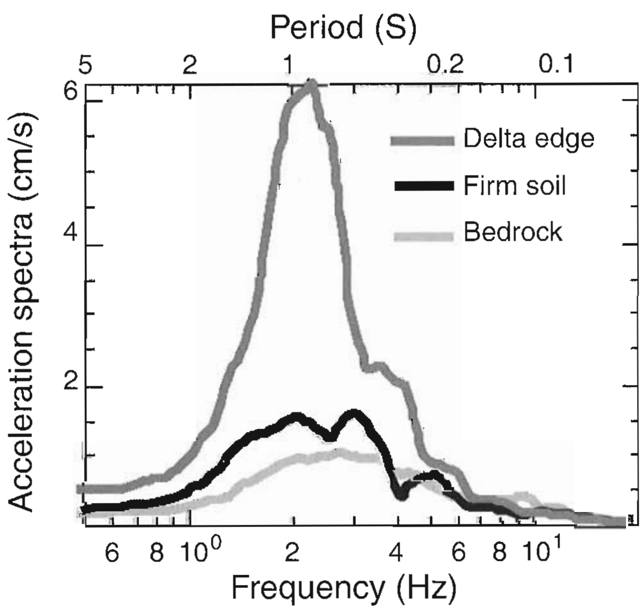

Figure 4. Frequency spectra of ground response from Duvall magnitude 5.3 earthquake in May 1996, comparing responses in bedrock, firm ground (till), and the northern edge of the Fraser River delta. The delta site shows amplification almost six times that of bedrock at a frequency of 2–3 Hz (Rogers et al., 1998).

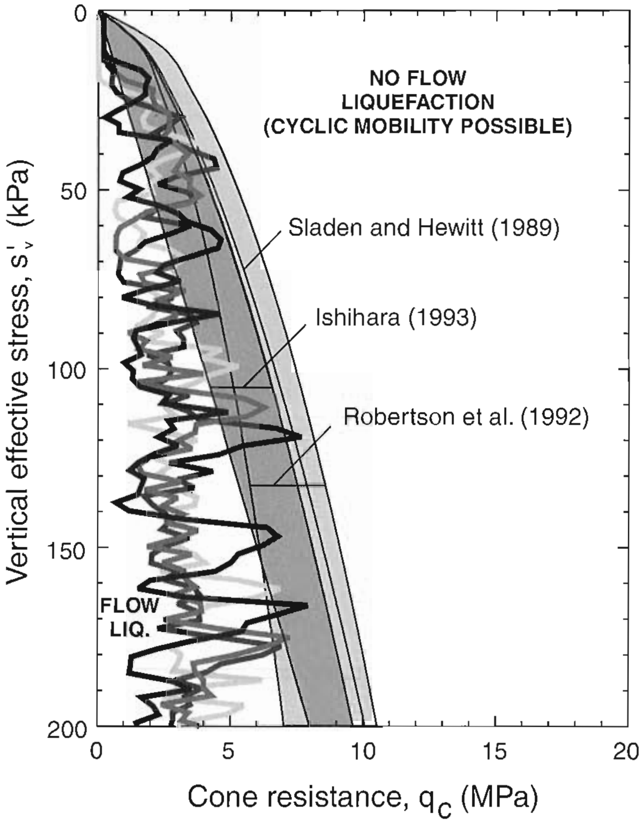

Figure 5. Crossplot of vertical effective stress (s'_v) (sediment load) versus cone resistance (q_c) for four cone penetration test (cpt) sites from the southwestern margin of the Fraser River delta. For comparison, empirical correlations showing the threshold boundaries between flow liquefaction (flow liq.) and no flow liquefaction, as compiled by several authors, are shown.

Figure 5 shows cone-bearing (q_c) data (i.e. resistance to pushing an instrumented cone-shaped rod into the sediment) from engineering test holes on the southwestern margin of the delta, plotted against effective overburden stress (s'_v), i.e. the cumulative weight of the sediment. The penetration resistance profiles generally fell well within the zone for flow liquefaction, based on empirical correlations developed by Sladen and Hewitt (1989), Robertson et al. (1992), and Ishihara (1993).

Over the last ten years, research has related the shear-wave velocities of cohesionless, water-saturated soils to liquefaction resistance of soils mobilized during earthquakes (Ado and Robertson, 1992; Lunne et al., 1997). Empirically developed assessment charts are available that relate surface earthquake shaking parameters to measured shear-wave velocities of soils. Figure 6a shows the suggested potential liquefaction boundary in terms of peak horizontal ground acceleration and soil shear-wave velocity (Andrus and Stokoe, 1996) for magnitude 6.9 to 7.0 earthquakes, based on observational data. Also shown are guidelines indicating threshold shear-wave velocities for 0.1 g, 0.2 g, 0.3 g, and 0.4 g peak horizontal accelerations; cohesionless water-saturated soils with shear-wave velocities less than these values have high cyclic liquefaction potential. Figure 6b is a compilation of shear-wave velocities versus depth for 75 regional sites in the Fraser River delta, from measurements made by surface refraction, borehole, and seismic cone penetration tests (SCPT) techniques. Also shown are the threshold guidelines from Figure 6a for the four values of peak horizontal site accelerations. Measured shear-wave velocities plotting to the left of a guideline indicate liquefaction potential for that particular peak acceleration condition. These data suggest that liquefaction potential is high in the near-surface materials throughout the area. The depth extent of the potential liquefiable zone will depend on site amplification effects (a_{max}), as well as soil type and condition.

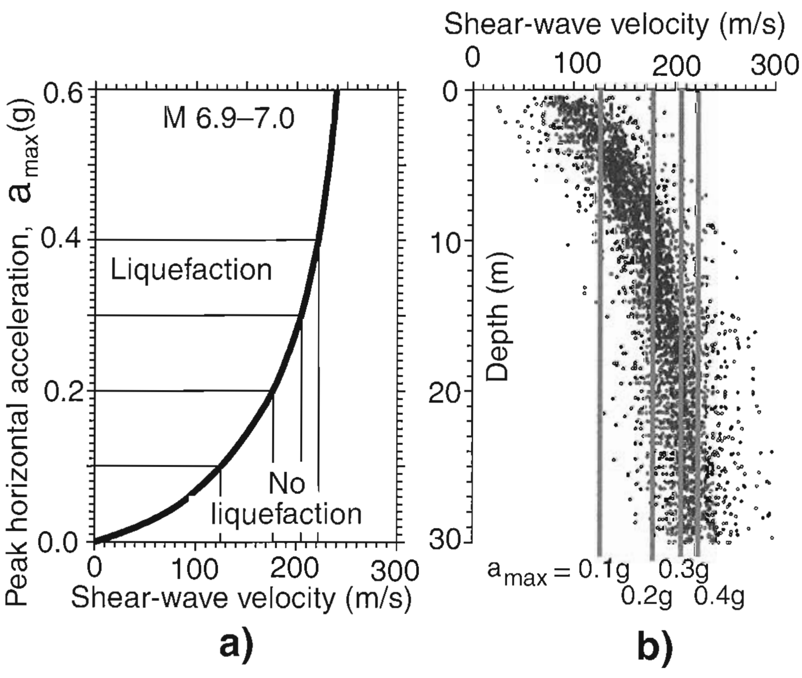

Figure 6.

***a)** Suggested liquefaction boundary from shear-wave velocity versus ground acceleration for a magnitude 6.9–7.0 earthquake* (after *Andrus and Stokoe, 1996). **b)** Shear-wave velocity measurements versus depth below ground surface. Each of the vertical lines represents a different ground acceleration. Liquefaction is likely to occur in sediments with shear velocities to the left of the line, given these ground acceleration conditions.*

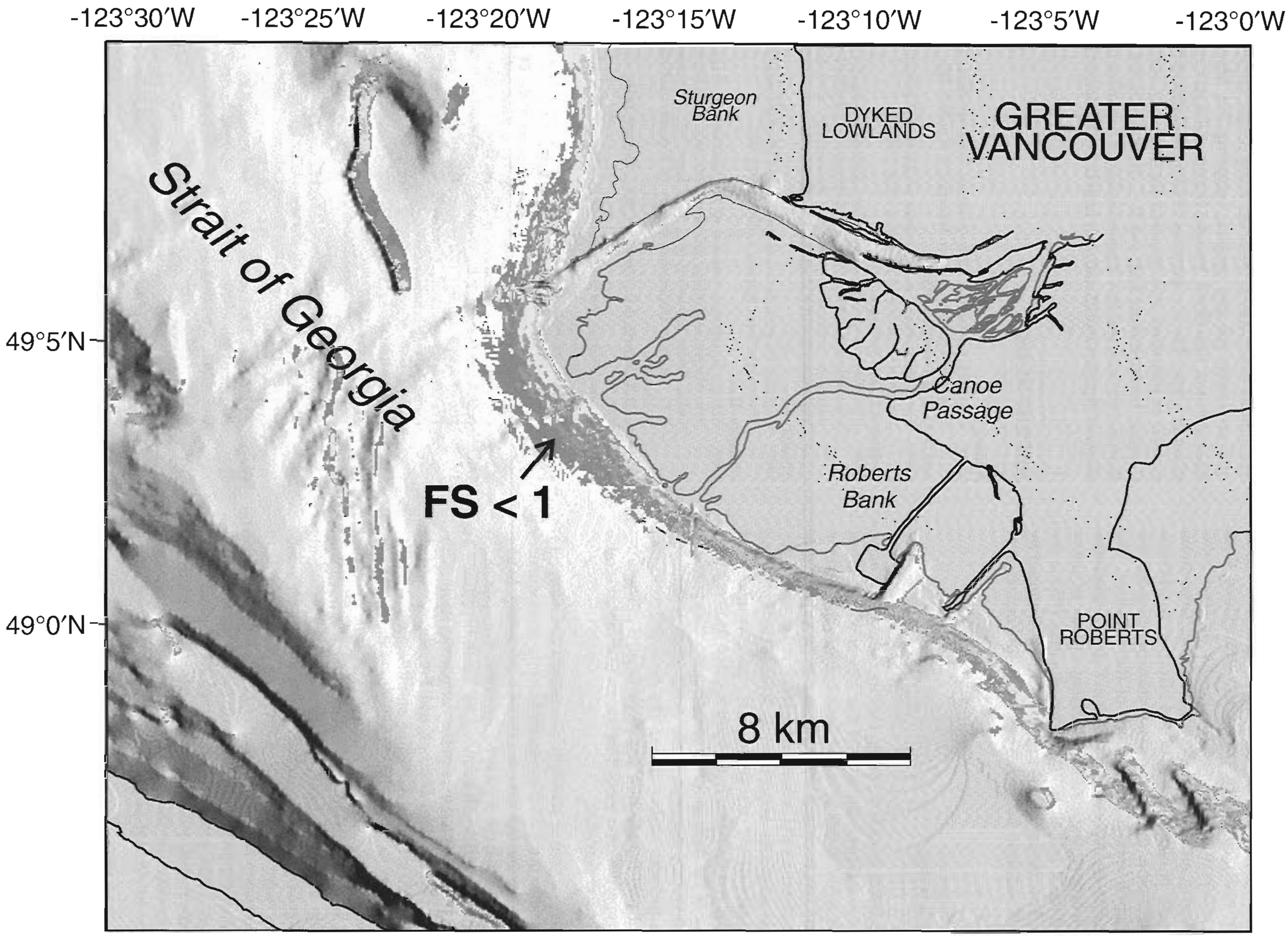

Figure 7. *Infinite slope stability analysis for post-liquefaction conditions of the southwest margin of the Fraser River delta. Zones with a factor of safety (FS) of less than 1 are highlighted with dark grey.*

Christian et al. (1997) and Christian (1998) modelled the postliquefaction stability of the present foreslope of the delta using an infinite slope stability analysis coupled with digital bathymetry and engineering parameters determined from cone penetration test and borehole results. In their most nonconservative analysis, the postliquefaction, large-strain shear strength is taken as 6% of the effective overburden stress. In this case, the static driving stresses exceeded the postliquefaction strength over much of the foreslope. The zone of likely mass movement is shown in Figure 7, where the shaded region depicts the zone possessing a factor of safety against sliding of less than 1.0. Factor of safety (FS) is the ratio of static resisting forces to driving forces imposed by gravitational sediment loading. Slope instability can occur if FS<1.

CONCLUSIONS

The Fraser River delta is a young, rapidly sedimented basin that occupies a significant area of the Lower Mainland of British Columbia. It lies in the highest seismic risk zone in Canada, and has been and will continue to be subjected to intense urbanization and industrialization. It is a region of key societal and economic importance to British Columbia and Canada. State-of-the-art geological, geophysical, and geotechnical technologies have been applied to investigate the stability of the delta in terms of its liquefaction potential and ground-surface response in the event of an earthquake. This work includes understanding the geology, collecting evidence of past liquefaction and slope failures, measuring physical properties, and modelling ground-surface response and liquefaction potential.

The ultimate goal of scientific assessment and interpretation of these data is to successfully forecast the consequences of an earthquake and not have to rely on hindcasting. In general, it is realized that the delta is complex and that response to ground shaking will be determined by local conditions as much as by the characteristics of the earthquake itself. Sediment thickness and local bedrock and Pleistocene surface geometry will affect ground shaking amplification. Amplification likely will be most significant where the unconsolidated sequence is less than 100 m thick, such as on the lateral margins of the delta or over basement and Pleistocene surface highs within the delta; hence the need to understand the subsurface geology. Cone-penetration and shear-wave velocity analyses suggest that much of the delta is susceptible to cyclic liquefaction within the top 10 to 20 m below surface, given design earthquake parameters (in the absence of amplification and local effects) (Richmond Earthquake Task Force, unpub. report, 1991). In areas of a free-face, such as at the break-in-slope of the delta, slope angles significantly increase the likelihood of postfailure, large-scale sediment flowslides.

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REFERENCES

Adams, J.
1990: Cascadia subduction zone: evidence from turbidites off the Oregon–Washington margin; Tectonics, v. 9, p. 569–583.

Ado, K.O. and Robertson, P.K.
1992: Shear-wave velocity measurements of soils using Rayleigh waves; Canadian Geotechnical Journal, v. 29, p. 558–568.

Andrus, R.D. and Stokoe, K.H., II
1996: Guidelines for evaluating liquefaction resistance using in situ shear wave velocity; *in* Proceedings of a Symposium on Recent Developments in Seismic Liquefaction Assessment, Conetec Ltd., Vancouver, British Columbia, p. 1–23.

Atwater, B.F.
1987: Evidence for great Holocene earthquakes along the outer coast of Washington State; Science, v. 236, p. 942–944.

Christian, H.A.
1998: Seismic liquefaction potential of the southwestern Fraser River delta Margin; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 231–240.

Christian, H.A., Barrie, J.V., Courtney, R.C., Mosher, D.C., and Mulder, T.
1997: Geomorphology and potential slope instability on the Fraser River delta foreslope, Vancouver, British Columbia; Canadian Geotechnical Journal, v. 34, p. 432–446.

Christian, H.A., Barrie, J.V., and Monahan, P.A.
1994a: Deep-hole geotechnical investigation adjacent to the BC Hydro Canoe Pass Submarine Cable Terminal, Fraser River delta, British Columbia; Geological Survey of Canada, Open File 2861, 26 p.

Christian, H.A., Robertson, P.K., Weemes, I., and Woeller, D.W.
1994b: Use of SASW and SCPT to evaluate liquefaction potential of the Fraser delta foreslope, Vancouver, British Columbia; *in* 47th Canadian Geotechnical Conference, 21–23 September, 1994, Halifax, Nova Scotia, p. 166–175.

Clague, J.J. and Bobrowsky, P.T.
1994: Evidence for a large earthquake and tsunami 100-400 years ago on western Vancouver Island, British Columbia; Quaternary Research, v. 41, p. 176–184.

Clague, J.J., Hebda, R.J., and Luternauer, J.L.
1983: Sedimentary environments and post-glacial history of the Fraser Delta and lower Fraser Valley, British Columbia; Canadian Journal of Earth Sciences, v. 20, p. 1314–1426.

Clague, J.J., Hunter, J.A. Luternauer, J.L., and Pullan, S.E.
1991: Postglacial deltaic sediments, southern Fraser River Delta, British Columbia; Canadian Journal of Earth Sciences, v. 28, p. 1386–1393.

Clague, J.J., Naesgaard, E., and Mathewes, R.W.
1998: Geological evidence for prehistoric earthquakes; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada Bulletin 525, p. 177–194.

Clague, J.J., Naesgaard, E., and Sy, A.
1992: Liquefaction features on the Fraser Delta: evidence for prehistoric earthquakes?; Canadian Journal of Earth Sciences, v. 29, p. 1734–1745.

Dallimore, S.R., Clague, J.J., Edwardson, K.A., Hunter, J.A., and Luternauer, J.L.
1995: Composite geotechnical logs for two deep boreholes in the Fraser River Delta, British Columbia; Geological Survey of Canada, Open File 3018, 1 sheet.
Dallimore, S.R., Clague, J.J., Edwardson, K.A., Hunter, J.A., Luternauer, J.L., and Meldrum, J.L.
1996: Composite geotechnical logs for a deep borehole at Richmond City Hall; Geological Survey of Canada, Open File 3356, 2 p.
Dragert, H. and Hyndman, R.D.
1994: Continuous GPS monitoring of elastic strain in the Northern Cascadia Subduction Zone; Geophysical Research Letters, v. 22, p. 755–758.
Dragert, H., Hyndman, R.D., Rogers, G.C., and Wang, K.
1995: Current deformation and the width of seismogenic zone of the Northern Cascadia Subduction Thrust; Journal of Geophysical Research, v. 99, p. 653–668.
Hamilton, T.S.
1991: Seismic stratigraphy of unconsolidated sediments in the central Strait of Georgia: Hornby Island to Roberts Bank; Geological Survey of Canada, Open File 2350, 9 map sheets, scale 1:250 000.
Hamilton, T.S. and Luternauer, J.L.
1983: Evidence of seafloor instability in the south-central Strait of Georgia: a preliminary compilation; *in* Current Research, Part A; Geological Survey of Canada, Paper 83-1A, p. 417–421.
Hamilton, T.S. and Wigen, S.O.
1987: The foreslope hills of the Fraser Delta: implications for tsunamis in Georgia Strait; International Journal of the Tsunamis Society, v. 5, p. 15–33.
Hart, B.S.
1993: Large-scale in situ rotational failure on a low-angle delta slope: the foreslope hills, Fraser Delta, British Columbia, Canada; Geo-Marine Letters, v. 13, p. 219–226.
Hart, B.S., Barrie, J.V., Christian, H.A., Hamilton, T.S., Davis, A.M., and Law, L.K.
1993: Marine geological, geophysical and geotechnical investigations of the submarine portions of the Fraser Delta: implications for submarine failures; *in* Proceedings, Canadian Coastal Conference, Vancouver, 5–7 May, p. 25A.
Hart, B.S., Barrie, J.V., Currie, R.G., Hamilton, T.S., and Prior, D.B.
1992a: Marine geophysical and geological surveys of the Fraser Delta slope and adjacent strait of Georgia: 1991 geophysical survey tracklines and 1983–1992 core locations; Geological Survey of Canada, Open File 2543, 5 map sheets, scale 1:25 000 and 1:100 000.
Hart, B.S., Frydecky, I., Horel, G., and Olynyk, H.W.
1992b: An airgun seismic survey of the Fraser Delta slope; *in* Current Research, Part E; Geological Survey of Canada, Paper 92-1E, p. 33–39.
Hart, B.S., Hamilton, T.S., Barrie, J.V., and Prior, D.B.
1995: Seismic stratigraphy and sedimentary framework of a deep-water Holocene delta: The Fraser delta, Canada; *in* Geology of Deltas, (ed.) M.N. Oti and G. Postma; Balkema, Rotterdam, p. 167–178.
Hart, B.S., Prior, D.B., Barrie, J.V., Currie, R.G., and Luternauer, J.L.
1992c: A river mouth submarine channel and failure complex, Fraser Delta, Canada; Sedimentary Geology, v. 81, p. 73–87.
Hunter, J.A., Douma, M., Burns, R.A., Good, R.L., Pullan, S.E., Harris, J.B., Luternauer, J.L., and Best, M.E.
1998: Testing and application of near-surface geophysical techniques for earthquake hazards studies, Fraser River delta, British Columbia; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 123–145.
Hyndman, R.D.
1995: Giant earthquakes of the Pacific Northwest; Scientific American, v. 273, p. 50–57.
Ishihara, K.
1993: Liquefaction and flow failure during earthquakes; Geotechnique, v. 43, p. 351–415.
Johnson, S.Y., Dadisman, S.V., Mosher, D.C., Blakely, R.J., and Childs, J.R.
2001: Active tectonics of the Devils Mountain fault and related structures, northern Puget Lowland and eastern Strait of Juan de Fuca region, Pacific Northwest; United States Geological Survey, Professional Paper 1643 (65 p. text, 2 tables, 38 figs., 2 plates).
Johnson, S.Y., Potter, C.J., Armentrout, J.M., Miller, J.J., Finn, C., and Weaver, C.S.
1996: The Southern Whidbey Island Fault: an active structure in the Puget Lowland, Washington; Geological Society of America, Bulletin, v. 108, p. 334–354.
Lunne, T., Robertson, P.K., and Powell, J.J.M.
1997: Cone Penetration Testing in Geotechnical Practice; Blackie Academic and Professional, London, United Kingdom, 312 p.
Luternauer, J.L. and Hunter, J.A.
1996: Mapping Pleistocene deposits beneath the Fraser River Delta: preliminary geological and geophysical results; *in* Current Research 1996-E; Geological Survey of Canada, p. 41–48.
Luternauer, J.L., Clague, J.J., Hunter, J.A., Pullan, S.E., Roberts, M.C., Woeller, D.J., Kostaschuk, R.A., Moslow, T.F., Monahan, P.A., and Hart, B.S.
1993: The Fraser River Delta, British Columbia: architecture, geological dynamics and human impact; *in* Deltas of the World; Proceedings, 8th Symposium on Coastal and Ocean Management, New Orleans, Louisiana, July 19–23, p. 99–113.
Mathews, W.H., Fyles, J.G., and Nasmith, H.W.
1970: Postglacial crustal movements in southwestern British Columbia and adjacent Washington State; Canadian Journal of Earth Sciences, v. 7, p. 690–702.
Monahan, P.A.
1999: The application of core penetration test data to facies analysis of the Fraser River Delta, British Columbia; Ph.D. thesis, School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, 392 p.
Monahan, P.A., Luternauer, J.L., and Barrie, J.V.
1993a: A delta topset sheet sand and modern sedimentary processes in the Fraser River Delta, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 93-1A, p. 263–272.
1993b: A delta plain sheet sand in the Fraser River Delta, British Columbia, Canada; Quaternary International, v. 20, p. 27–38.
Mosher, D.C.
1996: Southern Roberts Bank nearshore survey: PGC95003; Geological Survey of Canada, Open File 3202, 26 p.
Mosher, D.C. and Hamilton, T.S.
1998: Morphology, structure, and stratigraphy of the offshore Fraser delta and adjacent Strait of Georgia; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 147–160.
Mosher, D.C. and Law, L.K.
1996: Application of concurrent marine electromagnetic and marine seismic high resolution profiling, British Columbia, Canada; Journal of Environmental and Engineering Geophysics, v. 1, p. 215–228.
Mosher, D.C., Christian, H.A., and Barrie, J.V.
1994: Hazards to development in the offshore of the Fraser River Delta; *in* Geological Society of America, 1994 Annual Meeting, Seattle, Washington, Program with Abstracts, p. A469.
Mosher, D.C., Christian, H.A., Hunter, J.A., and Luternauer, J.L.
1997: Onshore/offshore geohazards in the Vancouver Region of western Canada; field, modelling and mapping techniques and results; *in* Engineering Geology and the Environment, (ed.) P.G. Morinos, G.C. Koukis, G.C. Tsiambaos, and G.C. Stournaras; A.A. Balkema, Rotterdam, p. 875–883.
Mosher, D.C. and Johnson, S.Y. (ed.)
2001: Neotectonics of the eastern Juan de Fuca Strait; a digital geological and geophysical atlas; Geological Survey of Canada, Open File D3931, 1 CD-ROM.
Mosher, D.C., Nichols, B.C., and Scientific Party of PGC95001
1995: Multichannel and high resolution seismic reflection survey of the marine portion of the Fraser River Delta, Vancouver, British Columbia: Tully PGC95001; *in* Current Research 1995E; Geological Survey of Canada, p. 37–45.

National Research Council of Canada
1995: National Building Code of Canada; issued by the Canadian Commission on Building and Fire Codes, National Research Council, Ottawa, Ontario, 571 p.

Pullan, S.E., Hunter, J.A., Jol, H.M., Roberts, M.C., Burns, R.A., and Harris, J.B.
1998: Seismostratigraphic investigations of the southern Fraser River delta; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 91–122.

Pullan, S.E., Jol, H.M., Gagné, R.M., and Good, R.L.
1989: Compilation of high resolution "optimum offset" shallow seismic reflection profiles from southern Fraser River delta, British Columbia; Geological Survey of Canada, Open File 1992, 16 p.

Reiter, L.
1990: Earthquake Hazard Analysis: Issues and Insights; Columbia University Press, New York, New York, 254 p.

Robertson, P.K., Woeller, D.J., and Finn, W.D.L.
1992: Seismic cone penetration test for evaluating liquefaction potential under cyclic loading; Canadian Geotechnical Journal, v. 29, p. 686–695.

Rogers, G.C.
1994: Earthquakes in the Vancouver area; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia; (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 221–229.

Rogers, G.C., Cassidy, J.F., and Weichert, D.H.
1998: Variations in earthquake ground motion on the Fraser delta from strong-motion seismograph records; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 195–210.

Shearer, P.M. and Orcutt, J.A.
1987: Surface and near-surface effects on seismic waves: theory and borehole seismometer results; Bulletin of the Seismological Society of America, v. 77, p. 1168–1196.

Sladen, J.A. and Hewitt, K.J.
1989: Influence of placement method on the in-situ density of hydraulic fills; Canadian Geotechnical Journal, v. 26, p. 453–466.

Sy, A., Lo, R.C., Henderson, P.W., Sui, D.Y., Finn, W.D.L., and Heidebrecht, A.C.
1991: Ground motion response for Fraser Delta, British Columbia; *in* Proceedings of the 4th International Conference on Seismic Zonation, August; Stanford, California, v. 2, p. 232–350.

Tiffin, D.L.
1969: Continuous seismic reflection profiling in the Strait of Georgia, British Columbia; Ph.D. thesis, Department of Oceanography, University of British Columbia, Vancouver, British Columbia, 196 p.

Turner, R.J.W., Clague, J.J., and Groulx, B.J.
1996: Geoscape Vancouver; Geological Survey of Canada, Open File 3309, 1 sheet.

Watts, B.D., Seyers, W.C., and Stewart, R.A.
1992: Liquefaction susceptibility of Greater Vancouver Area soils; *in* Symposium on Geotechnique and Natural Hazards; Vancouver Geotechnical and Canadian Geotechnical Societies, 6–9 May, p. 145–157.

APPENDIX A

Techniques

Geological

Surface and subsurface geology provide the framework for understanding geohazards and ground-surface responses. The geological record can also contain datable features from previous earthquakes. Geological mapping of the Fraser River delta has included standard geological field mapping techniques, i.e. studying outcrop and delta morphology (Clague et al., 1983), as well as taking advantage of urban development opportunities, e.g. examining trenches and construction excavations, and many engineering boreholes and water-well data (Clague et al., 1992, 1998; Monahan et al., 1993a, b). A number of boreholes have been drilled for the express purpose of studying the geology and geotechnical properties of the sediment, and it is from these boreholes that the most relevant information has come (Christian et al., 1994a, H.A. Christian, J.V. Barrie, J.B. Harris, J.A. Hunter, J.L. Luternauer, and P.A. Monahan, unpub. report, 1995; Dallimore et al., 1995, 1996). These dedicated boreholes have generally been drilled with the intent of continuous core recovery and have included traditional split-spoon sampling, retractor core-barrel Shelby tube sampling, as well as vibrasonic drilling. These techniques have been applied onshore and from a barge in the shallow offshore. Sediment samples from deep water in the Strait of Georgia have been acquired through surface sediment grab sampling and gravity, piston, and vibro-coring from surface vessels.

Geophysical

Various types of surface and borehole geophysical techniques have been applied to the on- and offshore portions of the survey area. Surface morphology and sediment type can be studied in detail in the offshore using technologies such as sidescan sonar and swath bathymetry. Much of the foreslope of the Fraser River delta has been surveyed with sidescan sonar (Hart et al., 1991; W.T. Collins, unpub. report, 1994). The recent advent of swath bathymetry, combined with computer imaging, opens a new dimension in seafloor mapping (Currie and Mosher, 1996).

To obtain the configuration of the buried bedrock surface and stratigraphic subsurface relationships, seismic reflection techniques have been employed. Over 300 line kilometres of combined industry and GSC seismic-reflection data have been collected for the onshore portion of the delta (Luternauer and Hunter, 1996; Pullan et al., 1989, 1998). In addition, the GSC has collected thousands of line kilometres of seismic reflection data in the offshore (Hamilton, 1991; Hart et al., 1992a, b, 1993; Mosher, 1996; Mosher et al., 1995; Mosher and Hamilton, 1998). Routine velocity analysis on multichannel data yields important sediment velocity information for earthquake-response modelling (e.g. Hunter et al., 1996). In many areas, high-resolution compressional (P-wave) reflection techniques are limited because of the presence of small quantities of interstitial gas (methane). The presence of gas results in high attenuation of the seismic signal, either obliterating any coherent signal from the subsurface or resulting in low-frequency content of reflection events (Hart and Hamilton, 1993; A.G. Judd, unpub. report, 1995).

Shear-wave reflection profiling and shear-wave velocities are proving to be important in understanding the structure of the delta and its geotechnical properties (Hunter et al., 1993; Christian et al., 1994b; Harris et al., 1996). Shear-wave velocities are being used to predict ground-surface response through modelling and empirical relationships to known liquefaction events. As shear waves are less affected by interstitial gas, shear-wave reflection profiling tests have recently been conducted for both on- and offshore (Hunter et al., 1993; Davis et al., 1993; Pyrah, 1996), with good results.

Seismic refraction methods have been in routine use in engineering and environmental studies for many years. Interstitial gas in the deltaic sediments precludes the compressional (P) wave refraction approach as it does in reflection; however, shear-wave refraction methods have been tested and shown to work well. Approximately 100 shallow-penetration shear-wave refraction sites have been occupied in the delta area to obtain shear-wave velocity-depth profiles to at least 50 m subsurface.

Seismic surface-to-borehole logging techniques have been routinely applied at over 40 boreholes drilled by the GSC on the Fraser River delta. These seismic experiments have included both compressional and shear-wave velocity methods. Downhole seismic velocity data have been collected in a similar manner with a seismic cone penetrometer (*see below*).

Boreholes have also been used to collect passive geophysical logs such as natural gamma radiation, magnetic susceptibility, and electrical conductivity. These data have been utilized to characterize the Quaternary sediments in the survey area. Boreholes have been logged with these technologies, mostly to depths of 30 m to 120 m below surface. Natural gamma radiation generally gives high count rates in association with fine-grained sediments, and hence is useful for discriminating between sand, silt, and clay. Magnetic susceptibility is a measure of the ferrimagnetic mineral content (mainly magnetite) of the overburden material. The Holocene deltaic sand and silt are characteristically low in ferrimagnetic mineral content, whereas Pleistocene materials usually contain higher amounts. Electrical conductivity is mostly a function of pore fluid and porosity, and to a lesser degree sediment type. It is very useful, therefore, in identifying aquifers and aquitards, and salinity of the pore water.

Surface electromagnetic (EM) sounding also has been employed on- and offshore. Offshore, conductivity data from EM results have been used to create porosity-depth profiles, yielding physical property information to about 30 m below seafloor (Mosher and Law, 1996). Onshore, EM methods have been used to detect the presence of a low-conductivity layer associated with the top of Pleistocene deposits. It lies beneath an 80–90 m conductive layer dominated by Holocene deltaic saline pore water.

Geotechnical

Given the extreme difficulty in obtaining representative samples of soil in the undisturbed state, it was recognized that in situ testing provided an alternative means of characterizing soil state and thereby afforded a better approach to identifying liquefiable deposits. In situ soil-profiling tests such as the cone penetration test (CPT), the seismic cone penetration test (SCPT), spectral analysis of surface waves (SASW), and crosshole and downhole shear-wave tests allow detailed and cost-effective investigation of soil characteristics.

Cone testing of soils provides data on the bearing capacity, pore-pressure response, and sleeve friction. Empirical correlations have been developed relating tip resistance (q_c) and cyclic resistance ratio (CRR), which defines the threshold of cyclic liquefaction. It is compared to the cyclic stress ratio (CSR) imposed by the earthquake shaking (Seed and Idriss, 1971; Seed et al., 1983; Robertson and Campanella, 1985; Robertson et al., 1992; Christian, 1998). The CPT, however, is unsuitable for evaluating cyclic liquefaction potential in fine-grained soils because the empirical database is for sands with less than 35% fines.

Empirical methods have also been developed to evaluate liquefaction resistance directly from shear-wave velocity (Bierschwale and Stokoe, 1984). In addition to conventional downhole studies, as discussed above, significant advancement in the measurement of seismic wave velocities has been made through the development of the seismic cone penetration test (SCPT) (Robertson et al., 1992). Shear-wave velocity (V_s) is influenced by many of the variables that influence liquefaction, such as soil density, confining stress, stress history, and geological age. Thus, shear-wave velocity can be used as a field index in the evaluation of liquefaction susceptibility.

Analogous to downhole electric logging, as discussed above, cones also have been outfitted with resistivity meters to measure conductivity/resistivity of the soils. This is known as a resistivity cone penetration test (RCPT) (Campanella and Weemees, 1990; D.J. Woeller, unpub. report, 1993).

References

Bierschwale, J.G. and Stokoe, K.H., II
1984: Analytical evaluation of liquefaction potential of sands subjected to the 1981 West Moreland earthquake; Geotechnical Engineering Report GR-84-15, University of Texas at Austin, Austin, Texas, 17 p.

Campanella, R.G. and Weemees, I.
1990: Development and use of an electrical resistivity cone for ground water contamination studies; Canadian Geotechnical Journal, v. 27, p. 557–567.

Christian, H.A.
1998: Seismic liquefaction potential of the southwestern Fraser River delta; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 231–240.

Christian, H.A., Barrie, J.V., and Monahan, P.A.
1994a: Deep-hole geotechnical investigation adjacent to the BC Hydro Canoe Pass Submarine Cable Terminal, Fraser River delta, British Columbia; Geological Survey of Canada, Open File 2861, 26 p.

Christian, H.A., Robertson, P.K., Weemes I., and Woeller, D.W.
1994b: Use of SASW and SCPT to evaluate liquefaction potential of the Fraser delta foreslope, Vancouver, British Columbia; *in* 47th Canadian Geotechnical Conference, 21–23 September, 1994, Halifax, Nova Scotia, p. 166–175.

Clague, J.J., Hebda, R.J., and Luternauer, J.L.
1983: Sedimentary environments and post-glacial history of the Fraser Delta and lower Fraser Valley, British Columbia; Canadian Journal of Earth Sciences, v. 20, p. 1314–1426.

Clague, J.J., Naesgaard, E., and Mathewes, R.W.
1998: Geological evidence for prehistoric earthquakes; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada Bulletin 525, p. 177–194.

Clague, J.J., Naesgaard, E., and Sy, A.
1992: Liquefaction features on the Fraser delta: evidence for prehistoric earthquakes?; Canadian Journal of Earth Sciences, v. 29, p. 1734–1745.

Currie, R.G. and Mosher, D.C.
1996: Swath bathymetric surveys in the Strait of Georgia, British Columbia; *in* Current Research 1996-E, Geological Survey of Canada, p. 33–40.

Dallimore, S.R., Clague, J.J., Edwardson, K.A., Hunter, J.A., and Luternauer, J.L.
1995: Composite geotechnical logs for two deep boreholes in the Fraser River Delta, British Columbia; Geological Survey of Canada, Open File 3018, 1 sheet.

Dallimore, S.R., Clague, J.J., Edwardson, K.A., Hunter, J.A., Luternauer, J.L., and Meldrum, J.L.
1996: Composite geotechnical logs for a deep borehole at Richmond City Hall; Geological Survey of Canada, Open File 3356, 2 p.

Davis, A.M., Christian, H.A., Huws, D.G., Parrott, R.D., and Barrie, J.V.
1993: Seabed stability evaluation studies using shear wave propagation phenomena; *in* International Conference on Acoustic Classification and Mapping of the Seabed, University of Bath, United Kingdom, 14–16 April, p. 25–32.

Hamilton, T.S.
1991: Seismic stratigraphy of unconsolidated sediments in the central Strait of Georgia: Hornby Island to Roberts Bank; Geological Survey of Canada, Open File 2350, 7 map sheets, scale 1:250 000.

Harris, J.B., Burns, R.A., Good, R.L., Hunter, J.A., and Luternauer, J.L.
1996: Observation of shear-wave splitting in Holocene sediments of the Fraser River Delta, British Columbia; *in* Abstracts, 7th International Workshop on Seismic Anisotropy, February 19–23, Miami, Florida.

Hart, B.S. and Hamilton, T.S.
1993: High-resolution acoustic mapping of shallow gas in unconsolidated sediments beneath the Strait of Georgia, British Columbia; Geo-Marine Letters, v. 13, p. 49–55.

Hart, B.S., Barrie, J.V., Christian, H.A., Hamilton, T.S., Davis, A.M., and Law, L.K.
1993: Marine geological, geophysical and geotechnical investigations of the submarine portions of the Fraser Delta: implications for submarine failures; *in* Proceedings, Canadian Coastal Conference, Vancouver, 5–7 May, p. 25A.

Hart, B.S., Barrie, J.V., Currie, R.G., Hamilton, T.S., and Prior, D.B.
1992a: Marine geophysical and geological surveys of the Fraser Delta slope and adjacent strait of Georgia: 1991 geophysical survey tracklines and 1983–1992 core locations; Geological Survey of Canada, Open File 2543, 5 map sheets, scale 1:25 000 and 1:100 000.

Hart, B.S., Barrie, J.V., Currie, R.G., Luternauer, J.L., Macdonald, R.D., and Prior, D.B.
1991: High resolution seismic and side-scan sonar mapping of the Fraser Delta front and adjacent Strait of Georgia, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 91-1E, p. 19–23.

Hart, B.S., Frydecky, I., Horel, G., and Olynyk, H.W.
1992b: An airgun seismic survey of the Fraser Delta slope; *in* Current Research, Part E; Geological Survey of Canada, Paper 92-1E, p. 33–39.

Hunter, J.A., Harris, J.B., and Britton, J.R.
1996: Compressional and shear wave interval velocity data for Quaternary sediments in the Fraser River delta from multichannel seismic reflection surveys; Geological Survey of Canada, Open File 3325, 228 p.

Hunter, J.A., Woeller, D.J., Addo, K.O., Luternauer, J.L., and Pullan, S.E.
1993: Application of shear wave seismic techniques to earthquake hazard mapping in the Fraser River Delta, British Columbia; *in* Expanded Abstracts, 1993 Technical Program, 63rd Annual Society of Exploration Geophysicists Meeting, September 26–30, 1993, Washington, D.C., p. 501–503.

Luternauer, J.L. and Hunter, J.A.
1996: Mapping Pleistocene deposits beneath the Fraser River Delta: preliminary geological and geophysical results; *in* Current Research 1996-E; Geological Survey of Canada, p. 41–48.

Monahan, P.A., Luternauer, J.L., and Barrie, J.V.
1993a: A delta topset sheet sand and modern sedimentary processes in the Fraser River Delta, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 93-1A, p. 263–272.
1993b: A delta plain sheet sand in the Fraser River Delta, British Columbia, Canada; Quaternary International, v. 20, p. 27–38.

Mosher, D.C.
1996: Southern Roberts Bank nearshore survey: PGC95003; Geological Survey of Canada, Open File 3202, 26 p.

Mosher, D.C. and Hamilton, T.S.
1998: Morphology, structure, and stratigraphy of the offshore Fraser delta and adjacent Strait of Georgia; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 147–160.

Mosher, D.C. and Law, L.K.
1996: Application of concurrent marine electromagnetic and marine seismic high resolution profiling, British Columbia, Canada; Journal of Environmental and Engineering Geophysics, v. 1, p. 215–228.

Mosher, D.C., Nichols, B.C., and Scientific Party of PGC95001
1995: Multichannel and high resolution seismic reflection survey of the marine portion of the Fraser River Delta, Vancouver, British Columbia: Tully PGC95001; *in* Current Research 1995E; Geological Survey of Canada, p. 37–45.

Pullan, S.E., Hunter, J.A., Jol, H.M., Roberts, M.C., Burns, R.A., and Harris, J.B.
1998: Seismostratigraphic investigations of the southern Fraser River delta; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 91–122.

Pullan, S.E., Jol, H.M., Gagné, R.M., and Good, R.L.
1989: Compilation of high resolution "optimum offset" shallow seismic reflection profiles from southern Fraser River delta, British Columbia; Geological Survey of Canada, Open File 1992, 16 p.

Pyrah, J.R.
1996: An integrated geotechnical-geophysical procedure for the prediction of liquiefaction in uncemented sands; Ph.D. dissertation, University of Wales, Bangor, United Kingdom, 201 p.

Robertson, P.K. and Campanella, R.G.
1985: Liquefaction of sands using the CPT; Journal of Geotechnical Engineering Division, American Society of Civil Engineers, v. 22, p. 298–307.

Robertson, P.K., Woeller, D.J., and Finn, W.D.L.
1992: Seismic cone penetration test for evaluating liquefaction potential under cyclic loading; Canadian Geotechnical Journal, v. 29, p. 686–695.

Seed, H.B. and Idriss, I.M.
1971: Simplified procedure for evaluating soil liquefaction potential; Journal of Geotechnical Engineering Division, American Society of Civil Engineers, v. 97, p. 458–482.

Seed, H.B., Idriss, I.M., and Arango, I.
1983: Evaluation of liquefaction potential using field performance data; Journal of Geotechnical Engineering Division, American Society of Civil Engineers, v. 109, p. 458–482.

Sedimentary processes and their environmental significance: lower main channel, Fraser River estuary

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Kostaschuk, R.A. and Luternauer, J.L., 2004: Sedimentary processes and their environmental significance: lower main channel, Fraser River estuary; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 81–92.*

Abstract: Sedimentary processes in the main channel of the Fraser River estuary are controlled by river discharge and sediment load, tidal conditions, and the intrusion of salt water into the channel. Many contaminants are adsorbed on mud particles that are transported in suspension and deposited within the estuary and in the Strait of Georgia. Contaminants within sediment pass into the food chain and have been found in elevated levels in birds, mammals, and fish. The construction industry dredges sand from the bed of the estuary, and channelization has confined sand movement to a narrow corridor within the channel. Most sand deposition occurs at the river mouth, contributing to slope failures that are hazardous to a lighthouse and jetty. Sand that once replenished sediment lost to coastal erosion of the tidal flats is now lost by sediment flows to deep water. This loss of sand affects intertidal habitat and may increase slope erosion elsewhere on the delta.

Résumé : Les processus sédimentaires qui prennent place dans le chenal principal de l'estuaire du Fraser sont régis par le débit fluvial et la charge solide, par les marées et par l'intrusion d'eau salée dans le chenal. De nombreux contaminants sont adsorbés sur les particules de boue transportées en suspension qui se déposent dans l'estuaire ainsi que dans le détroit de Georgia. Les contaminants dans les sédiments passent dans la chaîne alimentaire; on en a retrouvés en concentrations élevées dans des oiseaux, des mammifères et des poissons. L'industrie de la construction extrait du sable du lit de l'estuaire par dragage, et la canalisation a confiné le mouvement du sable à un étroit corridor du chenal. Le sable se dépose surtout à l'embouchure du fleuve, ce qui contribue à des ruptures de versants qui constituent un risque pour un phare et sa jetée. Le sable qui remplaçait autrefois les sédiments enlevés par l'érosion côtière des bas-fonds intertidaux se perd maintenant dans des coulées de sédiments en eau profonde. Cette perte de sédiments se répercute sur l'habitat intertidal et risque d'accélérer l'érosion des pentes ailleurs dans le delta.

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INTRODUCTION

An estuary is an inlet of the sea extending into a river valley as far as the upper limit of tidal rise (Fairbridge, 1980). By this definition, the estuary of the Fraser River is the reach of the river between the Strait of Georgia and the upstream influence of the tide (Thomson, 1981). During low river discharge, the tidal influence reaches as far upstream as Chilliwack, 120 km from the Strait of Georgia. High river discharge limits the tidal influence to Mission, 75 km upstream of the strait. The estuary in the Fraser River delta contains three major distributary channels — main channel, north arm, and middle arm — and a number of smaller distributary channels and tributary creeks.

The Fraser River estuary is profoundly affected by the rapid industrial and urban growth occurring on the delta, and several key environmental issues in the main channel (Fig. 1) are related to the movement of mud (silt and clay) and sand. Pollutants enter the estuary from several sources, including pulp mills along the Fraser River upstream of the estuary as well as municipal and industrial sources on the delta. Many contaminants are adsorbed on mud particles in suspension and are transported through the estuary and deposited in the Strait of Georgia (Stronach et al., 1988; Luternauer et al., 1994). There is also some evidence for a turbidity maximum, a localized high concentration of potentially contaminated mud held in suspension in the estuary (Kostaschuk et al., 1992a). Toxins from sediment can bioaccumulate in the food chain and have been found in elevated levels in birds, mammals, and fish (Servizi, 1989).

The construction industry has recently increased its demand for borrow dredging of sand from the bed of the main channel. In addition, channelization of the lower reaches of the main channel, resulting from construction of flow-control structures, has confined sand movement to a narrow corridor within the channel. These changes in the patterns of sand transport have several implications. Deposition of sand is restricted to the river mouth area near Sand Heads, contributing to submarine landslides and slumping that present a hazard to the local lighthouse (McKenna et al., 1992) (Fig. 1). Sand that once replenished sediment lost to coastal erosion of the surrounding tidal flats is now lost by mass flows to deep water (Kostaschuk et al., 1992b). This loss of sand compromises intertidal habitat and may enhance slope erosion and instability elsewhere on the submarine delta (Kostaschuk et al., 1995).

The purpose of this paper is to summarize recent research on sedimentary processes in the lower main channel of the Fraser River estuary (Fig. 1). We provide a brief summary of sedimentation within the estuary, then focus on two related groups of processes in the lower channel: 1) plume dynamics, and 2) river-mouth slope failures and sediment flows.

SEDIMENTATION IN THE ESTUARY

Sedimentary processes in the Fraser River estuary are controlled by river discharge and sediment load, tidal conditions, and the intrusion of salt water into the channel. Here we summarize the influence of these factors on flow and sediment dynamics in the main channel.

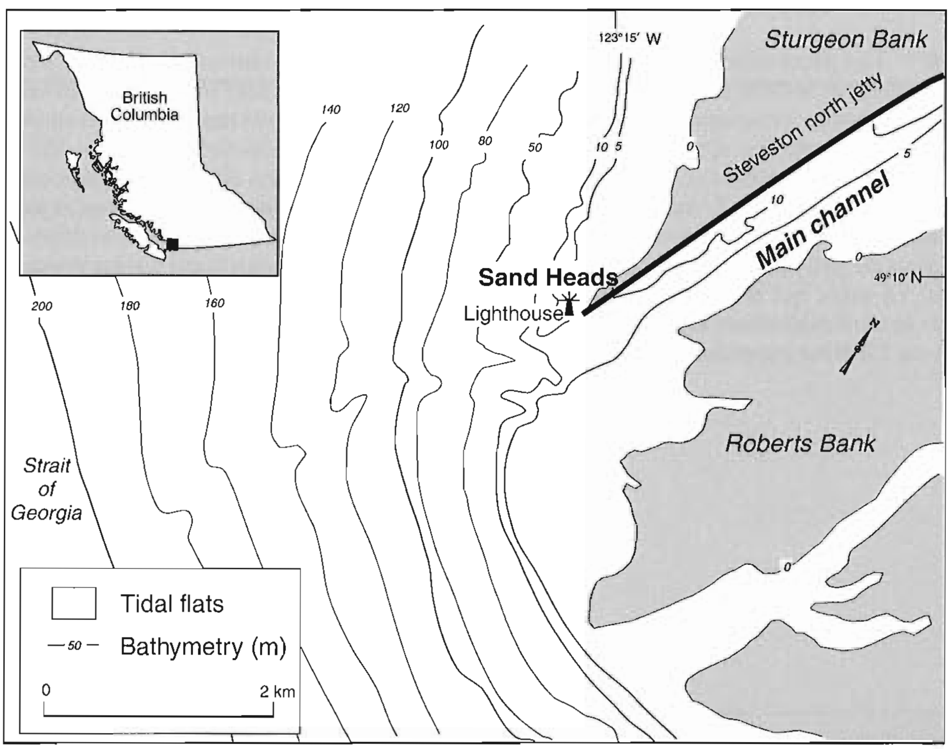

Figure 1. The lower main channel of the Fraser River and the Strait of Georgia in the river-mouth area.

River and marine conditions

The Fraser River is over 1200 km long and drains 250 000 km^2 of mountainous terrain in southern British Columbia. Mean annual discharge at Mission is 3400 m^3/s, and daily discharges follow a pronounced seasonal pattern dominated by a snowmelt freshet in the spring (Fig. 2). Sediment loads in the river are divided into wash load and bed-material load (McLean and Church, 1986). Wash load is fine, muddy sediment (particle size of less than 0.125 mm in diameter) that is transported in permanent suspension and is not found in appreciable quantities on the bed. The coarser, sandy bed-material load is transported episodically in suspension or along the bottom as bed load. Suspended-sediment concentration at Mission follows a pattern similar to that of discharge, but usually peaks before discharge during the freshet (Fig. 2). The lag, or hysteresis, between discharge and concentration peaks reflects the declining supply of wash-load material over the freshet season (Milliman, 1980). Wash load is supplied directly from high banks along the river that are weathered by frost action during the winter, producing debris which is entrained in the spring. The supply of easily eroded sediment quickly declines, producing the lag effect. The Fraser River supplies an average of 17.3 million tonnes of sediment annually to the delta, of which 35% is sand (McLean and Tassone, 1991).

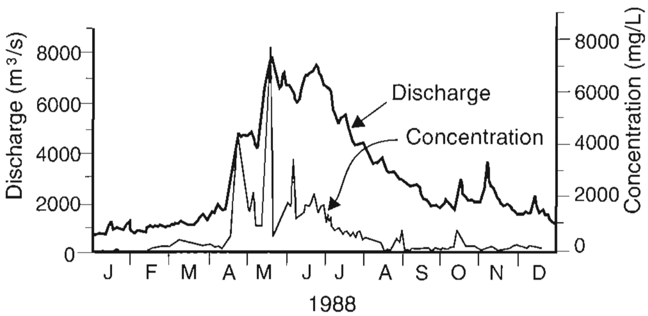

__Figure 2.__ Daily mean discharge and depth-integrated suspended-sediment concentration for the Fraser River at Mission, 1988 (unpub. data from Water Survey of Canada, 1988).

The Strait of Georgia is a semi-enclosed, high-energy marine basin. The size of waves in the strait is limited by the short distances across which the wind blows over open water. Maximum significant one-third wave heights are 2.1 m on Sturgeon Bank and 2.7 m on Roberts Bank (Thomson, 1981) (Fig. 1). Tides are mixed semidiurnal, with two high- and two low-water stands per day (Fig. 3). Tides have a mean range of 3.1 m near the mouth of the main channel, but differences in tidal range occur over fortnightly and longer cycles. Spring tides approach 5 m and neap tides 2 m in range. The tidal range in the main channel decreases both upstream of the river mouth and with increasing river discharge.

Estuarine flow and sediment dynamics

The salinity structure and circulation of the Fraser River estuary vary seasonally and over single tidal cycles. Kostaschuk et al. (1992a) examined the saltwater intrusion during high river discharge and concluded that the estuary behaves as a highly stratified salt-wedge estuary with a distinct boundary between fresh and salt water (Fig. 4). Hodgins et al. (1977) measured salinity during low river discharge in winter and found that the increased tidal mixing of fresh and salt water produces a stratification characteristic of a partially mixed estuary. Geyer and Farmer (1989) examined the salinity structure over the rise and fall of the tide during low river discharge. They found that the saltwater intrusion behaved as a salt wedge as it migrated landward during the flood tide, but that during the ebb tide, vertical mixing intensified and the estuary was partially mixed. Although the Fraser River estuary is clearly not always a salt-wedge system, the term 'salt wedge' is usually used to describe the saltwater intrusion in the main channel — this convention is adopted here.

The bed of the main channel is composed almost entirely of sand with a mean particle size of 0.25 to 0.35 mm, with little seasonal variation (Kostaschuk et al., 1989a; Villard, 1995). Bed-material load in the estuary is sand and coarser sediment, whereas wash load consists of silt and clay (Villard, 1995). Sand is moulded into large dunes over 5 m in height and 100 m in length (Kostaschuk and MacDonald, 1988; Kostaschuk and Villard, 1996a). Considerable periods of time are required to rearrange the large volumes of sand within the dunes, so changes in dune height and length lag behind changes in flow velocity in the channel (Kostaschuk

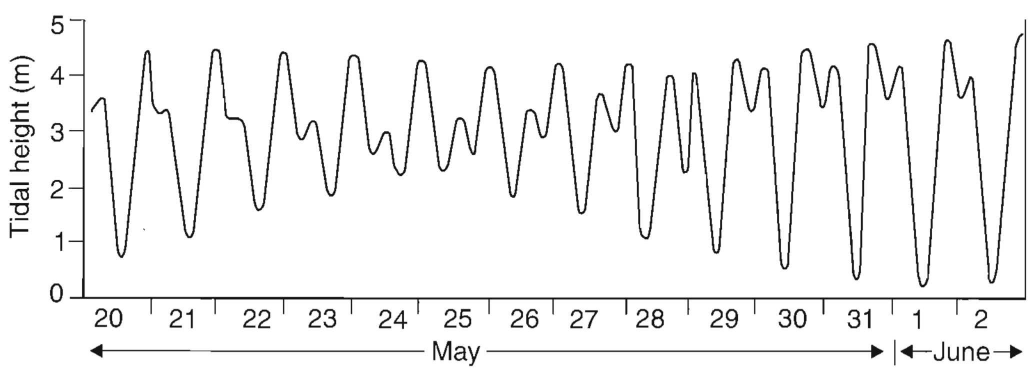

__Figure 3.__ Tidal curves at Point Atkinson for selected days in 1989 (unpub. data from Canadian Hydrographic Service, 1989).

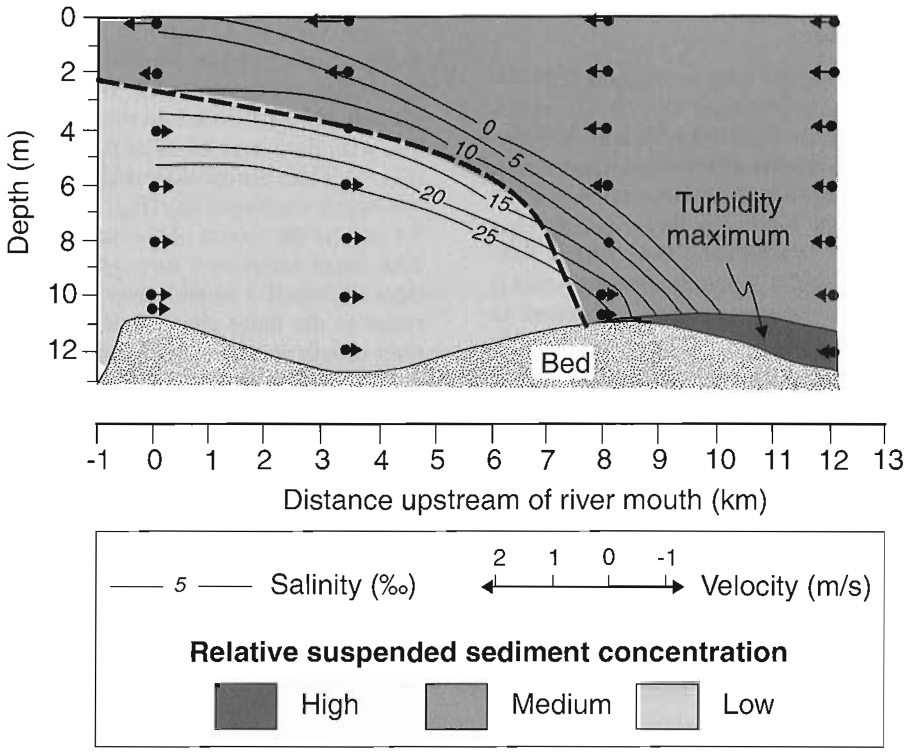

***Figure 4.** Along-channel variation in salinity, velocity, and suspended-sediment concentration in the salt-wedge intrusion on July 6, 1987. The dashed line separates medium (above) and low (below) suspended-sediment concentrations. Note the location of the turbidity maximum near the upstream tip of the salt wedge.* Modified from *Luternauer et al. (1994, Fig. 6).*

et al., 1989a; Ilersich, 1992). Over 95% of the sand transported in the estuary is in suspension (Kostaschuk and Ilersich, 1995), and most of this sand is contained in large turbulent structures evident as boils at the flow surface (Kostaschuk and Church, 1993; Kostaschuk and Villard, 1996b).

Suspended-sediment transport in the main channel is affected by time lag (hysteresis) on both seasonal and tidal time scales (Kostaschuk et al., 1989b; Kostaschuk and Luternauer, 1989). Fluvial (river-related) hysteresis in the main channel reflects the influence of seasonal changes in wash-load transport in the Fraser River. The annual peak in daily sediment concentration precedes the peak in river discharge (e.g. Fig. 2) because the supply of fine mobile sediment is exhausted early in the spring snowmelt freshet. Hysteresis on a tidal time scale occurs because the peak in sediment concentration follows the peak in velocity. This may be due to enhanced turbulence during decelerating flows caused by the rising flood tide (Kostaschuk et al., 1989b).

Suspended sediment is transported seaward in the upper layer of fresh water overlying the salt wedge (Kostaschuk et al., 1992a) (Fig. 4). Upper-layer currents are stronger and lower-layer currents weaker at low tide than at high tide, in response to flow acceleration and the seaward movement of the salt wedge as the tide falls. Suspended-sediment concentration is higher at low tide because sand is entrained and suspended by the strong, unstratified flow upstream of the salt wedge. The concentration of suspended sediment in the upper layer decreases exponentially with seaward distance (Kostaschuk et al., 1992a), resulting in the turbidity maximum of fine suspended sediment near the upstream end of the salt wedge. Virtually nothing is known of the character or behaviour of the turbidity maximum, but it may provide an ideal environment for pollutants to be adsorbed onto mud in the channel. This mud is subsequently deposited within the estuary and on the tidal flats and seafloor of the Strait of Georgia, providing potential pathways for the transfer of contaminants into the food chain.

PLUME DYNAMICS

In this section we describe the plume of turbid river water caused by the outflow from the main channel into the Strait of Georgia. The behaviour of the Fraser River plume is analogous to that of the salt-wedge intrusion, except that the plume is not confined laterally by channel jetties. The salt wedge intrudes into the channel when river discharge is low, and low outflow velocity in the fresh-water plume is accompanied by a weak landward saltwater return flow. When river discharge is high and the tide is low, the salt wedge is forced out of the main channel and plume velocities are high. Wash-load concentrations decrease offshore in the plume and fine sediment settles to the seabed. Wind and tidal currents transport the remaining fine suspended sediment throughout the Strait of Georgia. During periods of high river discharge, sandy bed material is suspended and transported seaward in the plume, where it settles out rapidly offshore. Most sand is deposited on a shallow bar at the mouth of the river. Suspended-sediment concentrations decrease seaward in the plume, because plume velocity declines and sediment that settles out is not replaced from the seabed.

Temporal variations at the river mouth

Kostaschuk et al. (1989b) found that temporal variations in salinity and velocity near Sand Heads (Fig. 1) are controlled by river discharge, tidal height, and the position of the salt wedge. Figure 5 illustrates salinity and velocity over tidal cycles at an anchor station 1 km upstream of Sand Heads (Fig. 1). Two sets of conditions are represented by moderate river discharge in May and high river discharge in June. The salt wedge is located in the main channel at high tide, but at low tide it is flushed out of the channel, and flow is unstratified at the river mouth. Currents are weak at high tide, and the fresh surface layer flows downstream. Weak currents in the lower layer are directed upstream. The full water column becomes downstream-directed during the falling tide, and velocity reaches maximum values just before low tide. The rising tide produces a rapid deceleration of downstream currents followed by weak upstream flows.

Figure 6 summarizes mean cross-sectional velocity and suspended-sediment concentration over tidal cycles for the site 1 km upstream of Sand Heads (Kostaschuk et al., 1989b). Suspended-sediment concentration at high tide is extremely low regardless of river discharge. As the tide falls, flow becomes unstratified and accelerates, resulting in bed-material suspension and an increase in sediment concentration (e.g. Kostaschuk and Luternauer, 1989). Concentration remains high as the tide begins to rise, then rapidly decreases to low values at high tide.

Plume processes

Stronach et al. (1988) examined the flow dynamics of the plume using field evidence and a mathematical model. They found that the plume extended well offshore during high river

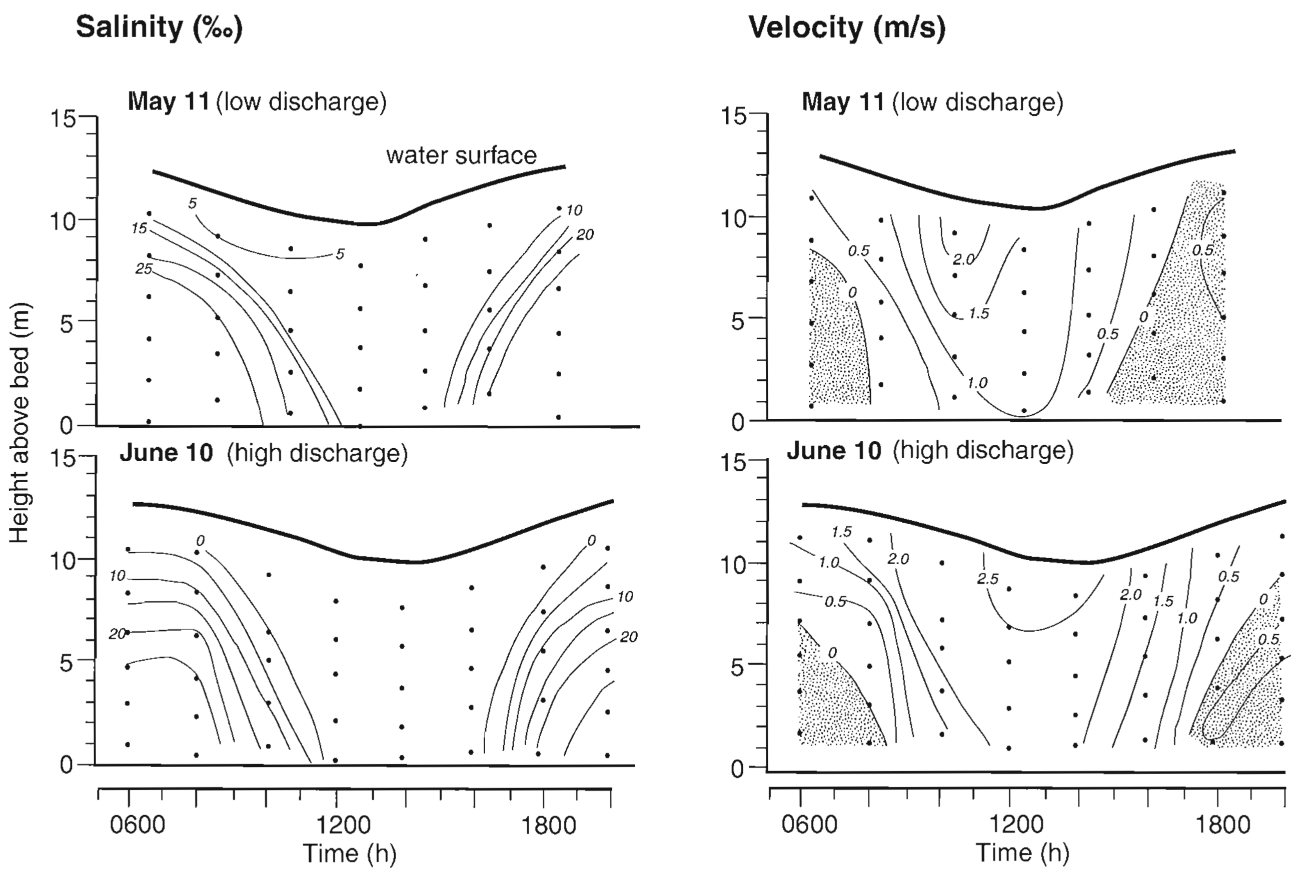

Figure 5. Contours of equal salinity and velocity over a falling and rising tide during low and high discharge. A launch was anchored at a station 1 km upstream of Sand Heads (Fig. 1) in 1986. The data points represent sampling positions for velocity and salinity, and the water surface illustrates tidal stage. The stippled areas represent upstream flow. Low discharge is 3380 m³/s at Mission, high discharge is 10 700 m³/s at Mission. Modified from *Kostaschuk et al. (1989b, Fig. 2, 3).*

discharge but was a local river-mouth feature during low discharge. Tides and winds affect the position of the plume (LeBlond, 1983). During calm conditions, the Coriolis force (caused by the rotation of the Earth) and the rising flood tide deflect the plume toward the north. Falling ebb tides sweep the plume to the south. Winds reduce the velocity of the outflow and also shift the direction of the plume (LeBlond, 1983; Stronach et al., 1988; Stephan, 1990). Cordes et al. (1980) found that saltwater entrainment contributes to seaward deceleration of the plume. Stephan (1990) measured the planform shape of several plumes during calm winds and slack tides and found that the north side of the plume was parabolic in shape, a form consistent with models of effluent expansion of buoyant outflows (e.g. Wright, 1985). The south side of the plume was more linear because the shallow water adjacent to Roberts Bank (Fig. 1) restricts plume expansion southward.

Kostaschuk et al. (1993) examined offshore changes in salinity, velocity, and suspended-sediment concentration in eleven Fraser River plumes during periods of calm winds and relatively constant river discharge. Four of the eleven plumes were associated with unstratified conditions at the river mouth, and seven with stratified river-mouth conditions (e.g. Fig. 7). Unstratified conditions resulted when the salt wedge was flushed out of the channel at low tide and forced to a position over the distributary mouth bar. Flow velocities were high at the river mouth, often exceeding 2 m/s at the surface in the centre of the channel. Plume velocities and plume thickness decreased consistently with distance seaward of the river mouth, and plume salinity increased. Stratified river-mouth conditions occurred when the salt wedge had intruded into the estuary channel during the rising tide. River-mouth flow velocities were lower under stratified conditions than under unstratified conditions. Plume velocities remained relatively constant to a distance of about 3 km offshore, then decreased consistently seaward. Plume thickness decreased seaward of the river mouth, and salinity increased.

Kostaschuk et al. (1993) found that unstratified river-mouth flows were associated with high suspended-sediment concentrations of coarse silt and sand, whereas stratified river-mouth flows were associated with much lower concentrations of silt and clay. Sediment concentrations consistently decreased with distance seaward of the river mouth (Fig. 8). The high concentrations of coarse sediment at the mouth under unstratified conditions reflect the suspension of sandy bed material by the flow. Suspended sediment had already travelled over the saline intrusion in the estuary channel under stratified-flow conditions, resulting in low concentrations of fine wash-load particles at the mouth (Kostaschuk et al., 1992a).

The decline in the plume's sediment concentration seaward of the mouth may be due to a number of factors. First, the plume is isolated from the bed by a strong salinity gradient across which very little transport or mixing occurs. Thus, sediment that settles out of the plume is not replaced by resuspension from the seafloor. Second, the seaward decrease in plume velocity would cause a corresponding decline in the ability of the plume to suspend sediment. The decrease in plume velocity may also indicate a seaward decline in turbulence. It is well known that turbulent velocity fluctuations control sediment suspension, so a decline in turbulence may reduce the capacity of the plume to suspend sediment. Finally, salinity can cause aggregation of silt and clay particles, with the composite aggregates having greater settling velocities than individual particles. The seaward increase in salinity in the Fraser River plume may enhance sediment aggregation along the plume axis.

Kostaschuk et al. (1992a) proposed an empirical model based on physical reasoning to predict sediment concentration in the flow above salinity intrusions in the Fraser River estuary. The model showed that suspended-sediment concentration above the salt wedge is controlled by river conditions, tidal height, and

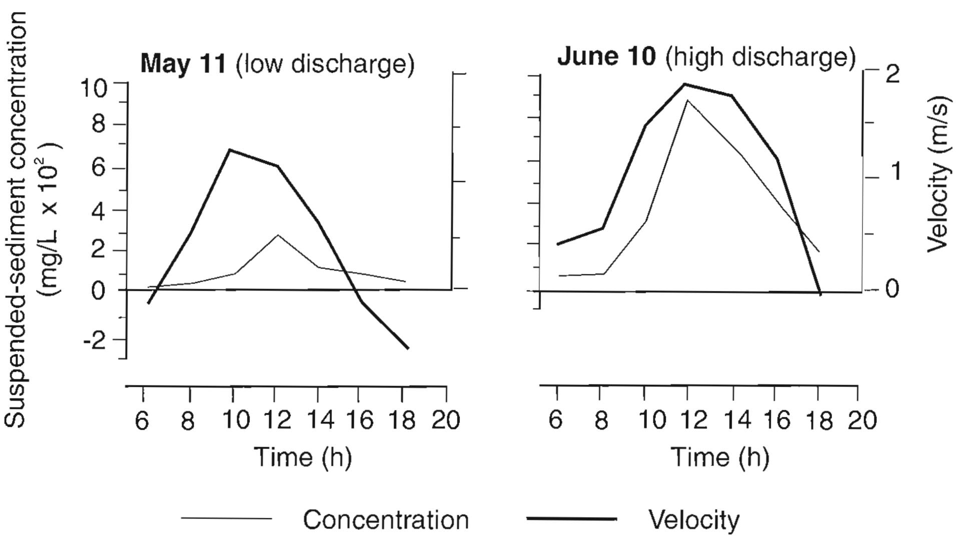

Figure 6. Mean cross-sectional channel velocity and suspended-sediment concentration during low and high discharge, based on three anchor stations located 1 km upstream of Sand Heads (Fig. 1) in 1986. Low discharge is 3380 m^3/s at Mission, high discharge is 10 700 m^3/s at Mission. Tidal stage is shown on Figure 5. Modified from *Kostaschuk et al. (1989b, Fig. 4).*

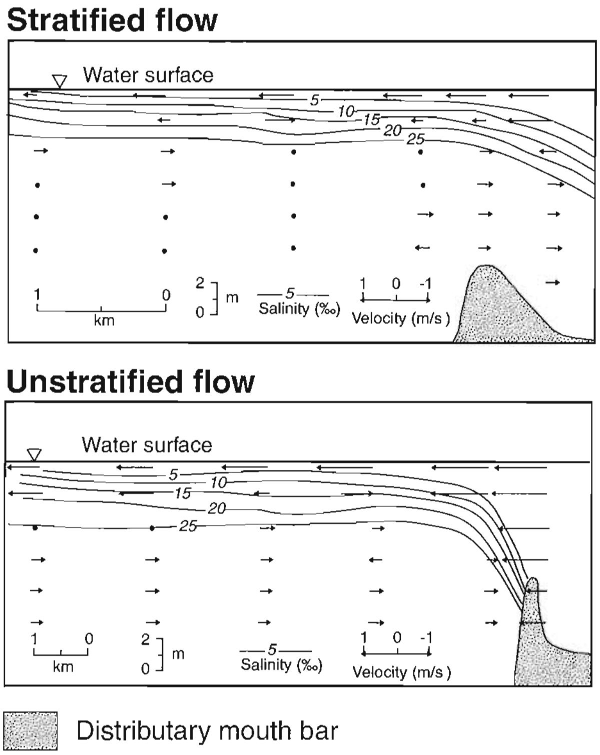

Figure 7. Velocity and salinity in the centre of the plume under stratified and unstratified flow conditions at the river mouth on May 20, 1989. Under stratified conditions, the salt wedge has migrated upstream of the distributary mouth bar. Under unstratified conditions, the salt wedge is seaward of the bar. Modified from *Kostaschuk et al. (1993, Fig. 4).*

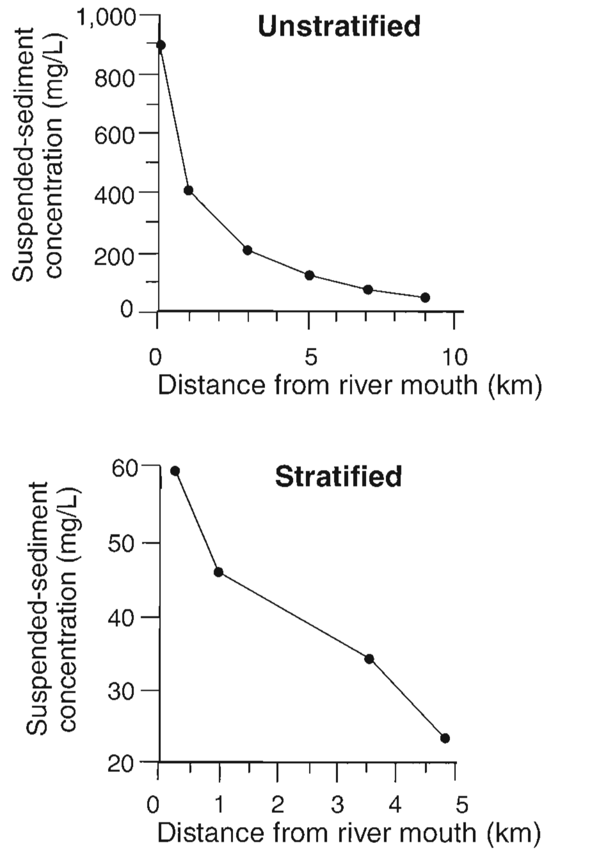

Figure 8. Suspended-sediment concentration in the centre of the plume during unstratified and stratified flow at the river mouth on May 20, 1989. See *Figure 7 for velocity and salinity structure.* Modified from *Kostaschuk et al. (1993, Fig. 5).*

distance seaward along the buoyant flow, the same factors that affect suspended-sediment concentration in the plume. Kostaschuk et al. (1993) applied the Kostaschuk et al. (1992a) salt-wedge model to the plume and found that suspended-sediment concentration along the Fraser River plume axis is controlled primarily by distance from the river mouth, followed by tidal height, and then by river-sediment concentration.

Deposition

The position of the salt wedge in the estuary is a function of river discharge and tidal height (Kostaschuk and Atwood, 1990). Kostaschuk and Atwood (1990) produced an empirical, logarithmic multiple-regression model for salt-wedge position and used it to examine deposition in the estuary. They argued that since bed-material transport occurs primarily during the four- to five-hour period around low tide (e.g. Fig. 6), salt-wedge position at low tide is crucial to depositional patterns. The model shows that the salt wedge is consistently forced to the river mouth at Sand Heads during low tides below 1 m (Fig. 9). The frequency of this occurrence increases with river discharge and as such is greatest in June. Bed-material transport is also greatest in June, so persistent deposition in the channel should occur near the river mouth in June.

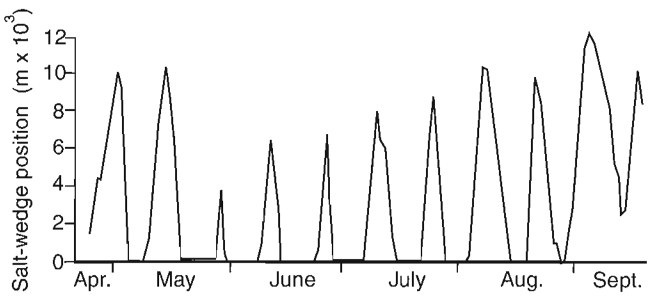

Figure 9. Lower low-tide salt-wedge position upstream of Sand Heads for several months in 1985. Salt-wedge position is predicted from the empirical model of Kostaschuk and Atwood (1990). Modified from *Kostaschuk and Atwood (1990, Fig. 7).*

Kostaschuk and Luternauer (1987) used cross-sectional bed profiles and dredging records to examine patterns of bed-material erosion and deposition in the lower estuary. They found that net erosion occurs during rising river discharge, and deposition during falling discharge. Persistent deposition occurs at the river mouth near Sand Heads over the entire flow season, and this area requires constant dredging. This result supports Kostaschuk and Atwood's (1990) prediction of deposition of bed material at Sand Heads.

Fine-grained wash load remains in suspension in the plume for considerable distances seaward of the river mouth, and depositional patterns follow the plume path. The plume can flow directly offshore from the river mouth when winds are calm and outflow is strong (e.g. Fig. 7). Strong winds, the Coriolis force, and tidal currents deflect the plume to the north or south. Wash-load deposition occurs as a suspension fallout that drapes underlying subsurface topography (Hart et al., 1992), and sampling has shown that the drape consists of silty clay with minor disseminated organic material, rare parallel laminations, and weak burrowing (Evoy et al., 1993).

RIVER-MOUTH SLOPE FAILURES AND SEDIMENT FLOWS

This section examines slope failures and sediment flows that originate at the mouth of the main channel. Slope failures of over 1 400 000 m^3 in volume have been recorded, threatening Sand Heads lighthouse and Steveston north jetty. Such failures could be triggered by gas generation in sediment, undercutting by tidal currents, storm waves, and earthquakes, although rapid deposition at the river mouth appears to be the most important factor. Slope failures generate sandy sediment flows that travel downslope in a submarine channel. The channel system consists of tributary channels near the river mouth, a single sinuous channel, and distributary channels at the base of the slope.

Slope failures at Sand Heads

Submarine mass movements on the Fraser River delta threaten several engineering structures including dykes, jetties, sewage-outfall pipelines, submarine power cables, the Tsawwassen ferry terminal, and the Roberts Bank coal port (McKenna et al., 1992; Kostaschuk et al., 1995). Slope failures are common at river mouths on deltas (Wright, 1985), so Sand Heads lighthouse and Steveston north jetty (Fig. 1) at the mouth of the main channel may be at risk (McKenna et al., 1992). McKenna et al. (1992) examined over 100 bathymetric charts near Sand Heads and identified five large slope failures which occurred over a fifteen-year period. The smallest event, in 1972, involved about 75 000 m^3 of sediment, and the slope retrogressed 40 m. The largest mass-wasting event, in 1985, involved over 1 400 000 m^3 of sand (Atkins and Luternauer, 1991) and a slope retrogression of 350 m (Fig. 10). This slope failure extended to within 100 m of Sand Heads lighthouse and Steveston north jetty, and could have caused considerable damage to these structures. McKenna et al. (1992) believed that the failures result from liquefaction of the silty sand deposited at the river mouth.

There are several possible triggering mechanisms for the mass-wasting events (Luternauer and Finn, 1983; McKenna et al., 1992), but most events probably result from a combination of causes. Interstitial gas generated by decomposing organic matter in the sediment increases pore pressures and lowers the strength of the material. This process probably occurs continuously, and additional mechanisms are required to trigger discrete events. Rapid deposition of sand at the river

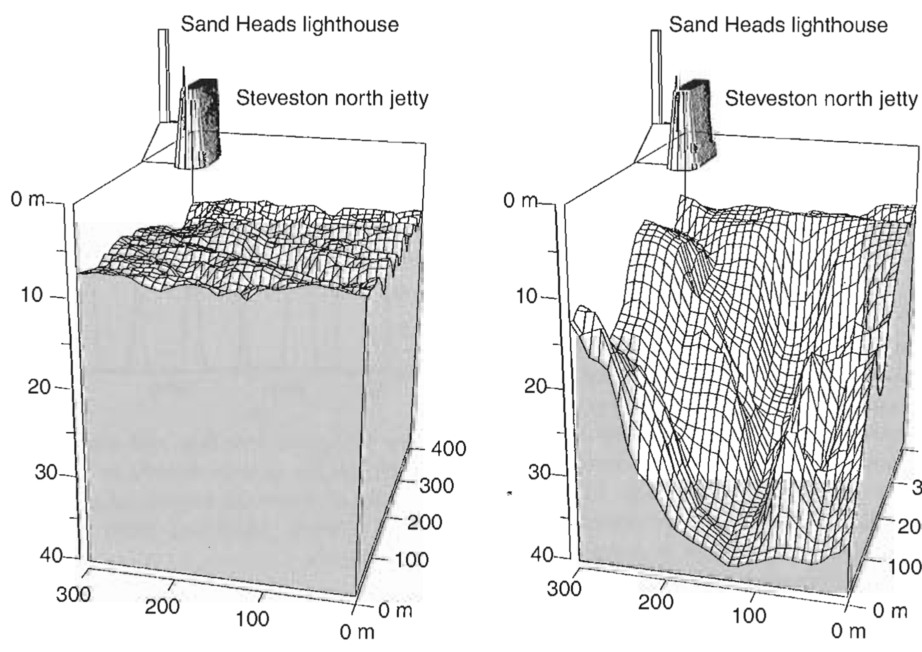

Figure 10. *River-mouth bed before and after a major slope failure in 1985.* Modified from *Atkins and Luternauer (1991, Fig. 5).*

mouth appears to be a major factor over the longer term. Deposition 'loads' the underlying sediment, resulting in an increase in pore pressure that may lead to liquefaction. The passage of storm waves also can increase pore pressure, although recent investigations by Christian et al. (1995) suggested that tidal loading is more important than storm waves and that wave loading alone is not capable of causing slope failures. Earthquakes can 'shake' sandy sediment until it changes its structure and liquefies; however, failures at Sand Heads have not been linked to earthquakes.

Sediment flows

Slope failures at the river mouth generate mass sediment flows that travel downslope in a submarine channel called Sand Heads seavalley (Kostaschuk et al., 1992b; Hart et al., 1992). The seavalley is over 5 km in length and sits on a depositional ridge. Kostaschuk et al. (1992b) described a channel system of upslope tributary channels that coalesce into a single sinuous channel which splits into distributary channels at the base of the slope. Hart et al. (1992), however, found no evidence for distributary channels in their surveys. Tributary channels are relatively straight in plan view and are deeply eroded into the upper slope. The sinuous channel contains five distinct bends, with levees along the banks and irregular ridges and arcuate troughs on the bed (Fig. 11). The ridges may be bedforms from tidal currents or pressure ridges from sediment flows. The arcuate troughs likely reflect scour from mass flows. Slumps and gullies occur on the outside of bends, suggesting lateral movement of the channel. The distributary channels are situated on a subdued fan, and slump scarps indicate deformation along channel banks.

Kostaschuk et al. (1992b) and Shepard and Milliman (1978) interpreted the seavalley as a product of turbidity currents generated by periodic liquefaction of sandy sediment at the mouth of the river. Hart et al. (1992), however, believed that sediment transport occurs primarily by submarine debris flows. Evoy et al. (1994) recovered a core of normally graded beds, with pronounced coarsening- and thickening-up sequences, from the seavalley channel. They interpreted this as representative of deposition from traction at the base of a turbidity-current channel. Evoy et al. (1994) found no evidence for debris-flow deposits in the seavalley area. Hart et al. (1992) described a core composed of massive, medium-grained sand overlain by undisturbed mud from the seavalley, and interpreted the sand as a debris-flow deposit. Regardless of the mechanism of sediment transport, Sand Heads seavalley is the primary offshore conduit of sand movement at the river mouth.

Moslow et al. (1993) and Evoy et al. (1993) used ^{137}Cs dating to examine deposition rates in cores from the seavalley area. (Cesium-137 is a product of atmospheric nuclear testing, which appeared in 1954 and peaked in 1963.) They found that deposition rates of river sediment between 1954 and 1989 ranged from nearly 3 cm per year in 200 m depth near the seavalley to about 0.5 cm per year in 60 m depth north of Sand Heads on Sturgeon Bank. Lower deposition rates on Sturgeon Bank reflect less input of suspended sediment from the plume and no sediment supply from mass flows in the seavalley. All cores showed lower deposition rates from 1963 to 1989 compared with the period from 1954 to 1963. The reason for this is not clear, but Moslow et al. (1993) suggested that it may be related to lower sediment loads in the river, due to dredging and channelization. The lower deposition rates could also reflect 'natural' variations in sediment supply from the river and from mass movements at the river mouth.

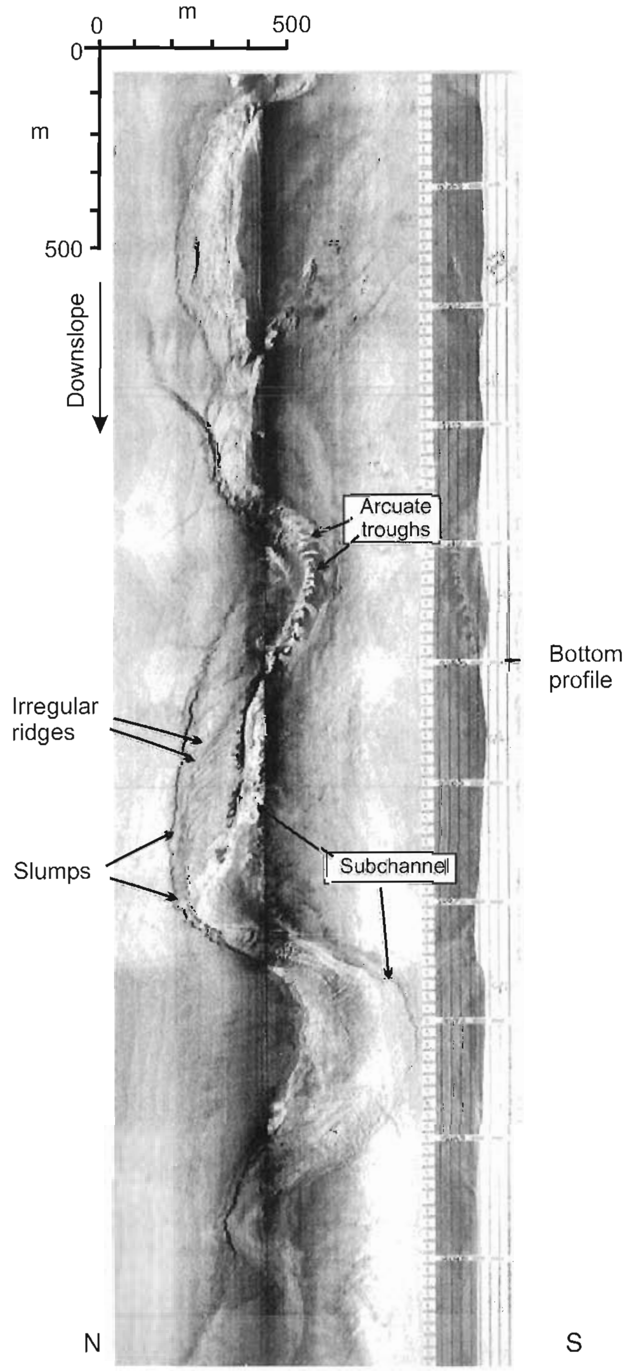

Figure 11. *Side-scan sonar record of the Sand Heads seavalley sinuous channel (bathymetry on Fig. 1). Downslope is to the left. See text for explanation of features.* Modified from *Kostaschuk et al. (1992b, Fig. 6).*

SUMMARY

Figure 12 summarizes sedimentary processes for two sets of extreme river and tidal conditions in the lower main channel. The presence of the salt wedge in the channel during low river discharge produces a stratified river mouth (Fig. 12a). Outflow velocity in the freshwater plume is low and there is a weak, landward, saltwater return flow. Bed-material load is trapped upstream by the salt wedge, and only low concentrations of wash load are transported to the river mouth. Wash-load concentrations decrease offshore in the plume, and fine sediment settles to the seabed. Wind and tidal currents transport the fine suspended sediment throughout the Strait of Georgia.

When river discharge is high and the tide is low, the salt wedge is forced out of the main channel (Fig. 12b). The river mouth is unstratified and plume velocities are high. Wash load is transported seaward of the river mouth in the high-energy plume and settles slowly offshore. Tidal and wind currents distribute wash load throughout the strait. Sandy bed material is suspended, transported seaward in the plume, and settles out rapidly offshore. Most bed material is deposited on the distributary mouth bar.

Submarine slope failures of over 1 400 000 m^3 in volume occur on the distributary mouth bar at the river mouth and could threaten some vital coastal infrastructures (*see* Mosher et al., 2004). Triggering mechanisms could include generation of interstitial gas, undercutting by tidal currents, depositional loading, storm waves, tidal fluctuations in water

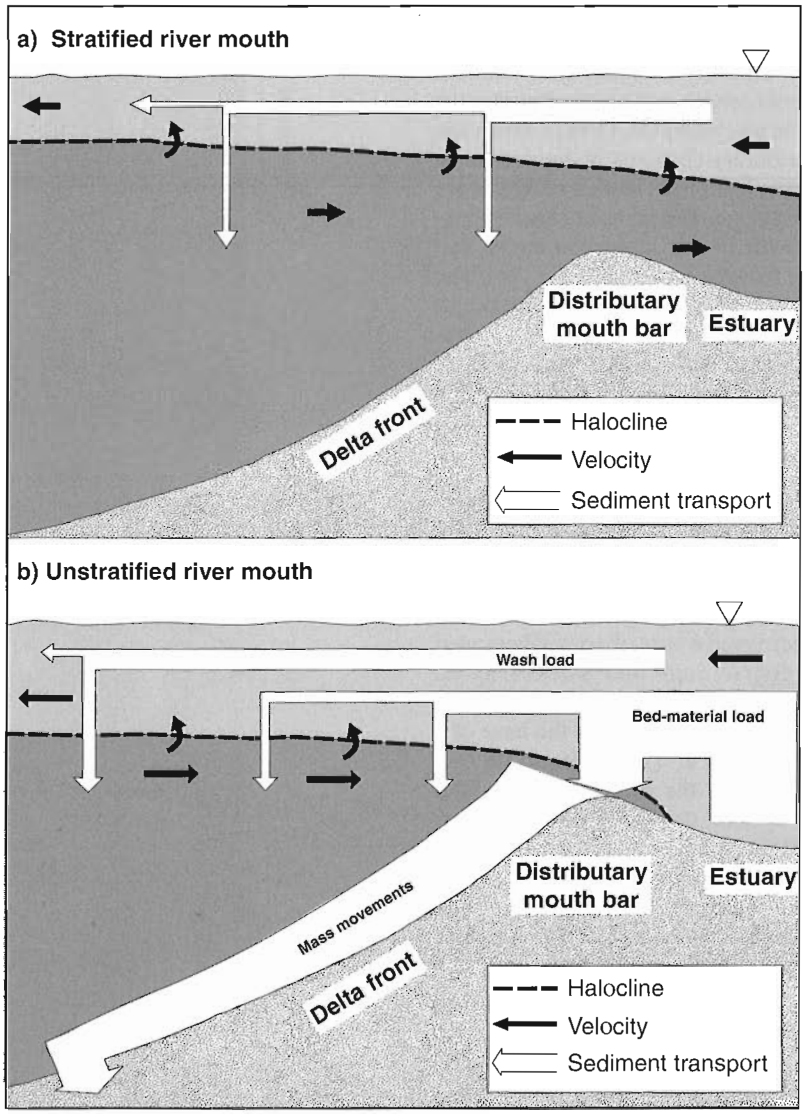

Figure 12. *Conceptual model of sedimentary processes in the lower main channel of the Fraser River estuary.* See *text for explanation. Halocline is the area of transition from salt water to fresh water.*

level, and earthquakes, although rapid deposition at the river mouth appears to be the major factor. Slope failures generate mass flows that travel downslope in a submarine channel. The channel system is composed of upslope tributary channels that coalesce into a single sinuous channel which splits into distributary channels at the base of the slope. The submarine channel is the main conduit for offshore sand transport.

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REFERENCES

Atkins, R.J. and Luternauer, J.L.
1991: Re-evaluation of slope failure volume estimates involving 3D computer graphics for the Fraser River delta front, British Columbia; *in* Current Research, Part E; Geological Survey of Canada, Paper 91-1E, p. 59–65.

Christian, H.A., Barrie, J.V., MacDonald, R., Monahan, P.A., Hunter, J.A., and Luternauer, J.L.
1995: Slope stability on Roberts Bank, Fraser River delta, Vancouver, British Columbia; *in* 48th Canadian Geotechnical Conference, Vancouver, British Columbia, v. 2, p. 937–944.

Cordes, R.E., Pond, S., de Lange Boom, B.R., and LeBlond, P.H.
1980: Estimates of entrainment in the Fraser River plume, British Columbia; Atmosphere-Ocean, v. 18, p. 15–26.

Evoy, R.W., Moslow, T.F., Kostaschuk, R.A., and Luternauer, J.L.
1994: Origin and variability of sedimentary facies of the Fraser River delta foreslope, British Columbia; Marine Geology, v. 118, p. 49–60.

Evoy, R.W., Moslow, T.F., Patterson, R.T., and Luternauer, J.L.
1993: Patterns and variability in sediment accumulation rates, Fraser River delta foreslope, British Columbia, Canada; Geo-Marine Letters, v. 21, p. 212–218.

Fairbridge, R.W.
1980: The estuary: its definition and geodynamic cycle; *in* Chemistry and Biogeochemistry of Estuaries, (ed.) E. Olausson and I. Cato; John Wiley and Sons, Toronto, Ontario, p. 1–36.

Geyer, W.R. and Farmer, D.M.
1989: Tide-induced variation of the dynamics of a salt-wedge estuary; Journal of Physical Oceanography, v. 19, p. 1060–1072.

Hart, B.S., Prior, D.B., Barrie, J.V., Currie, R.G., and Luternauer, J.L.
1992: A river mouth submarine channel and failure complex, Fraser delta, Canada; Sedimentary Geology, v. 81, p. 73–87.

Hodgins, D.O., Osborn, T.R., and Quick, M.C.
1977: Numerical model of stratified flow; American Society of Civil Engineers, Journal of the Waterways, Ports and Coastal Division, v. WW1, p. 25–42.

Ilersich, S.A.
1992: Bedforms and bedload transport: evaluating rate equations in the Fraser River, British Columbia, Canada; M.Sc. thesis, University of Guelph, Guelph, Ontario, 135 p.

Kostaschuk, R.A. and Atwood, L.A.
1990: River discharge and tidal controls on salt-wedge position and implications for channel shoaling; Canadian Journal of Civil Engineering, v. 17, p. 452–459.

Kostaschuk, R.A. and Church, M.A.
1993: Macroturbulence generated by dunes: Fraser River, Canada; Sedimentary Geology, v. 85, p. 25–37.

Kostaschuk, R.A. and Ilersich, S.A.
1995: Dune geometry and sediment transport: Fraser River, British Columbia; *in* River Geomorphology, (ed.) E.J. Hickin; John Wiley and Sons, Sussex, England, p. 19–36.

Kostaschuk, R.A. and Luternauer, J.L.
1987: Large-scale sedimentary processes in a trained, high-energy, sand-rich, salt-wedge estuary: Fraser River delta, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 87-1A, p. 727–734.
1989: The role of the salt-wedge in sediment resuspension and deposition; Journal of Coastal Research, v. 5, p. 93–101.

Kostaschuk, R.A. and MacDonald, G.M.
1988: Multi-track surveying of large bedforms; Geo-Marine Letters, v. 8, p. 57–62.

Kostaschuk, R.A. and Villard, P.V.
1996a: Flow and sediment transport over large subaqueous dunes: Fraser River, Canada; Sedimentology, v. 43, p. 849–863.
1996b: Turbulent sand suspension events: Fraser River, Canada; *in* Coherent Flow Structures in Open Channels, (ed.) P.J. Ashworth, S.J. Bennett, J.L. Best, and S.J. McLelland; John Wiley and Sons, Sussex, England, p. 305–320.

Kostaschuk, R.A., Church, M.A., and Luternauer, J.L.
1992a: Sediment transport over salt-wedge intrusions: Fraser River estuary, Canada; Sedimentology, v. 39, p. 305–317.
1989a: Bed material, bedforms and bed load in a salt-wedge estuary – Fraser River, British Columbia; Canadian Journal of Earth Sciences, v. 26, p. 1440–1452.
1989b: Suspended sediment hysteresis in a salt-wedge estuary – Fraser River, Canada; Marine Geology, v. 87, p. 273–285.

Kostaschuk, R.A., Luternauer, J.L., Barrie, J.V., LeBlond, P.H., and Werth von Deichmann, L.
1995: Sediment transport by tidal currents and implications for slope stability: Fraser River delta, British Columbia; Canadian Journal of Earth Sciences, v. 32, p. 852–859.

Kostaschuk, R.A., Luternauer, J.L., McKenna, G.T., and Moslow, T.F.
1992b: Sediment transport in a submarine channel system: Fraser River delta, Canada; Journal of Sedimentary Petrology, v. 62, p. 273–282.

Kostaschuk, R.A., Stephan, B.A., and Luternauer, J.L.
1993: Suspended sediment concentration in a buoyant plume: Fraser River, Canada; Geo-Marine Letters, v. 13, p. 165–171.

LeBlond, P.H.
1983: The Strait of Georgia: functional anatomy of a coastal sea; Canadian Journal of Fisheries and Aquatic Sciences, v. 40, p. 1033–1063.

Luternauer, J.L. and Finn, W.D.L.
1983: Stability of the Fraser River delta-front; Canadian Geotechnical Journal, v. 20, p. 606–613.

Luternauer, J.L., Barrie, J.V., Christian, H.A., Clague, J.J., Evoy, R.W., Hart, B.S., Hunter, J.A., Killeen, P.G., Kostaschuk, R.A., Mathewes, R.A., Monahan, R.W., Moslow, T.F., Mwenifumbo, P.K., Olnyk, C.J., Patterson, R.T., Pullan, S.E., Roberts, M.C., Robertson, P.K., Tarbotton, M.R., and Woeller, D.J.
1994: Fraser River delta: geology, geohazards and human impact; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 197–220.

McKenna, G.T., Luternauer, J.L., and Kostaschuk, R.A.
1992: Large-scale mass-wasting events on the Fraser River delta front near Sand Heads, British Columbia; Canadian Geotechnical Journal, v. 29, p. 151–156.

McLean, D.G. and Church, M.A.
1986: A re-examination of sediment transport observations in the lower Fraser River; Environment Canada, Inland Waters Directorate, Water Survey of Canada, Sediment Survey Section, Report IWD-HQ-WRB-SS-86-6, 52 p.

McLean, D.G. and Tassone, B.
1991: A sediment budget of the lower Fraser River; *in* Proceedings, 5th Federal Interagency Sedimentation Conference, Las Vegas, Nevada, p. 2-33–2-40.

Milliman, J.D.
1980: Sedimentation in the Fraser River and its estuary, southwestern British Columbia (Canada); Estuarine and Coastal Marine Science, v. 10, p. 609–633.

Mosher, D.C., Christian, H.A., Hunter, J.A., and Luternauer, J.L.
2004: Onshore and offshore geohazards of the Fraser River delta; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Moslow, T.F., Evoy, R.W., and Luternauer, J.L.
1993: Implications of Cs-137 sediment profiles for sediment accumulation rates on the Fraser River delta foreslope, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 93-1A, p. 255–261.

Servizi, J.A.
1989: Protecting Fraser River salmon from wastewater: an assessment; *in* Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonoid Stocks, (ed.) C.D. Levings, L.B. Holtby, and M.A. Henderson; Canadian Special Publication of Fisheries and Aquatic Sciences, v. 105, p. 136–153.

Shepard, F.P. and Milliman, J.D.
1978: Sea-floor currents on the foreset slope of the Fraser River delta, British Columbia (Canada); Marine Geology, v. 28, p. 245–251.

Stephan, B.A.
1990: Sedimentary processes at the mouth of the Fraser River, British Columbia, Canada; M.Sc. thesis, University of Guelph, Guelph, Ontario, 134 p.

Stronach, J.A., Crean, P.B., and Murty, T.S.
1988: Mathematical modelling of the Fraser River plume; Water Pollution Research Journal of Canada, v. 23, p. 179–212.

Thomson, R.E.
1981: Oceanography of the British Columbia coast; Canadian Special Publication of Fisheries and Aquatic Sciences, no. 56, 291 p.

Villard, P.V.
1995: Spatial and temporal behaviour of turbulent sand suspension over dunes: Fraser River, British Columbia; M.Sc. thesis, University of Guelph, Guelph, Ontario, 125 p.

Wright, L.D.
1985: River deltas; *in* Coastal Sedimentary Environments, (ed.) R.A. Davis; Springer-Verlag, New York, New York, p. 1–76.

Flooding in the Fraser River delta and urban estuary

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Abstract: The Fraser River, with a drainage basin of some 233 000 km^2, is the largest river in British Columbia. Depending on ground elevation and location along the river, flooding of the estuary and delta can be caused by winter storm surges originating from the Strait of Georgia, and/or by high spring freshet flows on the Fraser River. As well, heavy fall and winter rainfalls exacerbated by poor drainage and tide levels combine to cause high water tables and overland flows within dyked areas requiring extensive drainage and pumping facilities.

Current issues relating to flood control include maintenance of works in light of changing public priorities and environmental conflict. Future consideration could be given to upgrading existing works to higher standards justified by rapidly increasing population and development levels in the benefiting areas. Concerns may be directed to the effects of sedimentation, earthquakes, relative sea-level changes, and possible changes in climatic conditions.

Résumé : Le fleuve Fraser, dont le bassin hydrographique couvre environ 233 000 km^2, est le plus important cours d'eau en Colombie-Britannique. Les inondations de l'estuaire et du delta peuvent, selon l'altitude et la position le long du fleuve, être causées par les ondes de tempête qui prennent naissance dans le détroit de Georgia ou par le débit élevé dû aux crues printanières du Fraser. En outre, les fortes pluies automnales et hivernales, conjuguées au drainage médiocre et au haut niveau des marées, causent l'élévation de la surface des nappes d'eau souterraines et l'inondation des zones endiguées, ce qui nécessite d'importantes installations de drainage et de pompage.

Une des questions d'actualité par rapport à la lutte contre les inondations a trait à l'entretien des ouvrages compte tenu de l'évolution des priorités gouvernementales et des conflits relatifs à l'environnement. On pourrait envisager de moderniser les ouvrages existants en fonction de normes plus strictes, ce que justifie l'ampleur de la croissance démographique et du développement dans les zones visées. Une attention particulière pourrait être accordée aux effets de la sédimentation, des tremblements de terre, des variations relatives du niveau de la mer et d'éventuels changements climatiques.

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FRASER RIVER FLOODING

The Fraser River basin rises on the western slopes of the Rocky Mountains, extends northwest through the Rocky Mountain Trench, skirts the northern portion of the Columbia Mountains, and flows diagonally southward from Prince George through a deeply incised canyon across the Interior Plateau and then westward to the ocean at the southern end of the Coast Mountains at Hope. While the eastern mountains constitute less than one-third of the drainage basin, this area yields about 60% of the annual runoff. The large Interior Plateau contributes about 36% with the remaining 4% runoff being generated in the 2% of the basin draining the Coast Mountains (Fraser River Board, unpub. final report, 1963). Flows in the spring period occur due to rising temperatures initiating snowmelt. Flood flows are often supplemented by moist air and rainfall usually resulting in peak flows in late May to June (lesser peaks have occurred as late as July).

The river is gauged by the Water Survey of Canada at various locations, with gauges at Hope and Mission recording since 1912 and 1876, respectively. The flood of record for the system occurred in 1894, corresponding to an estimated flow of 16 990 m^3/s at Hope and a gauge reading at Mission of 7.92 m (Geodetic Survey of Canada datum). The 1948 flood was the highest flow measured at Hope at 15 180 m^3/s, corresponding to a gauge reading of 7.61 m (Geodetic Survey of Canada datum) (Table 1). By comparison, the mean annual peak daily flood computed for 1969 is about 9000 m^3/s.

The 1894 flood occurred at a time of early development so damages were limited. Flooding of farms and farmlands was extensive in the Fraser River valley, including Lulu Island and Delta. Dyking had begun as early as 1864 on Lulu Island, and extensive damage occurred to those early works. The frequency of the 1894 flood is variously estimated to lie between about 160 and 200 years.

The 1948 flood was more significant in terms of the effects on human habitation and lasting impact on flood control and floodplain management. The flood severed all land transportation from the interior, inundated 22 300 ha of land, destroyed or damaged 2000 homes, and caused some $20 million of damages (in 1948 dollars; Fraser Valley Dyking Board, unpub. final report, 1950). Only isolated flooding occurred in 1948 downstream of New Westminster due to the presence of flood protection dykes. Unprotected areas in the vicinity of the railway crossing on the north arm near Fraser River Park in Burnaby as well as unprotected islands and marginal lands on both the north arm and the main stem flooded at this time.

Table 1. Major flood levels and/or flows.

	Flow at Hope	Gauge height at Mission
Design crest height	N/A	8.53 m
1894	16 990 m^3/s	7.92 m
1948	15 180 m^3/s	7.61 m
Patrols initiated	N/A	6.5 m
Floodplain level	N/A	6.0 m

N/A = not available

The public drama and concern generated by the 1948 flood provided the needed political impetus for rehabilitation and improvements to the flood-protection system. As a result, approximately 217 km of existing dykes were reconstructed and 17.4 km of new dykes were built, cost-shared by federal (75%) and provincial (25%) governments. The works were funded under the federal-provincial Fraser Valley Dyking Board which disbanded in March 1950.

This was followed by a program of bank-protection works initially managed by the federal Department of Public Works, cost-shared by federal (37.5%), provincial (37.5%), and local (25%) governments and, in turn, by the Fraser River Board which replaced the earlier Dominion-Provincial Fraser River Basin Board in 1955. The Fraser River Board submitted its final report in 1963 that examined flood control and hydroelectric potential (Inland Waters, 1969a). These studies led, in due course, to the May 24, 1968 "Agreement Covering a Plan for Flood Control in the Lower Fraser Valley, British Columbia" with a mandate to undertake "...a program of studies and work for flood control aimed at substantially reducing the flood threat to the area".

FRASER RIVER FLOOD CONTROL PROGRAM

Whereas upstream storage has long been considered as a means of flood reduction, the principal lines of defence are the dyking systems (Fig. 1). It also has been estimated that about a 4% reduction in flood peak would be possible due to flow regulation by the Kenny Dam on the Nechako River (Inland Waters, 1969b). The Nechako and Bridge River reservoir systems were, for instance, credited with significant reduction in peak of about 1130 m^3/s at Hope (i.e. about 0.3 m stage at Mission) during the 1972 flood (Fraser River Joint Advisory Board, unpub. report, 1976).

There is a total of about 247 km length of dykes in the lower Fraser River valley which were improved under the Fraser River Flood Control Program from 1968 to 1995. The expenditures under the program totalled about $146 million.

Fraser River Flood Control Program standards

According to the original Fraser River Flood Control Program standards for riverine dykes, main stem dykes would be constructed to protect against a recurrence of the flood of record, i.e. the 1894 flood, and have a design crest of approximately two feet (0.6 m) of freeboard. Sea dykes were to be constructed to protect against the highest tide on record with approximately one foot (0.3 m) of freeboard plus an allowance for wave runup (this criteria was later changed to provide freeboard plus wave runup over a computed 1:200 tide level). Program standard dykes were designed with a minimum 12 foot (3.7 m) crest width to facilitate patrolling and maintenance by the responsible local authority (Water Investigations Branch, unpub. report, 1973; Fraser Basin Management Board, unpub. report, 1994).

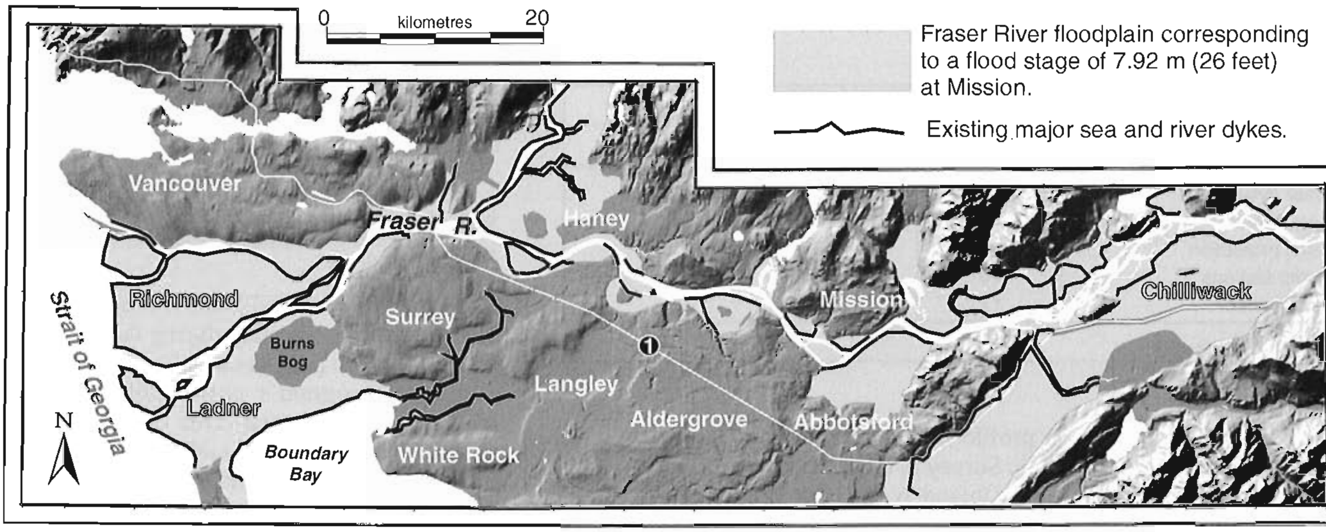

Figure 1. Location map of Fraser River delta. Map data derived from "A task force report to the Fraser Basin Management Board, May 26, 1994", *unpub. report (1994).*

Pumps, floodboxes (floodbox: a gated structure that conveys internal drainage through a flood-protection dyke when stream levels are low while preventing reverse flood flows from entering during high stream flows), and main drains were designed to remove runoff from a 1:10 year peak rainstorm from rural areas in 24 hours with consideration of up to a 1:25 year peak daily rainstorm from urban areas, including allowance for underseepage at the maximum design river flood level. Drainage pumps were designed to remove the internal drainage design runoff at the average annual peak river level.

Bank-protection requirements were reviewed early in the program, including site inspections, erosion records, spot velocity measurements, and observations of boat and wave wash (Fraser River Flood Control Program-Bank Protection Work Group, unpub. report, 1971). Measurements of river velocity at low tide varied from about 0.9 m/s to 2.1 m/s locally in the estuary. Waves of up to about 0.6 m high were observed due to boat wash, which was determined to be a dominant factor compared to those generated by wind. The report recommended that 1) shot rock riprap bank protection be utilized, 2) no slopes be steeper than 1.5:1 (later changed to 2:1), 3) hydraulically smooth horizontal alignments not be required in wave areas, and 4) a filter layer be provided under the riprap.

Specific identified areas of concern included Gravesend Reach just east of Deas Island and upstream to Lafarge Cement Ltd. where scour holes to depths of 15 m exist (these also were reported to be closely related to locations of old dyke failures).

Sea dykes

Sea dykes were designed to accommodate high-tide and storm conditions originating in the Strait of Georgia. Early reports noted that strong southwesterly winds produce a build up of water along the western shores of the Vancouver mainland approximately 0.8 m over the predicted high-tide level, causing high water backing up to the vicinity of Mitchell Island (CBA Engineering, unpub. report, 1967).

An analysis of records from Steveston in 1967 determined that the highest recorded tide to that time was about an elevation 2.6 m (Geodetic Survey of Canada datum) on December 5, 1967. This was later statistically extrapolated to determine an estimated 1:200 year elevation of about 2.7 m (Geodetic Survey of Canada datum); freeboard and wave runup bring this to about 3.35 m (Geodetic Survey of Canada datum). This elevation was used for design of the sea dykes for Richmond and Delta. The level of the sea dyke intersects with the riverine profile at about kilometre 16.9 on the river near Ladner (Inland Waters, 1969a).

A later study analyzing tide data separated out the storm-surge component (Sea Consult Marine Research Ltd., unpub. report, 1990). The 1:200 year return-period storm surge was calculated to be 1.15 m for Point Atkinson (this compares to 1.28 m calculated for the 1:1000 year event). An updated storm surge of record at Point Atkinson was found to have occurred December 16, 1982, yielding a derived storm surge of 0.91 m.

Depending on location, the constructed sea dykes vary in elevation from about 3.3 m to 3.6 m (Geodetic Survey of Canada datum) in Delta and Richmond.

River dykes

The flood profile for the river dykes was computed by a steady-state backwater calculation using a high tide for tailwater and the estimated 1894 peak flood flow. The backwater model was calibrated to known high-water marks and then adjusted to account for the presence of modern dykes and constrictions. Adjustments also were reportedly made locally to increase levels where 1948 flood marks exceeded

Table 2. Completed Fraser River Flood Control Program flood-protection works.

	Municipality		
Flood-protection works	**Richmond**	**Delta**	**New Westminster**
River dykes	42 km	14.4 km	6.7 km
Sea dykes	5.5 km	25.7 km	NA
Bank protection	19 km	11.8 km	2.2 km
Pump stations	10	3	4
Floodboxes	17	8	3
NA = not applicable			

1894 data. The determined profile including freeboard is about elevation 4.2 m (Geodetic Survey of Canada datum) at the upstream end of Lulu Island (Inland Waters, 1969a).

Special potential problems associated with the dykes were determined early on to include underseepage, earthquake liquefaction, and instability of slopes. Subsurface investigation determined that old dykes were composed mainly of locally borrowed, fine-grained material often mixed with and underlain by organic material. Dyke fills were usually loose and sometimes stratified, indicating little or no compaction had been achieved in construction (W.C. Jones, unpub. report, 1963).

Subsurface investigations generally encountered 2 m to 4 m or so of silt overlying deep, pervious sands to the depth of drilling. The sands were open to the river, and piezometric levels responded almost simultaneously to changes in river and/or tide level. Boiling had been observed in many places in ditches at the landside toe of dykes and the possibility of piping (flow of water through subsurface erosion conduits) during extreme events was recognized. Accordingly, it was decided to fill toe ditches where possible, and provide filter drains and relief wells in other areas to relieve excess pore pressures.

There is recognition that earthquake forces may damage dykes through instability or even possibly liquefaction. These forces were, however, deemed to exceed both the financial means of the Fraser River Flood Control Program and the intended confidence level of the flood-protection works.

Internal drainage

About 75% of the mean annual precipitation for the lower Fraser River valley occurs during the six-month period from October to March. Frequently, this is caused by active frontal storms accompanied by southwesterly upper flows of moisture-laden Pacific Ocean air. Variation in rainfall increases gradually from southwest to northeast as air masses approach the south slopes of Vancouver and Burnaby. Early studies estimated the 25-year design storm intensities to vary from about one inch (2.54 cm) per hour for a one hour duration to about four inches (10.2 cm) per hour for five minutes duration (CBA Engineering, unpub. report, 1973). Drainage requirements, of course, also customarily reflect reductions to account for drainage detention and/or depression storage and infiltration losses.

Internal drainage is accommodated by drainage plans for affected municipalities with appropriate provision of floodboxes and pumping stations to remove surface runoff from behind the dyking systems.

Summary of Fraser River Flood Control Program works

The Fraser River Flood Control Program completed dyke rehabilitation during the period of 1968 to 1995 to program standards as justified under the program's cost-benefit analysis requirements. The total costs of works were about $18.4 million for Richmond, $16 million for Delta, and $3.2 million for New Westminster (Table 2). (Totals do not include municipal drainage works as these were excluded from the Fraser River Flood Control Program in 1975.)

OTHER FLOOD-PROTECTION WORKS

Various other flood-protection works exist in the Fraser River estuary that were constructed in earlier times to other than Fraser River Flood Control Program standards. Table 3 summarizes major works.

MAINTENANCE OF FLOOD-PROTECTION WORKS

Flood-protection dykes are owned and operated by local authorities and dyking districts. The province regulates these activities in the interests of public safety under authority of the Dyke Maintenance Act (Woods, 1996). Current activities of the Provincial Inspector of Dykes include providing information and increasing awareness, monitoring and auditing of dyking authorities, information and advice on dyke safety (British Columbia Ministry of Environment, Lands and Parks, 1999), and developing guidelines and provincial standards.

A major concern has been conflict with environmental agencies resulting from vegetation removal from dykes and associated structures. Because the flood-protection works line the river edge, trees and shrubs growing on them provide shelter, shade, and food, and as such are considered to be

Table 3. Other flood-protection works in the Fraser River estuary.

Municipality or Dyking District	Dyke length	Area protected
Colebrook Dyking District	7.1 km	424 ha
Mud Bay Dyking District	8.7 km	460 ha
Sea Island	15.2 km	255 ha
Southlands	3.7 km	300 ha
Westham Island	10.9 km	801 ha
Surrey Dyking District	75.6 km	4715 ha

animal habitat. Vegetation on dykes, on the other hand, presents public safety concerns by weakening fills and inhibiting visibility and access for inspection and maintenance, as well as reducing the expected lifetime and long-term effectiveness of dykes (P.J. Woods, paper presented at Watercourses conference, Vancouver, British Columbia, October, 1996). Work has been completed to develop environmental guidelines for vegetation removal to protect both public safety and the environment.

Principles regarding vegetation control were prepared by a joint committee of the Department of Fisheries and Oceans and British Columbia Environment, Lands and Parks to guide this process.

PRINCIPLES OF VEGETATION MANAGEMENT ON FLOOD-PROTECTION DYKES TO PROTECT PUBLIC SAFETY AND THE ENVIRONMENT

Vegetation-management guidelines for flood-protection dykes are determined by the public safety need for visibility for inspection, access for efficient operation and maintenance, and minimization of detrimental effects to dyke fills and bank protection.

Vegetation control should, where possible, include efforts to preserve and enhance fish and wildlife habitat in the overall stream-river corridor.

Vegetation (including roots and canopy) can improve both dyke safety and habitat through soil conservation and erosion control. For example, setback strips on the overbank and vegetation between flood-protection works and the watercourse are recognized for dyke safety and environmental and aesthetic values (British Columbia Ministry of Environment, Land and Parks, Department of Fisheries and Oceans, 1999).

OTHER ISSUES

Population growth and development is proceeding at unprecedented rates in the Lower Mainland. Much of this is on flood-prone lands protected by flood-protection dykes. The current flood-protection systems were justified on a cost-benefit basis (benefits were based on protected values ca. 1968) to guard against a recurrence of the flood of record (1894) approximating a 1:200 year event. Analysis in light of current and future development would likely find that upgrading protection to a higher standard could be justified in strict economic terms when costs of potential damages are compared with upgrade costs. In this regard it is noted that, while the province continues to promote floodproofing of new development to reduce residual flood damage in case of floods larger than the design event or dyke failure, large areas of Richmond and Delta are exempted as historical development areas and, hence, are at some risk.

It also is noted that the current flood-protection system is not built to withstand earthquake forces. While the economic viability of such provision could not be met by the Fraser River Flood Control Program, this raises the issue of expeditious repair should a future major earthquake severely damage the system. Other future concerns also may be directed to the effects of relative sea-level changes and possible changes in hydrological and climatic conditions. Sedimentation processes and effects of dredging for shipping also remain ongoing concerns as these impacts do not fall specifically within normally defined maintenance of flood-control structures.

These issues will demand a high degree of interagency co-operation to ensure effectiveness of flood-control systems in the future.

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REFERENCES

British Columbia Ministry of Environment, Lands and Parks
1999: Guidelines for Management of Flood Protection Works in British Columbia; British Columbia Ministry of Environment, Lands and Parks, 25 p.

British Columbia Ministry of Environment, Land and Parks, Department of Fisheries and Oceans
1999: Guidelines for Vegetation Management on Flood Protection Works to Protect Public Safety and the Environment; British Columbia Ministry of Environment, Land and Parks, Department of Fisheries and Oceans, 20 p.

Inland Waters
1969a: Fraser River Flood Profiles; Department of Energy, Mines and Resources, Engineering Division, Vancouver, British Columbia, 5 p.
1969b: Flood Frequencies of the Lower Fraser River; Department of Energy, Mines and Resources, Engineering Division, Vancouver, British Columbia.

Woods, P.J.
1996: Flood Protection Dykes and Environmental Concerns; Water Resources Branch, British Columbia Ministry of Environment, Lands and Parks, 20 p.

Impacts of future climate change on the Fraser River delta and its urban estuary

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Abstract: Increasing concentrations of greenhouse gases threaten to increase the average global temperature and total precipitation. Unchecked, the atmospheric concentration of carbon dioxide will have doubled relative to preindustrial times within the next 50–80 years. This may cause regional climate patterns around the world to change substantially. The magnitude and timing of these regional climate changes can only be estimated, making it difficult to accurately predict how physical and biological systems will change in the Fraser River delta or anywhere else in the world. Responses could range from a substantial rise in sea level that could threaten the dyking systems of the Fraser River delta, to an increased immigration pressure on the Fraser River delta from environmental refugees fleeing climate-change-ravaged homelands outside of Canada. Knowledge of the potential changes that might put pressure on the Fraser River delta will be useful in planning the development of the delta for the future.

Résumé : L'accroissement des concentrations de gaz à effet de serre risque de provoquer une élévation de la température moyenne du globe et une augmentation de la précipitation totale. Sans intervention, la concentration atmosphérique de dioxyde de carbone sera d'ici 50 à 80 ans le double de ce qu'elle était avant la révolution industrielle. Cette hausse pourrait provoquer des modifications importantes du régime climatique partout dans le monde. On ne peut qu'estimer l'ampleur et la chronologie de ces changements climatiques régionaux, ce qui complique la tâche de prévoir avec exactitude l'évolution des systèmes physiques et biologiques dans la région du delta ou ailleurs au monde. Les conséquences possibles vont d'une élévation substantielle du niveau de la mer, susceptible de menacer les systèmes d'endiguement du delta du Fraser, à l'accroissement de la pression d'immigration exercée par des réfugiés environnementaux fuyant des pays ravagés par les changements climatiques. La connaissance des changements éventuels qui pourraient exercer des pressions sur le delta du Fraser sera utile à la planification du développement de la région.

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INTRODUCTION

The distribution of all life forms on this planet has always been inextricably linked with the changing climate of the Earth. Hot and humid conditions in Alberta hundreds of million years ago nourished vast tropical wetlands that were home to strange reptiles, dinosaurs, and mammals. More recently, during the last glacial period, frigid conditions created kilometre-thick ice sheets that scoured much of North America, driving most plant and animal life well south of the 49th parallel. Even today, climate has a dominant influence on human life. Settlement patterns, housing, clothing, agriculture, transportation, and culture all reflect the influence wielded by climate.

SCIENCE OF CLIMATE CHANGE

The climate of a location is the assemblage of all the weather events of that location over a long period of time. Basic climate elements include the maximum, minimum, and average temperatures; rain and snow averages and extremes; and even wind-speed averages and extremes over time. These climate statistics can be based on hourly, daily, monthly, or annual values.

The climate of the Earth is controlled by what can be thought of as a giant heat engine. Feeding off the incoming energy from the sun, this engine generates winds, ocean currents, and precipitation. All of the sun's energy that enters the Earth's atmosphere eventually returns back to space (Hengeveld, 1995). These processes determine the climate. In a stable climate, the amount of energy leaving the atmosphere must balance the amount entering. If this balance is disturbed, the climate will change, and this change can be either abrupt or gradual.

Energy absorbed at the Earth's surface and in the lower atmosphere makes its way back into space in the form of outgoing infrared radiation; however, a small fraction of atmospheric gases (less than one per cent), along with clouds and other air particles, have the ability to intercept, reflect, and absorb some of this outgoing radiation before it escapes into space. The gases that absorb the outgoing radiation are called greenhouse gases because they act somewhat like an agricultural greenhouse by trapping heat in the atmosphere. The combined effect of these greenhouse gases and other absorbing particles is to dramatically warm the atmosphere. It has been calculated that the Earth's mean temperature would be 33°C colder if the atmosphere lacked this ability to absorb the outgoing radiation from the Earth's surface.

Unfortunately, there are clear indications that the balance between incoming solar radiation and outgoing infrared radiation is being disturbed by a continuous rise in atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2) due to emissions from human activities. This increased concentration is caused mainly by the burning of vast amounts of fossil fuels such as natural gas, petroleum, and coal and also by widespread forestry and agricultural activities. Unchecked, the concentration of the most important of the greenhouse gases, CO_2, will have doubled relative to preindustrial times within the next 50 to 80 years.

Theoretically, such an increased concentration of greenhouse gases should raise the global average temperature. Global temperatures rose 0.6 ± 0.2°C during the twentieth century (Climate Change 2001: the Scientific Basis, http://www.grida.no/climate/ipcc_tar/wg1/005.htm), and along the coast of British Columbia there has been a gradual rise in temperature of 0.4°C since 1900 (Gullett and Skinner, 1992). The Intergovernmental Panel on Climate Change has stated, "An increasing body of observations gives a collective picture of a warming world and other changes in the climate system" (Climate Change 2001: the Scientific Basis, http://www.grida.no/climate/ipcc_tar/wg1/005.htm).

CAN SCIENTISTS PREDICT THE FUTURE CLIMATE OF THE EARTH?

The atmosphere is a fluid composed of gases, water droplets, ice particles, and myriad other microscopic particles. Atmospheric scientists have developed a set of basic equations that can be used to describe the apparently chaotic behaviour of this fluid. With the help of powerful computers, these equations are combined to produce a mathematical representation of the atmosphere. This representation, called an atmospheric or weather forecast model, can be used to predict how the structure of the atmosphere will change over the next hours and days. Meteorologists from around the world rely on these atmospheric models to predict short-term changes in the weather and to produce daily weather forecasts.

Several different types of such weather forecast models have been developed since the 1960s. Most of the differences in these models relate to the way that the computers solve the basic equations; however, the capability of even the best of these weather forecast models to accurately predict weather more than four or five days in advance is generally very low. Nonetheless, these weather forecast models have been used as a basis for global climate models, which are mathematical representations of the Earth's climate. These global climate models can be used to estimate how the climate varies around the world. This estimation is done by including in the model more detailed information related to such factors as the greenhouse effect and seasonal changes in vegetation cover, sea ice, ocean temperatures, and ocean currents.

Powerful computers can run the climate models to simulate how the climate may vary over years, decades, and even centuries. Although the individual hourly or daily weather events that are predicted by the climate models are not an accurate forecast of the weather that will specifically occur throughout these long time periods, the models have been shown to simulate the present monthly and seasonal averages of temperature and precipitation correctly in most places throughout the world. Climate models are usually referred to as general circulation models. These general circulation models sometimes include a full mathematical simulation of the world's oceans in order to better simulate the entire climate

Table 1. Projections by three separate general circulation models for the change in temperature and precipitation in the Fraser River delta due to a doubled atmospheric CO_2 concentration. These projections disagree due to the way the models formulate and solve the atmospheric equations and to differences in the way climate processes are mathematically described.

GENERAL CIRCULATION MODEL	TEMPERATURE CHANGE (°C)		PRECIPITATION CHANGE (%)	
	Summer	Winter	Summer	Winter
Canadian Centre for Climate Modelling and Analysis (1992)	+3.3	+4.4	-7%	+40%
Goddard Institute for Space Studies (1995)	+1.5	+2.2	-5%	+5%
Geophysical Fluid Dynamics Laboratory (1991)	+2.7	+2.3	-25%	+7%

system, because the ocean has an important role in heating or cooling of the atmosphere as well as providing most of the atmospheric moisture.

General circulation models can be used to help predict how the climate might change during the next century due to increases in greenhouse gas concentrations. The concentration of carbon dioxide and other greenhouse gases in the model can be mathematically increased gradually or abruptly in order to estimate how these changes could affect the average monthly temperature and precipitation around the world. Results from these general circulation model experiments indicate that, as greenhouse gas concentrations grow, global mean temperature will likely rise by 1.4°C to 5.8°C over the period 1990 to 2100, a temperature increase greater than that experienced in the last 10 000 years (Climate Change 2001: the Scientific Basis, http://www.grida.no/climate/ipcc_tar/wgl/005.htm). Climate scientists at Environment Canada's Canadian Centre for Climate Modelling and Analysis have performed climate experiments using a general circulation model. The results from the general circulation model experiment project indicated that average temperatures in the Fraser River delta and much of the south coast of British Columbia will rise by 4°C to 5°C in winter and by 3°C to 4°C in summer by the end of the twenty-first century, due to increasing levels of greenhouse gases (Boer et al., 1992). These results also project that precipitation in the Fraser River delta could increase by 40% in winter while decreasing by 20 to 25% in May and June.

Adaptation to these 'average' changes in climate by the people and ecosystems of the Fraser River delta may not be an onerous problem; however, the indirect effects of these changes on the incidence and severity of occurrences such as flooding, summer drought, and decreased water availability and quality may be more problematic.

Though much work has gone into the formulation of general circulation models, scientists are still not entirely confident in these climate projections and, therefore, the model results are far from certain. Exercising caution is evident for climate projections from different general circulation models for the latter half of the twenty-first century based on a doubled carbon dioxide-CO_2 atmosphere. For example, Table 1 shows the per cent change in precipitation in the Fraser River delta projected by three different climate models under a doubled-CO_2 climate. Although all three general circulation models agree on the direction of the change in seasonal temperature and precipitation, there is disagreement on the magnitude of these changes, particularly with respect to precipitation. The reasons for these changes lie in the way that the models solve the basic atmospheric equations and how various climate processes are modelled mathematically. Until scientists can use these and other models to give a more accurate prediction of the future state of the climate in the Fraser River delta and elsewhere, society must plan for a wide range of possible changes.

PROJECTED CLIMATE OF THE TWENTY-FIRST CENTURY BASED ON INCREASED GREENHOUSE GAS CONCENTRATIONS

Figure 1 shows the monthly temperature and precipitation changes in the Fraser River delta projected by the Canadian Centre for Climate Modelling and Analysis general circulation model for a doubled concentration of CO_2 in the atmosphere. These changes might occur gradually over the next 80 to 100 years, or they could occur over a shorter time span if the state of the global climate was to shift suddenly. Atmospheric CO_2 concentrations are expected to double by the latter half of the twenty-first century in these model outputs.

Figure 1 shows that the model projects that the mean temperature will be warmer throughout the year with a doubled-CO_2 atmosphere. Winters will be wetter, whereas summers (May through September) will be drier. As measured at Vancouver International Airport, this means a winter (November through February) precipitation increase of 200 mm (rising from 600 mm to 800 mm) and a summer (May through September) precipitation decrease of 40 mm (falling from 240 mm to 200 mm).

The model results in Figure 1 also suggest that the fraction of winter precipitation falling as snow will be sharply reduced due to a changed climate. Assuming a standard atmospheric temperature decrease of 6.5°C per kilometre of altitude (Hess, 1959), the mean freezing level, which generally

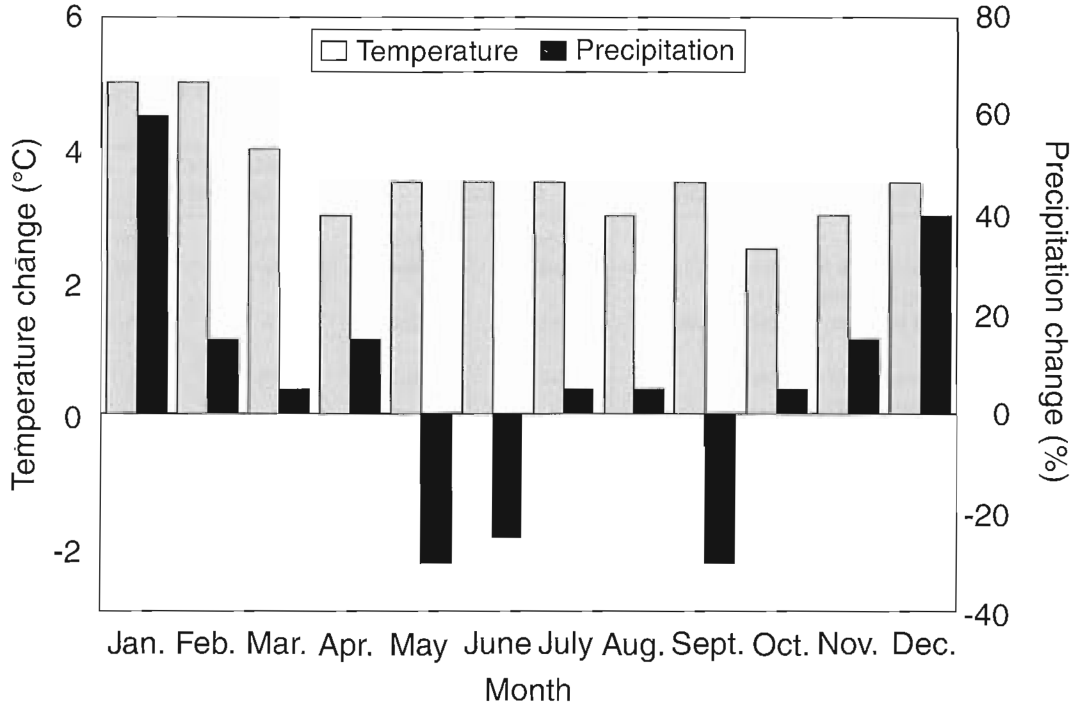

Figure 1. *Average temperature and precipitation changes projected by a Canadian Centre for Climate Modelling and Analysis general circulation model for the Fraser River delta for an atmosphere with a CO_2 concentration double that of preindustrial times.*

corresponds to the mountain snowline, in the Fraser River delta area could rise 500 to 800 m during the winter. This would cause much of the precipitation over the delta and the surrounding coastal mountains to fall as rain rather than snow. Snow events at sea level, now averaging about 15 days per year, could become relatively rare. Snow accumulation on the coastal mountains could be much reduced, with negative implications for summer water availability, hydrology, and winter recreation, as noted in the next section.

PROJECTED CLIMATE IMPACTS ON THE FRASER RIVER DELTA

If climate change occurs in the Fraser River delta as projected by general circulation models, there will be many local consequences. These include changes in water quantity and quality, stream and river flow, agriculture, human population health, sea level, fisheries, recreation and tourism, and extreme climatic events. Figure 2 summarizes some of these expected changes, which are discussed in detail below.

Water quantity and quality

Climate change may have significant impacts on water availability and quality for domestic and industrial use in the Fraser River delta. At the same time, population growth over the next 80 to 100 years will put increasing demand on the water-supply system.

The lower Fraser River valley is one of the fastest-growing regions in North America. Since the late 1980s, an average of 40 000 people have moved into the region annually. In 2000, the Greater Vancouver Regional District's population was 2.01 million. This population is expected to reach 2.7 million by 2021 (Livable Region Strategic Plan – Annual Report 2002, http://www.gvrd.bc.ca/growth/lrsp/lrsp-report2002.pdf). A continuation of this growth pattern would result in a population of 6 million by the latter half of the twenty-first century. Meanwhile, water consumption for the Greater Vancouver Water District rose from 460 ML/day in the 1960s to about 1100 ML/day in the late 1990s (Fig. 3). Assuming current per capita water consumption, the projected population growth alone would result in a quadrupling of the water demand for domestic and industrial use by the latter half of the twenty-first century.

Reservoirs that are dependent on local rainfall and snowmelt are the main water suppliers to people and industry in the Fraser River delta. If there are changes to the amount and timing of precipitation and snowmelt, the operation of these reservoirs may be impacted. Three reservoirs currently provide water to the Greater Vancouver Regional District: Capilano, Seymour, and Coquitlam. Three alpine lakes are used as supplemental reservoirs in the Seymour and Capilano watersheds. The Capilano and Seymour reservoirs currently each provide about 40% of the regional district's water demand. The reservoirs and alpine lakes are generally full to capacity in the spring, so that additional rain and snowmelt is

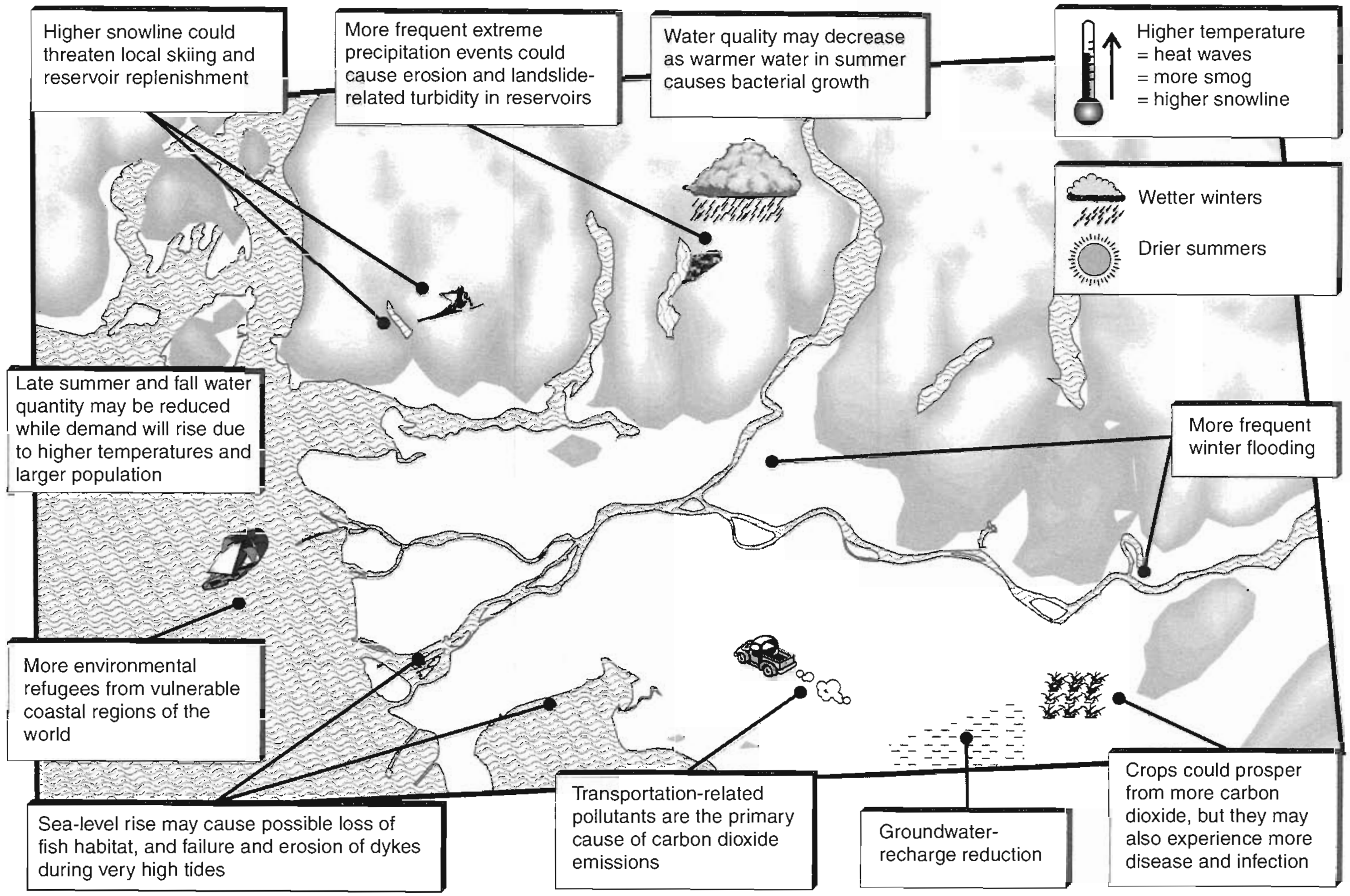

Figure 2. *Some potential impacts of future climate change in the lower Fraser River valley.*

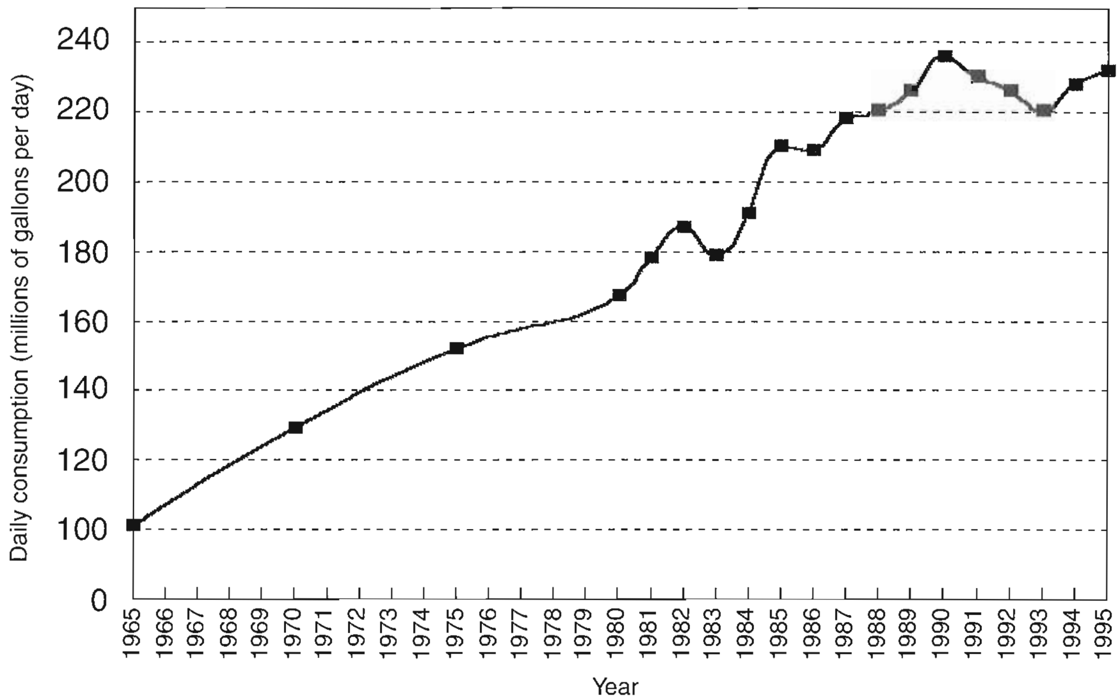

Figure 3. Average daily water consumption for Greater Vancouver from 1965 to 1995 (1995 Water Consumption Statistics Booklet, unpub. annual report from Greater Vancouver Regional District, 1995).

normally released over the dams until June or July (J. Morse, Greater Vancouver Water District, pers. comm., 1993). Reservoirs are drawn down due to water demand in the summer, usually reaching their lowest level in late September. They fill again to capacity during the winter and early spring.

If the climate changes as projected by the graphs in Figure 1, the reservoirs will likely fill earlier in the year than at present, because total winter precipitation is expected to increase significantly. The average snowpack in the reservoir watershed may be much lower or nonexistent by May 1, due to an increased fraction of mountainous winter precipitation falling as rain and to a higher winter snowline. This could lead to the drawdown of the reservoirs beginning earlier in the year, with little replenishment since snowmelt and May precipitation are expected to be 25% less abundant than at present. Due to increased temperatures after May 1, higher evapotranspiration and thus an increase in monthly water demand could occur until September if current per capita water consumption remains the same. Since the reserves of the Capilano and Seymour reservoirs sometimes already fall to 50% of their capacity, as happened in 1992 (Elsie, 1993), water resources in these reservoirs could fall to precariously low levels more frequently due to climate change. New water storage in the Coquitlam reservoir is expected to be added over the next decade to help alleviate this problem. Some of the Capilano water storage is presently being used by B.C. Hydro to generate power. Transfer of this water to the Greater Vancouver Water District will require the utility to purchase the lost power elsewhere. More investigation is needed to estimate how the reservoirs will be affected in the latter half of the twenty-first century by the combination of an earlier drawdown of the reservoir, a higher summer water demand, and a quadrupled population in the Fraser River delta region. Elsewhere in the province, climate-change-induced reservoir-level modifications also could have an impact on the production of hydroelectric power used by residents of the Fraser River delta.

The quality of the water supplied to the population of the Fraser River delta from mountain reservoirs may also be impacted by climate change. Temperatures are generally higher in shallow lakes than in deeper lakes in late summer. If the frequency of very low reservoir levels in late summer increases due to climate change, this would lead to increased average water temperature in the reservoir. Bacteria density in chlorinated tap water generally increases due to warmer water. The expected reservoir warming, in addition to the increased warming of the 500 km of supply mains and concrete storage reservoirs in the lower Fraser River valley due to increased ambient temperatures, could lead to a potential increase in the incidence of dangerous bacterial density in the water-distribution system of the valley. Planning is now underway to design rechlorination stations to deal with the current growth of bacteria in the water system (J. Morse, Greater Vancouver Water District, pers. comm., 1996). More study would likely be needed to assess whether these rechlorination stations are capable of adding sufficient chlorine disinfectant to the water to keep the bacterial regrowth in check in a warmer climate.

Water quality may also be adversely affected in fall and winter due to climate change. The turbidity of the water rises when naturally occurring landslides and soil erosion take place in the watersheds. This turbidity causes problems with both the appearance and quality of the water. This problem is compounded when heavy rain falls on snow in the alpine areas. Heavy rainfall causes rapid melting and instability of the snowpack. Avalanches and intense run off result in severe soil erosion on mountainsides, stream and river banks, logging roads, and the shores of the reservoirs. An example of this occurred on November 23, 1990, when 30 cm of rain fell over a 24-hour period, causing torrential run off, the erosion of stream banks, and landslides. In the month of November 1990, 145 cm of rain and snow fell in the watersheds compared to only 25 cm of rain at the Vancouver International Airport. Massive amounts of rain arriving at one time disturbs the exposed reservoir banks and stream beds and often causes much of the early-winter water-turbidity problems. If climate change causes the increase in winter precipitation shown in Figure 1, these kinds of turbidity and associated water-quality problems could be expected to increase in both frequency and intensity.

Climate change impacts on local streams in the lower Fraser valley

The hydrological system is potentially very sensitive to changes in climate. Changes in precipitation and temperature can change the timing of runoff and the frequency, duration, and intensity of droughts; however, due to the many uncertainties associated with the accuracy of the general circulation model (GCM) projections as well as to the lack of understanding of many hydrological processes, estimates of the effects of climate change on hydrology are uncertain.

General climate models are the basis for most experiments dealing with the impacts of climate change on hydrology. There is mounting evidence, after analysis of many general circulation model experiments, that a warmer climate will be one in which the hydrological cycle will in general be more intense (Climate Change 2001: the Scientific Basis, http://www.grida.no/climate/ipcc_tar/wg1/005.htm). One analysis of daily precipitation from five general circulation models simulating a doubled CO_2 climate found that there would be more frequent extreme summer precipitation events and an increased intensity of rainfall. Also, there is moderate confidence that, in general, the variability of river flows and the frequency of both high and low flows would increase with climate change.

All general circulation models project that average global precipitation will increase as temperatures rise; however, regional responses may vary considerably, with some areas likely to experience reduced precipitation.

The flow of low-elevation rivers and streams in the Fraser River valley is controlled mainly by high winter precipitation rather than by snowmelt. A recent investigation of the impacts of climate change on low-elevation streams in the lower Fraser River valley utilized the temperature and precipitation projections from the three separate general circulation models in Figure 1 for a doubled atmospheric CO_2 concentration (B. Taylor, unpub. report, 1996). Historical streamflow data from unregulated Kanaka Creek were used to develop a streamflow model. Monthly flow rates in Kanaka Creek are low, averaging 0.5 to 5 m^3/s through the year. In comparison, the Fraser River averages 900 to 5000 m^3/s . The results of the investigation were:

1. Flow rates in small streams like Kanaka Creek in the Fraser River delta area are much more sensitive to changes in monthly precipitation than to monthly mean temperature. In other words, a moderate increase in precipitation will have more of an effect on the flow rates of streams than a moderate increase in temperature.
2. All three climate model projections of a doubled atmospheric CO_2 concentration resulted in increased winter flow in small streams.
3. Two of the three climate model projections of a doubled atmospheric CO_2 concentration resulted in reduced summer flow rates in small Fraser River delta area streams. Because low water-flow rates generally lead to increased water temperatures, this also implies that summer water temperatures in Fraser River delta area creeks and streams would likely be greater.
4. The flow modelling for these small streams using doubled atmospheric CO_2 concentration revealed that the frequency of both very high-flow events and very low-flow events increased substantially under a changed climate.

The following conclusions could be drawn from these results regarding unregulated creeks near or in the Fraser River delta that are fed predominantly by rainfall rather than snowmelt:

1. Climate change may result in more winter flooding in and around the Fraser River delta and the adjacent slopes. Areas where forest cover and other vegetation has been removed may be more vulnerable to erosion.
2. Lower summer flow rates in small streams under a changed climate could hamper migrating fish stocks in the Fraser River valley due to both lower water levels and higher water temperatures.

Salmon stocks migrating up the Fraser River in the fall would also be affected as the river and its tributaries would likely experience lower flow rates and higher water temperatures (Levy, 1992). Also, since the fraction of winter precipitation falling as rain is expected to increase in the mountains surrounding the Fraser River delta, those creeks and streams that rely on snowmelt for a major portion of their flow would likely see a shift from spring to winter runoff (Intergovermental Panel on Climate Change Working Group II, 1995a, b). The major runoff peak of the Fraser River may also shift to an earlier time due to similar temperature increases in the watersheds of its tributaries in the British Columbia interior.

Warmer temperatures and the changing precipitation regime may result in lower groundwater levels in the Fraser River delta in summer and higher groundwater levels in winter (B. Hii, pers. comm., 1996).

Agriculture

Climate change would likely have both good and bad effects on agriculture in the Fraser River delta. Among favourable effects, a large number of experiments have shown that increased concentrations of atmospheric CO_2 have a fertilization effect on agricultural crops, increasing yields by 30% on average (Intergovermental Panel on Climate Change Working Group II, 1995a). Increased carbon dioxide concentrations have also been shown to improve water-use efficiency of crops; however, there is some evidence that plants may adapt to increasing levels of CO_2 and become less efficient at using the gas.

The growth of some crops such as perennials would benefit from a longer growing season, since the average frost-free season could begin up to five weeks earlier in the spring and extend for up to four weeks in the fall. Annual crops may not benefit from this lengthened growing season if spring and fall months are wetter than at present, which would inhibit planting and harvesting operations. The primary benefit of the extended growing season may be the possible introduction of a wider variety of crops into the Fraser River delta and surrounding area (B. Zebarth, Agriculture Canada, pers. comm., 1996).

Climate change could have a number of detrimental effects on agriculture in the Fraser River delta:

1. Most crops in the area currently are not irrigated. Higher temperatures and lower May through September rainfall would increase evapotranspiration and lower soil moisture. This could lead to substantial increases in both the area of land irrigated and the quantity of water used. If the spring freshet is reduced or occurs substantially earlier than at present, the subsequent lowering of the summer water table also would increase irrigation requirements (B. Zebarth, Agriculture Canada, pers. comm., 1996).
2. Weeds also would benefit from the effects of increased concentrations of CO_2.
3. Due to increased temperatures in the Fraser River delta, more insect pests could migrate from the United States, more insect species could overwinter in the delta and adjacent areas, insect growth rates could increase, and pests that currently have only one life cycle per season could complete two cycles (Intergovermental Panel on Climate Change Working Group II, 1995a). This could dramatically increase pest numbers in the Fraser River delta in late summer, and also in the spring if overwintering occurred due to milder winters (R. Vernon, Agriculture Canada, pers. comm., 1994).
4. Some crop diseases currently migrate to the Fraser River delta annually from the southern United States. A warmer climate would mean that these diseases would overwinter in more northerly states, so that the distance they need to travel to reach the Fraser delta would be shorter and they would arrive earlier in the year, thereby having a greater impact (B. Zebarth, Agriculture Canada, pers. comm., 1996).

Human population health

Human population health worldwide is anticipated to be affected by climate change. These changes would mostly be adverse (Intergovermental Panel on Climate Change Working Group II, 1995a; http://www.grida.no/climate/ipcc_tar/wg2-384.htm). Some of these worldwide impacts will be from increased frequency and intensity of heat waves. Extensive research has shown that heat waves cause excess deaths (Weihe, 1986). Extreme maximum temperatures of 37.5°C (Port Coquitlam, August 8, 1978) have been recorded in the urbanized area of the Fraser River delta (Environment Canada, 1981). Assuming that the maximum temperature will rise by the same amount as that expected of the mean temperature in summer (3.5°C), this would suggest that extreme maximum temperatures could reach 41.0°C in the Fraser River delta by the latter half of the century. This extreme temperature could be higher due to the urban heat island effect of a more densely populated region by the latter half of the next century. This possibility suggests that excess-heat-related deaths could occur in summer in the Fraser River delta due to increases in either the extreme maximum temperature of a summer or the length of heat waves.

Some vector-borne diseases such as malaria and vector-borne viral infections such as dengue may increase their range as climate changes. Dengue is a severe influenza-like disease which, in parts of Asia, is transmitted by the *Aedes aegypti* mosquito, now colonizing North America (Intergovermental Panel on Climate Change Working Group II, 1995a; http://www.grida.no/climate/ ipcc_tar/wg2/384.htm). Further investigation is needed to develop credible projections of the vulnerability of populations in the Fraser River delta to these kinds of diseases under climate change.

Air pollution is a public health issue in the lower Fraser River valley. The airshed in the valley is physically bounded on the north, east, and south by mountains. Under stagnant, stable meteorological situations when vertical mixing of the atmosphere is minimal, air pollutant concentrations near ground level gradually increase. This results in air quality advisories occasionally being issued to the public, particularly in summer during hot, relatively calm days. Air pollutants of concern include ground-level ozone in the summer and fine particulate matter all year round. Ground-level ozone and fine particulates are largely the result of air emissions from the transportation sector. Ozone and fine particulates have been shown to exacerbate asthma, impair lung function, and produce excess deaths in other jurisdictions (Beckett, 1991; Dockery et al., 1993; Schwartz, 1994). Annual health costs associated with air pollution in the Fraser River delta area were estimated at $830 million in 1990 and are projected to increase to $1.5 billion in 2005 (BOVAR-CONCORD, unpub. report, 1994; Fraser Basin Management Board, unpub. annual report, 1996). Since temperatures are expected to be higher in the Fraser River delta in a changed climate, this suggests that the warm stable atmospheric conditions that accompany very high temperatures could also be more frequent. These warm stable conditions are a critical component of elevated levels of ground-level ozone, because this pollutant is formed photochemically by the interaction of precursor chemicals and ultraviolet solar radiation under warm conditions. Stable atmospheric conditions also favour elevated concentrations of fine particulates. With the burgeoning population in the area, the supply of precursor pollutants and fine particulates, primarily from automobiles, will likely increase in the next 50 to 80 years. This suggests that the frequency of summer days with elevated concentrations of both ground-level ozone and fine particulates will increase and negatively impair human health in the Fraser River delta by the end of the next century. Combined with an aging population, this could cause the annual health costs associated with poor air quality to rise well beyond $1.5 billion during the latter half of the century.

In winter, concentrations of fine particulates increase under clear, calm, and cold conditions in the Fraser River delta. This meteorological situation usually occurs as a ridge of high pressure builds over the British Columbia interior and pushes cold, dry air westward over the Fraser River delta. The pollutant concentrations increase due to a combination of increased burning of fuels for space heating during cold days and the stable atmosphere near the ground under high-pressure areas and in cold, clear conditions. If climate change results in milder and wetter conditions in the Fraser River delta, as is projected by the general climate model of the Canadian Centre for Climate Modelling and Analysis, the frequency of these cold, clear conditions may decrease, resulting in fewer episodes of elevated concentrations of fine particulates in winter. This beneficial aspect of climate change could be offset, however, by the increasing emission rates from the transportation sector.

Sea-level rise

The lowlands of the Fraser River delta are one of the two coastline sites in British Columbia that have been identified as highly vulnerable to sea-level rise (J.R. Marko, unpub. report, 1994). The best current estimate for the expected rise in global sea levels due to climate change is 9 to 81 cm by the year 2100 (Intergovermental Panel on Climate Change Working Group II, 1995a; http://www.grida.no/climate/ipcc_tar/wg2/384.htm); however, this will be offset somewhat in the Fraser River delta by isostatic rebound, a process where the land continues to rise in response to the removal of glacial ice about 10 000 years ago. Because of this, the current estimate of sea-level change in the delta varies from a fall of 50 cm to a rise of 50 cm by the year 2100 (R. Thomson, unpub. report, 1997).

The lowlands of the Fraser River delta, including large parts of the municipalities of Richmond and Delta, are protected from the invading sea and from the Fraser River by an extensive system of dykes. These dykes may have to be reinforced due to sea-level rise; however, climate change would also cause changes in the intensity and timing of the Fraser River's peak flow in the spring. If the height of the peak flow decreases, this could offset some of the need for dyke reinforcements in the estuary. If the height of the peak flow increases, this could increase the need for dyke reinforcement.

Tidal wetlands and estuarine areas that would normally migrate inland as sea level rises would be unable to do so in many areas of the Fraser River delta because of dyke barriers. These wetlands represent critical waterfowl-wintering and fish-rearing habitats, and the reduction of their already limited area or productive capacity would be detrimental to these species (M.W. Dunn, unpub. report, 1988).

Sea-level rise in less developed countries could have an indirect impact on many developed areas of the world, including the Fraser River delta area. Forty million people in the developing world are now estimated to annually experience flooding due to storm surges under present climate and sea-level conditions. Anticipated sea-level changes due to climate change could increase this number to between 80 million and 120 million (Intergovermental Panel on Climate Change Working Group II, 1995a). This could lead to increasing pressure on developed countries to admit vast numbers of environmental refugees from around the globe.

Fisheries

The commercial and sports fishery is an important resource for the human population of the Fraser River delta. Climate change may have a marked influence on this resource, as fish production could be significantly altered as temperatures rise. Fraser River salmon, an important commercial and sports resource, would generally be negatively affected by climate change, particularly those species that rely on freshwater habitats for juvenile rearing that are located near the southern margin of their geographic range (Levy, 1992). This would be due both to changes in river flow caused by precipitation shifts in the interior and rising water temperatures, which adversely affect salmon in both early and late stages of their life cycle.

All salmon species spend the majority of their life in ocean environments. Experiments with general circulation models project that northeast Pacific Ocean sea-surface temperatures may rise 2°C to 4°C and that average wind speeds in the area will diminish. Calmer winds would lead to decreases in nutrient-rich ocean upwelling of cold waters from the ocean bottom. These nutrients maintain the population of zooplankton, a key element of the food chain for salmon in the ocean. Warmer sea-surface temperatures would mean a significant loss of thermal habitat area (the ocean area that is cool enough for fish to both survive and thrive) for at least one species important to the Fraser River: sockeye salmon. This would lead to lower salmon survival (S. Cox and S. Hinch, presentation at Canadian Conference for Fisheries Research, Ottawa, Ontario, January 6–7, 1995).

Since the mid-1970s, warmer sea-surface temperatures along the west coast of North America and changes in nearshore currents associated with more frequent El Niño events appear to have contributed to remarkable increases in the productivity of Alaskan salmon stocks and to declining runs of some salmon that spawn in Washington, Oregon, and California. In 1994, these trends culminated in an all-time record Alaskan salmon harvest and the complete closure of the once-thriving coho and chinook fisheries in Washington and Oregon . If climate change leads, as some scientists predict, to more frequent El Niño conditions, closures of southern rivers, including the Fraser River, to salmon harvesting could become more common.

Recreation and tourism

Climate change may both benefit and harm recreation and tourism in the Fraser River delta. Warmer, longer, and dryer summers would likely provide more recreational opportunities in summer and favour increases in tourism; however, recreational activities could be curtailed in winter due to increased rainfall in the delta area. Also, milder temperatures could lead to an increasing proportion of precipitation in the surrounding ski hills falling as rain rather than snow, resulting in shortened ski seasons. Table 2 gives the approximate height, above sea level, of ski hills in north and west Vancouver.

If the mean freezing level in the Fraser River delta were to rise in winter by an average of 500 to 800 m due to climate change, the mean snowline could, by inference, also rise by this amount. The mean snowline in the present climate averages about 800 to 900 m in January and February (Grouse Mountain Resorts, pers. comm., 1996). Climate change could increase this average snowline to between 1300 m and 1700 m. A January snowline of this elevation is effectively above all the ski runs of the north shore mountains and would result in the elimination of a viable skiing industry from this area without sufficient artificial snow-making.

Extreme climatic events

Climate change may result in a change of the frequency and severity of extreme climatic events such as heavy rain episodes. In the period 1950–1995, heavy rain episodes in the Fraser River delta, as characterized by a daily precipitation of more than 50 mm, occurred from October to early February (Fig. 4). The highest frequency of these events occurred from

Table 2. Height of main ski mountains near the Fraser River delta. The average snowline is estimated at 900 m for the current climate in January, and 1300 m for a changed climate.

Mountain	Height (m)	Elevation above average snowline in January in current climate	Elevation above average snowline in January in changed climate
Seymour	1468	568	168
Fromm (Grouse)	1182	282	0
Hollyburn	1344	444	44
Stron (Cyprus)	1476	576	176

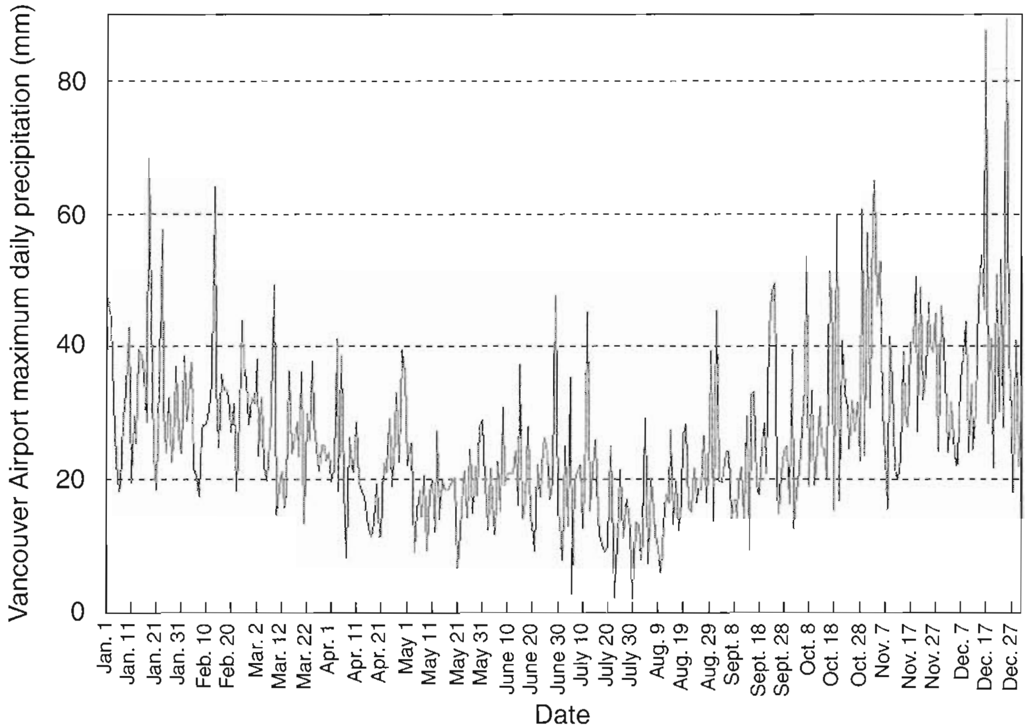

Figure 4. Maximum one-day precipitation at Vancouver International Airport, in the western section of the Fraser River delta, between 1950 and 1995.

late October to early November. The three general circulation models all project increased precipitation in the Fraser River delta in winter. If, as projected by the Canadian Centre for Climate Modelling and Analysis model, the majority of this increase occurs in December and January, then by inference the frequency of heavy rain episodes in December and January may also increase. This would result in increased flooding in low-lying areas of the Fraser River delta and in increased flow rates for small streams in the surrounding mountains, with a resultant increase in streambank erosion. Increased incidence of erosion around reservoirs would also lead to an increase in high-turbidity events in late fall and winter.

CONFRONTING FUTURE CLIMATE CHANGE IN THE FRASER RIVER DELTA

The issue of climate change can be addressed in a number of ways. The global atmospheric concentrations of greenhouse gases could be reduced or stabilized by improved industrial processes, better land-use practices, and a reduction in the burning of fossil fuels. The Framework Convention on Climate Change is an international effort attempting to achieve stabilization of greenhouse gas emissions early in the twenty-first century. Canada is a signatory to this convention, and domestic programs are now in place to support the convention. Municipalities in the Fraser River delta area could take meaningful steps to support Canada's contribution to responding to the climate change issue, including joining other metropolitan areas across the country in becoming a member of the '20 Percent Club'. Each of this group of cities has a goal of reducing their greenhouse gas emissions by 20% by the year 2005. In the Fraser River delta, burning fossil fuels, specifically in the transportation sector, has been linked to other environmental problems such as air pollution. Therefore, a reduction in burning fossil fuels would contribute to the improvement of other environmental and health concerns as well as reducing greenhouse gas emissions. Continuing the implementation of improved forestry and agricultural practices in the areas surrounding the Fraser River delta could both decrease the stress on a number of environmental sectors as well as reduce atmospheric greenhouse gas emissions.

Due to the significant increase in greenhouse gas concentrations that has already taken place since preindustrial times, and to the continuing anthropogenic emissions of these gases, some degree of climate change is already inevitable. Because of this, it may be wise for the population of the Fraser River delta and of its urban estuary to consider adapting to a climate that may cause some significant changes. Some sectors, such as agriculture, that are capable of responding relatively quickly to changes will be better able to adapt to a changed climate; however, other sectors, such as social infrastructure construction and maintenance, that require long-term planning and investment would benefit from the inclusion of climate-change adaptation measures into the planning process. An example in the Fraser River delta is water storage and distribution. If climate change threatens to disrupt water quantity and quality over the next 80 to 100 years, it may be beneficial to consider measures to address such threats. These could include: 1) controlling water use and land use; 2) devising incentives to conserve water and reduce per capita consumption; 3) improving and expanding water storage, distribution, and management systems; 4) increasing the available supplies of water, perhaps by the incorporation of the Coquitlam reservoir into the Fraser River delta water supply; and 5) improving the efficient use of water through better technology. Work on the last four of these measures is currently being planned in the Greater Vancouver Water District (J. Morse, Greater Vancouver Water District, pers. comm., 1996).

Other major projects that should include the issue of climate change in long-term planning are systems such as dykes, sewers, roadways, and railways that may be at risk due to climate-change-induced sea-level rise or winter flooding. Improvements or replacement of these structures, which have a lifespan of 50 to 100 years, could be expensive. For instance, S. Kitajima (unpub. report, 1993) estimated that the cost of protecting Japanese ports, harbours, and adjacent coastal areas against sea-level rise would total $92 billion.

Another activity that could be considered as indirect adaptation to climate change in the Fraser River delta is the support of foreign aid by residents of the area. The Intergovernmental Panel on Climate Change has noted that if climate change produces millions of refugees from developing countries under the present economic conditions, it may be beneficial for the developed world to deliver economic services and opportunities to the refugees' countries of origin over the next 50 years in order to reduce population migration (Intergovermental Panel on Climate Change Working Group II, 1995a).

CONCLUSIONS

The Intergovernmental Panel on Climate Change has stated: "An increasing body of observations gives a collective picture of a warming world and other changes in the climate system" (Climate Change 2001: the Scientific Basis, 15-11-2001, http://www.grida.no/climate/ipcc_tar/wg1/005.htm). Climate scientists, using general circulation models, project that the changes now being observed in the global climate will continue through the twenty-first century. All regions of the world, including the Fraser River delta, are expected to experience these changes, some to a greater extent than others.

The specific magnitude and timing of how climate will change in the Fraser River delta, and the extent to which these changes will impact human activities and environmental health, cannot be accurately predicted; however, climate scientists can give some approximate projections. These include a milder and wetter winter on average for the region, and a warmer, dryer, and longer summer season. These kinds of changes would affect a number of human activities and environmental sectors important to the residents of the Fraser River delta. Water for domestic and industrial use could be in shorter supply if additional storage is not provided to capture high winter runoff. Air quality may deteriorate due to more frequent atmospheric stagnation episodes. Sea-level rise and winter flooding could threaten dykes and other social infrastructure. Critical waterfowl-wintering and fish-rearing habitats in the estuary could be threatened by sea-level rise. The salmon fishery, relied upon by a large number of citizens of the Fraser River delta, could be at risk. Winter ski recreation in the local mountains could disappear. Population could soar due to increased immigration from climate-change-impacted nations.

By participating in national and international efforts to curtail greenhouse gas emissions, citizens of the Fraser River delta can do their part in reducing the climate change threat. Another benefit to these efforts is that measures to curtail greenhouse gas emissions often lead to improvements in other environmental areas, such as local air quality. Planning to adapt to some level of climate change in the Fraser River delta will be a prudent approach, because most climate scientists believe some change is inevitable. Projects that have long lifetimes will benefit most from the inclusion of climate change in their planning process. Acknowledging the very real possibility of future gradual or rapid climate change, and responding to it by including it in long-term planning decisions, will better prepare us for its effects and proactively prevent unduly large expenditures to repair or compensate for problems when they occur.

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REFERENCES

Beckett, W.S.
1991: Ozone, air pollution, and respiratory health; Yale Journal of Biology and Medicine, v. 64, p. 167–175.

Boer, G.J., McFarlane, N.A., and Lazare, M.
1992: Greenhouse gas-induced climate change simulated with the Canadian Centre for Climate Modelling and Analysis second generation general circulation model; Journal of Climate, v. 5, p. 1045–1077.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., and Speizer, F.E.
1993: An association between air pollution and mortality in 6 major U.S. cities; New England Journal of Medicine, v. 329, p. 1753–1759.

Elsie, B.
1993: Surrey/North Delta Leader, Surrey, British Columbia, June 1993.

Environment Canada
1981: Canadian Climate Normals, Temperature and Precipitation, 1971–1990, British Columbia, Environment Canada

Gullett, D.W. and Skinner, W.R.
1992: The State of Canada's Climate: Temperature Change in Canada 1895–1991; A State of the Environment Report, Environment Canada, Meteorologial Service of Canada, Downsview, Ontario, p. 20.

Hengeveld, H.
1995: Understanding Atmospheric Change; A State of the Environment Report, Environment Canada, Meteorological Service of Canada, Downsview, Ontario, p. 13.

Hess, S.
1959: Introduction to Theoretical Meteorology; Holt, Rinehart and Winston, New York, New York, p. 85.

Intergovernmental Panel on Climate Change Working Group II
1995a: Climate Change 1995, The Science of Climate Change; Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change; Press Syndicate, University of Cambridge, New York, New York.
1995b: Intergovernmental Panel on Climate Change Working Group I 1995: Summary for Policymakers; Press Syndicate, University of Cambridge, New York, New York.

Levy, D.A.
1992: Potential impacts of global warming on salmon production in the Fraser River watershed; Department of Fisheries and Oceans, Canadian Technical Report of Fisheries and Aquatic Sciences, number 1889.

Schwartz, J.
1994: Air Pollution and daily mortality: a review and meta-analysis; Environmental Research, v. 64, p. 36–52.

Weihe, W.H.
1986: Life expectancy in tropical climates and urbanization; Proceedings, WMO Technical Conference on Urban Climate; World Meteorological Organization, no. 652.

Urban environment and human health in the Lower Mainland

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Abstract: Three important population health issues for the Lower Mainland area are discussed. Variations in health status found across the Lower Mainland are outlined and given in greater detail within the City of Vancouver. Using a case study, issues in the quality of civic community in the Lower Mainland are addressed. The region's principal pollution-related public health issues are summarized. Two health problems associated with the chemical environment of the modern city have been demonstrated to pose large-scale threats to human health: lead exposures among children and threats to respiratory health from particulate air pollution. The paper argues that a willingness to respond to socio-economic disparities in health status in a constructive way, the level of awareness of significant local issues, and a willingness to tackle an issue (particulate air pollution) which imposes a significant health constraint on urban development are all tests of the quality of our civic community, and improving the quality of civic community should be an objective of urban development.

Résumé : Cet article traite de trois questions importantes qui ont trait à la santé de la population dans la vallée du bas Fraser. L'auteur y décrit les variations de l'état de santé dans l'ensemble de la région et, plus en détail, dans la ville de Vancouver. Par le biais d'une étude de cas, il traite de la qualité de la société civile dans la vallée du bas Fraser. Les principaux problèmes de santé publique liés à la pollution dans la région font l'objet d'un résumé. Il a été prouvé que deux problèmes de santé associés à l'environnement chimique de la ville moderne constituent des menaces à grande échelle pour la santé humaine : l'exposition des enfants au plomb, et les dangers que la pollution par les matières en suspension représente pour la santé respiratoire. L'auteur soutient que la volonté de réagir de manière constructive aux disparités de l'état de santé reliées à des facteurs socioéconomiques, le niveau de sensibilisation aux grands problèmes locaux, et la volonté de s'attaquer à un problème (la pollution par les matières en suspension) qui impose au développement urbain une importante contrainte reliée à la santé sont tous des critères de la qualité de notre société civile, et qu'un des objectifs du développement urbain doit être l'amélioration de cette société.

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INTRODUCTION

Variation in the level of population health by geographic region and socio-economic status is a feature of all wealthy societies (Evans et al., 1994). This observation might seem to suggest that health variations are of little interest to those wishing to improve the health of the whole population. If variation in health status is universal, one might argue it is probably immutable and, therefore, irrelevant to the task of improving population health; however, this inference would be wrong. It turns out the degree of variation in health status by geography and socio-economic status varies widely among wealthy societies (Kunst and Mackenbach, 1992). It is these differences in the level of health inequality that differentiate the relatively healthy and wealthy societies from the relatively unhealthy ones. Societies that have managed to minimize the variation in health status across geography and social class tend to be healthier on average than others that do not. In population health terms, it is said that these societies are doing the most (whether inadvertently or by design) to address the 'determinants of health'.

Recognizing variations in health status within the Lower Mainland is important, because the nature of these variations provides insight regarding the determinants of health. In particular, we are interested in the degree to which these variations relate to access to health care, environmental pollution, lifestyle and behavior, the quality of opportunity for healthy child development, and the effectiveness of civic community in promoting health and mitigating the health-damaging effects of social hierarchy. (The term 'civic community' is used here instead of the more familiar term 'social capital'. This choice has been made because social capital implies that the community characteristics at issue should be made to conform to the economists' concept of capital. This is not the intention of this paper, so the less technically loaded term 'civic community' will be used.) Civic community, as used in this paper, means those features of social organization, such as networks of learning and influence, social solidarity, trust, and institutional responsiveness, that facilitate co-ordination and co-operation for mutual benefit. Successful civic communities have been described as those that value solidarity, civic participation, and integrity, and where social and political networks are organized horizontally and not hierarchically (Putnam, 1993a).

Considering the determinants of health described above, differential access to health care in the Lower Mainland area is a marginal issue because the region enjoys universal access to care and high-quality health services are nearby for all residents. Instead, there are cultural barriers to access, based upon misunderstandings some individuals may have about their right to use the health system, its efficacy in relation to their health problems, and traditions of stoicism within some subcultures which lead to postponement of contact with the system. Regarding the other determinants of health, analysis of their impact is limited by the nature and quality of available data. This does not suggest that useful observations could not be made with respect to each of them, but rather that organizing the existing data would be a research project in and of itself.

It would be ideal to describe the variations in health status across the Lower Mainland and systematically account for them in terms of each determinant of health, but sufficient information does not exist to achieve this task in a thorough manner. Instead, this paper will define the scale of variations in health status across the region and provide insights into their origin when data permit. As a result, the paper is confined to three very important issues for which data are available for some part of the Lower Mainland area. First, it will outline the variations in health status found across the Lower Mainland and, because data permit, describe in greater detail variation within the Vancouver area. Second, using a case study, it will outline issues in the quality of civic community in the Lower Mainland. Finally, it will summarize the region's principal pollution-related public-health issues.

VARIATIONS IN HEALTH STATUS BY GEOGRAPHIC AREA

Lower Mainland

Figure 1 presents the 20 health regions of British Columbia as defined before the reorganization of late 1996 and shows the relationship between a composite socio-economic indicator as estimated for each region and age-standardized mortality as a representation of population health status. (It is readily acknowledged that there is more to health than the absence of death. Nonetheless, mortality has certain characteristics which make it an excellent surrogate for more multidimensional health measures. It is well measured, the data is well organized on a geographic basis, it is relatively invulnerable to reporting bias, and it correlates strongly with measures of morbidity and well-being; British Columbia Ministry of Health, 1996). Mortality by region increases with declining rank on the socio-economic indicator, as would be expected. The range of mortality is 44% from lowest (Richmond, second highest region on the socio-economic indicator) to highest (northern interior, second lowest on the indicator).

The seven regions of the Lower Mainland all score relatively high on the socio-economic indicator, and thus, are found on the left side of the figure; however, they do not cluster tightly around the 'best fit' line relating socio-economic status to health. Two regions, Richmond and the upper Fraser River valley, are well below the line. Two others, Vancouver and Simon Fraser, are well above it. North Shore, Burnaby, and Boundary are close to the line. In other words, Richmond and the upper Fraser River valley seem to be 'healthier' than expected on the basis of socio-economic status alone, whereas the reverse is true of Vancouver and Simon Fraser. There is strong evidence to support the notion that the principal determinants of health in wealthy societies are factors associated with socio-economic status. Thus, the character of the regions which are above or below the 'best-fit' line in Figure 1 is of great importance because they are either doing better or worse, respectively, than would be otherwise predicted on the basis of socio-economic status alone.

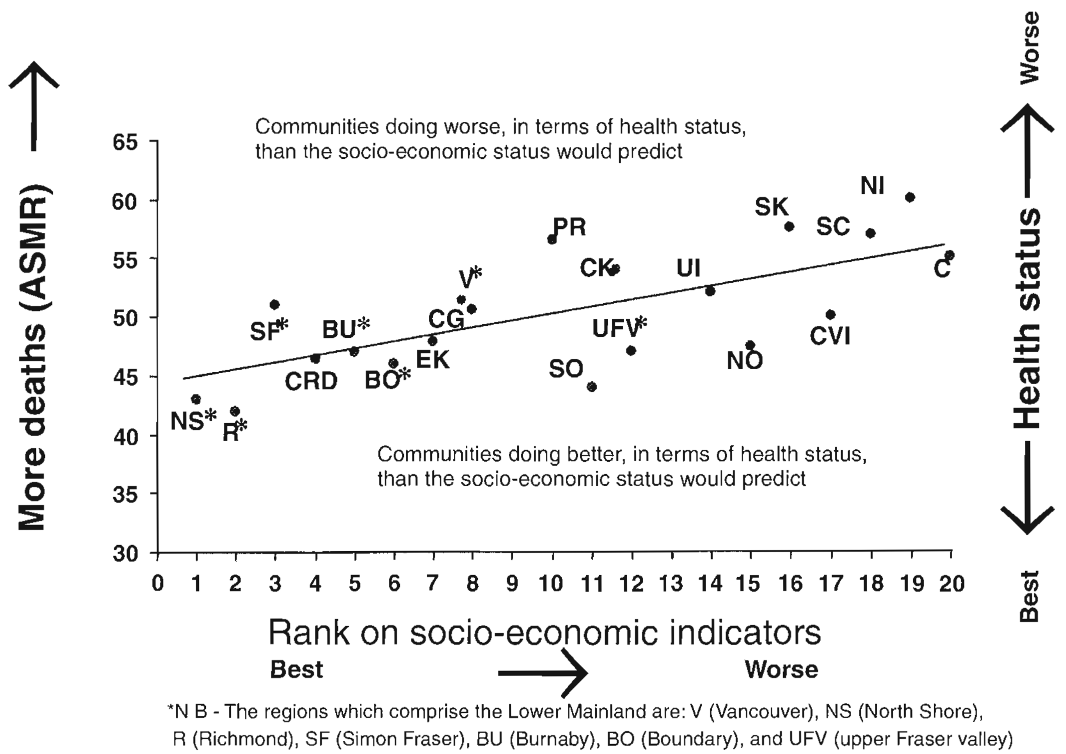

Figure 1. Age standardized mortality rates (ASMR) by health region in British Columbia, according to rank on an index of socio-economic status (British Columbia Ministry of Health, 1996).

Table 1 presents standardized mortality ratios, wherein the mortality rate for the whole province is set to 1.00, and the age- and sex-standardized mortality rates for each region of the Lower Mainland are presented as a ratio of that value. Whereas Figure 1 shows that Richmond and Simon Fraser are second and third, respectively, on the socio-economic indicator, Table 1 shows that standardized mortality is 22% higher in Simon Fraser than Richmond. This variation in mortality is not directly related to regional differences in socio-economic status, and so a crucial challenge is to determine its modifiable characteristics so that by addressing them local communities can be made healthier. From a 'determinants of health' perspective the community-level factors which support or undermine health at a given level of community socio-economic status are elements of civic community, and the range of variation in health status across regions with similar socio-economic status represents the maximum potential range of benefit from consciously improving the quality of civic community functions. Richmond, the principal community in the Fraser River delta, is an example of a healthy community in this sense. It is important to understand why this is so.

Table 1. Variation in mortality across the health regions of the Lower Mainland (British Columbia Ministry of Health, 1996).

Health region	Standardized mortality ratio (1990–1994)*
Richmond	0.87
North Shore	0.93
Boundary (Surrey–Delta–White Rock)	0.95
Upper Fraser valley	0.97
Burnaby	1.00
Vancouver	1.05
Simon Fraser (New Westminster and central Fraser valley)	1.06

*Standardized mortality ratio is based upon setting the age-and sex-adjusted rate of mortality for the province as a whole to 1.0 and scaling the rest as a ratio of this. Values less than 1.0 represent reduced mortality; those greater than 1.0 represent increases above the provincial average.

City of Vancouver

Consider the example of Vancouver, which is one of the communities doing worse in terms of health status than its socio-economic status would predict. Figure 2 shows the variation in mortality across neighbourhoods in the city based upon the standardized mortality ratio described above. The degree of variation in health status across neighbourhoods is much greater than among the regions of the Lower Mainland (British Columbia Ministry of Health, 1995). Mortality in the downtown area exceeds that in Dunbar by 114% after adjustment for age and sex. It turns out that all causes of death contribute to this pattern of variation. The range of mortality across neighbourhoods is 60% for heart and circulatory diseases, 45% for cancer, 133% for lung cancer, 161% for respiratory diseases, 292% for breast cancer, and 753% for accidents, suicide, and violence.

In general, the degree of variation is greater for diseases with a well defined behavioural component (e.g. lung cancer and accidents, suicide, and violence) than not (e.g. all cancers), but the pattern is not without contradictions. Breast cancer, for instance, does not have a well defined behavioural component, yet it shows a large variation across neighbourhoods. The neighbourhood pattern, however, is not the same as that for other diseases with a well defined behavioural component. Variations start at the beginning of life: there is a 68% difference between the lowest rate of low-birth-weight babies (4.1% in Kitsilano) and the highest (6.9% in the Downtown Eastside). This is important because low birth weight is a strong predictor of low subsequent health status.

Table 2 shows that there is a strong correlation between socio-economic characteristics and mortality by neighbourhood in Vancouver (British Columbia Ministry of Health, 1995). Could this be explained by a process of migration, wherein less healthy individuals congregate in particular neighbourhoods? With respect to HIV and/or AIDS and migration to the Downtown Eastside, the answer is certainly "yes." The level of variation in mortality from AIDS in Vancouver is sixty-fold, and the downtown neighbourhoods with AIDS services and facilities have the highest mortality; however, AIDS is the exceptional condition and the Downtown Eastside is the exceptional community. In general, the socio-economic 'gradient' in mortality by neighbourhood in Vancouver follows the same causal pathways as socio-economic gradients found across virtually all other jurisdictions in the countries of the Organization for Economic Co-operation and Development.

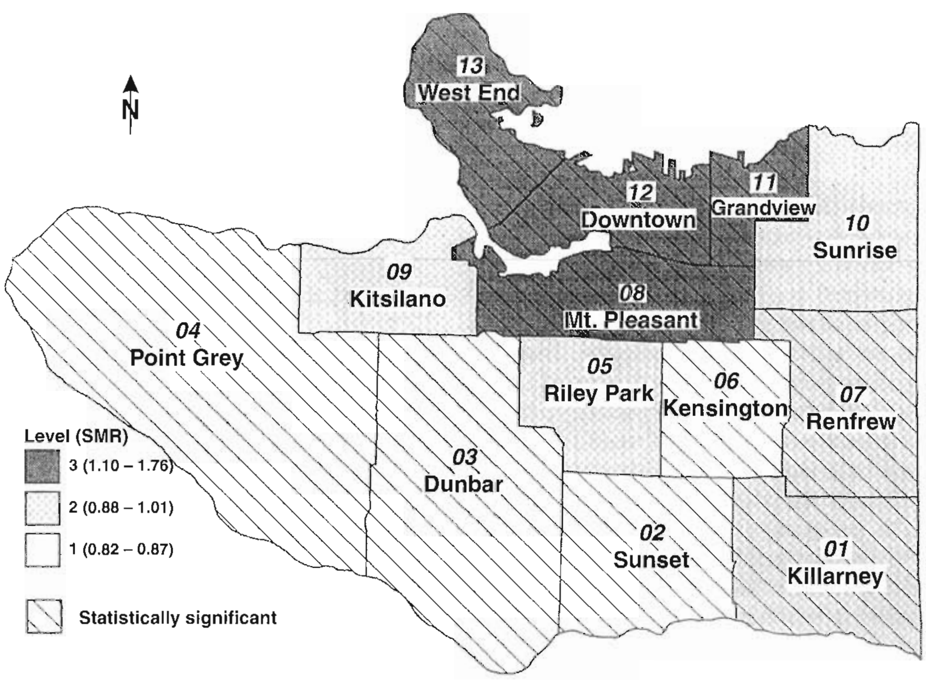

Figure 2. *Variations in mortality across neighbourhoods in Vancouver, 1990–1992. SMR = standardized mortality ratio. Data excludes deaths occurring in major and long-term care hospitals. Maps prepared by the Division of Vital Statistics (May 1995).*

Table 2. Mortality by socio-economic characteristics of neighbourhoods, 1990–1992 (British Columbia Ministry of Health, 1995). SMR = standardized mortality ratio.

Study area	All cause SMR	Average family income	Lone-parent families	Unemployment rate	Rented private dwellings	Less than grade 9 education	With university degree
Dunbar	0.82	1	1	1	2	1	1
Point Grey	0.83	1	1	1	1	1	1
Kensington	0.86	3	2	3	2	3	3
Sunset	0.87	2	1	2	1	3	2
Killarney	0.89	2	2	2	2	2	2
Renfrew	0.90	2	2	2	1	2	3
Kitsilano	0.93	1	2	1	2	1	1
Sunrise	0.94	3	2	2	1	3	3
Riley Park	1.01	2	3	1	2	2	2
West End	1.10	1	1	2	3	1	2
Mt. Pleasant	1.22	2	3	3	3	2	1
Grandview	1.39	3	3	3	3	2	2
Downtown	1.76	3	3	3	3	3	3

Note: The values of 1, 2, and 3 correspond to the 4 "best", 5 "middle", and 4 "worst" scores on each characteristic for each area.

Population health research over the last decade has shown that socio-economic status, as a nominal variable, represents very well the level of exposure to a series of stress factors, unfolding throughout the human life cycle, that gives rise to systematic variations in health status across the full range of disease, disability, and well-being (Hertzman and Weins, 1996); however, the 'steepness' of the socio-economic gradient in health status varies greatly from jurisdiction to jurisdiction. In some countries like Sweden and Japan, socio-economic gradients in health status are relatively shallow, and in others, like the United States and the United Kingdom, the gradients are very steep (E. van Doorslaer and A. Wagstaff, unpub. report, 1997). Those countries and jurisdictions with shallow gradients enjoy better health status on average than those countries with steep gradients. Moreover, the level of income equality within wealthy societies also matters. Societies with relatively high levels of income equality are healthier than those with more unequal income distributions (Wilkinson, 1992).

Most importantly, it has been shown, in a study of the 50 U.S. States, that the level of income inequality by state correlates strongly with social trust that in turn is a strong correlate of health status (Kaplan et al., 1996). In other words, societies which maintain a relatively equal income distribution have higher levels of social trust, lower levels of socio-economic variation in health status, and higher health status overall (Kawachi et al., 1997). Social trust is one of the key ingredients of the quality of civic community.

In Canada, the comparative study of health status, social trust, and income variations by community is in its infancy. It has been repeatedly shown that mortality varies in a predictable way by income level across census tracts in urban Canada, but little has been done to determine whether or not there are differences in the magnitude of this effect among Canadian cities. A quick comparison of 1991 census family income characteristics by census tract, done by the present author, shows that the range of income was twice as great in Greater Vancouver Regional Municipality as in Victoria. It also has been suggested that neighbourhood variations in health status do differ significantly between Canadian cities and that income disparities by neighbourhood in urban Canada have been increasing, too (Bourne, 1997). If so, the prospect is that urban Canadian regions, including the Lower Mainland, will become increasingly uncivic over time. Evidence of this would be found both in traditional indicators like crime and in the proliferation of 'opting out' behavior such as withdrawal of the elites from public education and the proliferation of gated neighbourhoods.

CIVIC COMMUNITY AND ENVIRONMENTAL HEALTH IN THE LOWER MAINLAND

This case study highlights the importance of connectedness with awareness of community issues among citizens of the Lower Mainland. These issues only represent one element of civic community, to be sure, but the case study demonstrates how much room for improvement there is and, in so doing, emphasizes the need to know more about the quality of civic community in the Lower Mainland.

The surveys discussed here were carried out in three communities in British Columbia which host or were slated to host waste incinerators. Cache Creek was the proposed site for a 'full service' hazardous waste management facility, the University of British Columbia campus was the proposed site for a medical waste incinerator, and Burnaby was the site of a municipal solid waste incinerator (Hertzman and Ostry, 1996). The initial purpose of our surveys was to identify community determinants of incinerator acceptability with a focus on health concerns; as the study progressed, however, it became apparent that we had misidentified the real issue, which was the way in which the level of awareness about local issues differed profoundly between the three communities. In particular, Cache Creek (the nonurban community) showed high levels of awareness while the urban communities did not. Recognizing this led us away from the consideration of waste incineration *per se* and to the issue of civic community.

The first survey was conducted in neighbourhoods at or adjacent to the University of British Columbia campus. In the fall of 1991, the university began a process of replacing a small, 20 year-old medical waste incinerator (MWI) with one capable of servicing both the university hospital and other British Columbia facilities producing medical waste. During the four months prior to the survey, the following public information activities occurred: three public meetings, 12 articles about the proposed medical waste incinerator (eight in local papers, one in a university newsletter, and two in major dailies), and a major mailout into the neighbourhood by a local environmentalist organization and a feature article in their newspaper. There was no major radio or TV coverage prior to the survey, and no special process of community involvement had yet been put in place, so the publicity was mostly in the form of the 'news item and reaction to the news item'.

Despite these efforts, the initial survey showed that the level of 'unsolicited awareness' of the facility was very low. Figure 3 shows that, of 265 survey respondents, only 18 (7%) were aware of the planned medical waste incinerator. Although this was somewhat surprising, there had been no public controversy up to this time.

In the interval between baseline and resurvey, the proposal became the subject of intense political controversy. A large amount of public information and/or involvement activities took place during this period. These included: three public meetings; 29 articles in newspapers and newsletters (nine in local papers, four in university newsletters, seven in the university student newspaper, nine in major dailies); a provincial election campaign in which opposition to the medical waste incinerator was a main plank in local New Democratic Party candidates' strategy (they won the election); a local ratepayers association mailout to all University Endowment Lands ratepayers; the summer 1992 appointment of a commissioner to hold public hearings and report on biomedical waste issues; and a community-based hazardous waste advisory committee set up by university planners.

Twenty months after the baseline survey, in the spring of 1993, we resurveyed the university respondents in order to determine the impact of the siting process over this time. Despite all the activity, the level of awareness in the community had not increased much. Figure 4 shows that of the 195 respondents still living in the area 20 months after the first survey and available for interview, only 23 (12%) demonstrated new awareness of the medical waste incinerator siting issue. Overall, 159 respondents (82% of the sample) still demonstrated no awareness.

It might be that this startling lack of awareness is due to the area's population transience. The study included one zone (the university endowment lands) where graduate students live, and 36 of the original 265 subjects had left the area by the time of the second survey; however, their level of awareness on the first survey was not significantly different from those who remained. Moreover, the 82% unawareness occurred among those who had remained in the area, of whom 62% owned their residence and can be presumed to have had a long-term interest in the community.

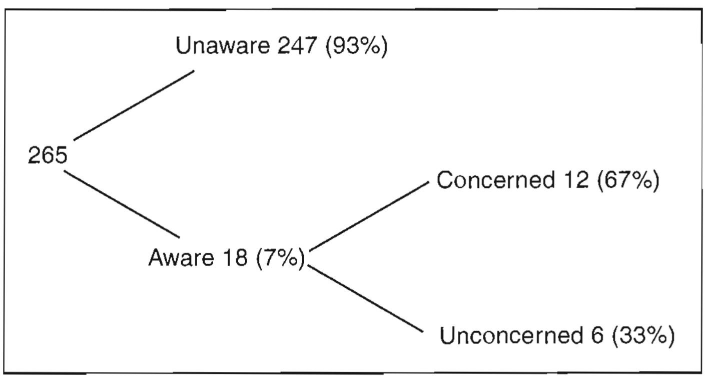

Figure 3.

Distribution of University of British Columbia respondents by awareness and concern about the proposed facility on the baseline survey.

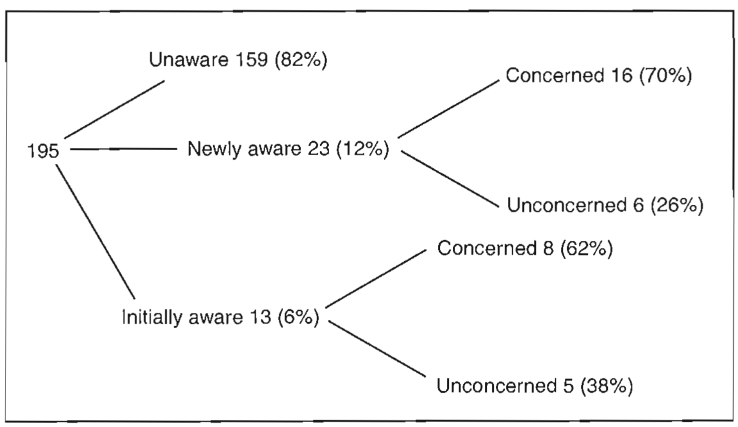

Figure 4.

Distribution of University of British Columbia respondents by awareness and concern about the proposed facility on the resurvey.

The next survey was conducted in Burnaby, where, in the early 1980s, a municipal solid waste incinerator was proposed at its southern boundary. Publicity surrounding the incinerator siting was most intense in 1985–1986. After limited opposition, the facility was constructed and started operating early in 1987. Since it opened, local community controversy has been minimal. Between December 1987 and July 1991, the Greater Vancouver Regional District Air Quality Management Division received only 75 complaints from residents, approximately 90% of which were about odours. The complaint rate fell by over 50% after the first two years of operation to approximately 12 complaints per year. In our survey, 37% of respondents were unaware of the incinerator, even though it had been operating in their community since 1987 and the incinerator stack was clearly visible from virtually all points in the study area.

The existence of these persistently unaware subgroups would have been difficult to predict without empirical evidence. Table 3 below shows that they are demographically different from the aware subgroup. They are more than ten times as likely to be renters; their average residence time in the neighbourhood is half as long (though still over ten years), and they are younger, more frequently female, more likely to be working, and less likely to be retired than the aware subgroup. Their level of connection to community networks also seems to be lower. In other words, the aware and the unaware groups differ in their level of civic engagement, a crucial aspect of civic community.

In the 1980s, two attempts were made to site a hazardous waste facility near Cache Creek. Figure 5 shows the distribution of respondents in the Cache Creek area by awareness and concern about the facility which was proposed but ultimately not sited in the area. It shows that 41% of the sample were aware of the proposed facility, a much higher proportion than at the University of British Columbia site. There was also a successful attempt to site a landfill in the area which would take waste from the Greater Vancouver Regional Municipality area. Awareness of this facility was in excess of 90% among the study sample.

Table 4 shows how the aware and unaware subgroups (with respect to the hazardous waste facility) differed with respect to sociodemographic factors and community networks. Once again, the unaware were more frequently renters than the aware group and were also more frequently female. More interesting from the standpoint of community process and communication is the fact that the two groups differed on four different measures of community networking: membership in a union, membership in one or more community organizations, reading the major provincial daily newspaper, and recently contacting an official. In each case, the unaware respondents were less involved in community processes than the aware.

Table 3. Characteristics for which there were statistically significant differences between those who were aware and unaware of the neighbourhood incinerator in Burnaby.

Socio-demographics	Aware	Unaware	(p)*
Per cent renters	3%	32%	<0.001
Mean number of years in neighbourhood	21.9	11.5	<0.001
Mean age (years)	54.6	45.5	<0.001
Sex (per cent female)	46%	65%	0.006
Per cent working	51%	70%	0.03
Per cent retired	36%	15%	0.03
Community networks	**Aware**	**Unaware**	**(p)***
Read major daily paper	74%	52%	0.007
Attended meetings in community	24%	10%	0.008
Contacted community official (for any reason)	22%	35%	0.04

* p-values based on Chi square for 2x2 contingency table when outcomes are expressed in proportions, and unpaired t-tests for continuous variables.

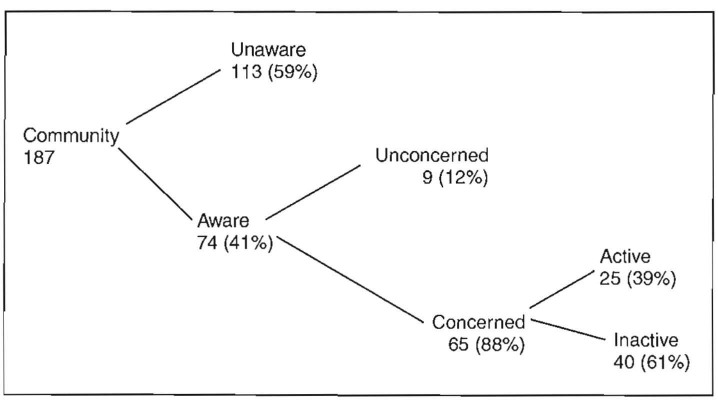

Figure 5.

Awareness and concern in the Cache Creek area in relation to the proposed, but withdrawn, hazardous waste facility.

Table 4. Characteristics for which there were statistically significant differences between those who were aware and unaware about the hazardous waste facility proposed for Cache Creek.

Socio-demographics	Aware	Unaware	(p)*
Per cent renters	5%	17%	0.02
Sex (percent female)	31%	46%	0.04
Community networks	**Aware**	**Unaware**	**(p)***
Per cent in a labour union	58%	37%	0.005
Per cent in community organizations	38%	22%	0.02
Per cent who read the major paper	30%	17%	0.04
Per cent contacting official	46%	31%	0.04

* p-values based on Chi square for 2x2 contingency table.

This case study shows that the level of citizen involvement in and awareness of community issues varies dramatically among regions of British Columbia. In particular, certain urban communities in the Lower Mainland seem to have a low level of civic engagement. Is this true across the urban region, or does it vary from community to community? If it varies, do the variations correlate with health status differences among communities with similar socio-economic status? Unfortunately, we do not have data available to answer these questions, but the variation in citizen involvement shown by this case study strongly suggests that having such data would be useful.

POLLUTION AND HEALTH IN THE LOWER MAINLAND

Pollution is important to consider in this paper for two reasons. First, certain forms of pollution have a direct impact on public health, making it a potentially important determinant of health in the urban environment. Second, the forms of pollution which affect human health are not only closely identified with urban environments but, at the same time, are remediable by planned modifications in urban form. Thus, the issue of pollution control in the urban environment is bound to the quality of civic community; the capacity to mount a co-ordinated effort to modify urban form in order to protect public health must surely be a valid test of the quality of civic community.

There is a wide range of substances used in industry and transport which are toxic to humans. Their toxic effects cover the full range of human pathology: cancer, respiratory disease, heart disease, dermatitis, hearing loss, and damage to the central and peripheral nervous systems. Workplace toxins can often enter the surrounding community primarily through airborne routes and at levels which affect the health of local residents (as described below); however, with a few prominent exceptions, workplace toxins rarely have a measurable impact on community health. This seems to be because stack and fugitive emissions (emissions that leave a plant by some route other than the engineered emission stream), although a possible threat to the general environment, are controlled well enough to keep their effects below an epidemiologically detectable level. Similarly, waterborne exposures rarely find their way into drinking water in concentrations that can be shown to cause human disease, and toxins brought home on work clothing affect a very circumscribed element of the population.

Human beings are not the most sensitive 'canary' for environmental pollution and degradation, but they are not immune either. There are two health problems associated with the chemical environment of the modern city which have been demonstrated to be large-scale threats to human health: low-level lead exposures among children and threats to respiratory health from particulate air pollution. In the Lower Mainland, lead is gradually becoming less of an issue, but particulate air pollution is of ongoing importance.

LEAD

Until the late 1960s, concerns over human exposure to lead in the environment were confined to high-dose exposures which resulted in acute symptoms such as intense stomach pain and seizures (Needleman and Bellinger, 1991). An occupational exposure limit of 80 mg/dL of lead in blood was meant to protect workers against such threats, and the guideline for children of 40 mg/dL was based upon similar considerations. Over the past 15 years, there has been an explosion of knowledge regarding the effects of long-term exposure to lead at much lower levels than those which cause acute symptoms. Among adult males, sperm counts appear to be adversely affected at blood lead levels as low as 25 to 40 mg/dL. Among females the principal concerns are increased risks of premature or low-birth-weight offspring. The National Institute of Occupational Health and Safety in the United States has set a target maximum occupational level of 25 mg/dL for the year 2000 for individuals of working age (Needleman and Bellinger, 1991).

Of much greater concern, however, are the effects on young children. The period of development from conception to age five is critical for the development of intellectual function in the growing child. The basic architecture of the brain is being laid down at that time, and the child's subsequent level of intellectual function and its life chances are profoundly affected by both chemical and 'psychosocial' influences. It turns out that the effects of lead mimic the effects of neglect and lack of stimulation. Intellectual function is reduced, and various 'neurobehavioural' barriers to learning, such as irritability and distractibility, increase. Intelligence Quotients (IQ) decline by 2 to 3 points for every 10 mg/dL increment in blood lead in early childhood (Baghurst et al., 1992). These effects have combined to reduce the school achievements of children exposed to lead, even in middle-class communities where a high premium is placed upon educational achievement. Moreover, there is no evidence of a lower threshold for this effect. Thus, exposures in the urban environment from point sources, transportation sources, contaminated soil, leaded paint, and lead water pipes are a public health concern for urban children.

In Canada, much like the United States, removal of lead from gasoline brought about a huge decline in the distribution of blood lead levels among children. Domestic paint with high lead content was not commonly used in Western Canada in the past, unlike some of the inner city areas of the eastern seaboard of the United States. In the Vancouver area, there are few industrial point sources of lead, and those that do exist are small. Lead in drinking water generally does not contribute significantly to total body burden, because of its low solubility in water. High lead concentrations in soil have been measured in Vancouver but are confined to narrow strips of soil within a few metres of high-volume intersections (Jin et al., 1995).

Because of these factors, it came as little surprise that a random sample of 172 Vancouver children aged 24 to 36 months, tested for blood lead in the fall of 1989 (Jin et al., 1995), revealed a mean blood lead level of only 6.0 mg/dL (0.29 mmol/L). Only one child had a blood lead level above 15 mg/dL. This level of lead exposure put Vancouver in the same range as some preindustrial societies, such as Nepal. By way of comparison, the mean blood lead level in Trail, British Columbia, the site of a large lead smelter, is above 10 mg/dL (Hertzman et al., 1991). In highly lead-contaminated communities in eastern Europe and Africa, average blood levels in children can range from 30 to 50 mg/dL (Hertzman, 1995; C. Hertzman, unpub. report, 1995). As would be expected, in areas of high lead exposure there is usually a socio-economic gradient such that lead levels decline with increasing status; however, in Vancouver there is virtually no socio-economic gradient of lead in children.

PARTICULATE AIR POLLUTION

Respirable particulates, regardless of their chemical structure, are a threat to human health. Table 5 summarizes current evidence regarding the dose-response characteristics of 'suspended particulates' with respect to six key respiratory and cardiovascular outcomes (Dockery and Pope, 1994). It shows that particulate exposures are associated in a causal fashion with major morbidity and mortality. The evidence is

Table 5. The health effect of variations in particulate air pollution (Dockery and Pope, 1994).

Health indicator	Per cent change per each 10 mg/m³ increase in PM_{10}*
Respiratory deaths	3.4
Cardiovascular deaths	1.4
Emergency department visits	1.0
Asthmatic attacks	3.0
Cough	1.2
Forced expiratory volume**	0.15

* PM_{10} is the fraction of suspended particulate matter less than 10 μg in mass median diameter.

** Forced expiratory volume is the volume of air that can be exhaled after a deep breath. It declines with increasing particulate air pollution.

Table 6. Suspended particulates in Canadian cities, 1987–1991 (Statistics Canada, 1994).

City	Annual average[1] (μg/m³)	Minimum[2]	Maximum[2]
Halifax	33.0	3.0	3.5
Québec	32.0	30	35
Montréal	47.6	28	106
Ottawa	39.7	27	55
Toronto	57.4	44	74
Hamilton	74.9	61	95
Winnipeg	40.5	26	56
Regina	35.4	20	53
Edmonton	48.7	39	72
Calgary	65.0	50	80
Vancouver	36.8	24	75

[1] Average of all readings taken over 5 years.
[2] Minimum and maximum based upon the 98th and 2nd percentile, respectively.

presented in terms of increased risk for a given increment of exposure because, like lead, no lower threshold of risk has been defined.

The implications for the Lower Mainland are indicated by Table 6. The table shows that whereas Vancouver is not a high-particulate area (cf. Hamilton), it nonetheless experiences particulate levels which are of public health significance. Control of transport, industrial, and fugitive sources of respirable particulates is a priority for the growing region of the Lower Mainland. In particular, policies that support population densification and reduced use of private motor vehicles can be seen as supporting population health.

CONCLUSIONS: HEALTH AND URBAN PLANNING IN VANCOUVER

All three of the issues raised above can be construed as challenges for civic community in the Lower Mainland. A willingness to respond to socio-economic disparities in health status in a constructive way, the level of awareness of significant local issues, and a willingness to address an issue (particulate air pollution) that imposes a significant health constraint on urban development are all tests of the quality of our civic community.

Putnam (1993b) has operationalized the concept of civic community through an index composed of measures of civic engagement, political equality, social structures of co-operation, and, finally, qualities of solidarity, trust, and tolerance. This index was applied to the regions of Italy, which showed marked variation in their index scores. In order to tell whether this construct was relevant to health, the present author obtained mortality data by region for Italy and compared it to the index scores. The results show that there is a strong association between increasing quality of civic community and decreasing infant mortality rates by region in Italy (proportion of variance, r^2, = 0.67 for 1951 data [$p<0.0005$]; r^2 = 0.49 for 1987 data [$p<0.005$]). Child mortality (ages 1–14), as a proportion of total mortality, is also lower in regions with a higher quality of civic community ($r^2 = 0.36$ for 1991 data [$p<0.01$]). Although there is no association with overall life expectancy ($r^2 = 0.11$ for the period 1986–1990), a startling pattern of sex difference emerges when life-expectancy gains are disaggregated by sex: quality of civic community is strongly correlated with gains in life expectancy for men, but not for women ($r^2 = 0.34$ for men [$p<0.01$], but only 0.02 for women, for the period 1971–1986). This raises important questions about the relationship between gender and the determinants of health, which are not the subject of this paper, but an avenue for future research.

The logic of the above analysis is that differences in the level of civic community may be predictive of differences in health status. But can this logic be reversed? That is, can differences in health status between defined geographic regions be used as the basis for a search for differences in the quality of civic community? This is a significant challenge for urban areas like the Lower Mainland of British Columbia.

Although the challenge sounds daunting, there is room for optimism. The idea of consciously striving to alter social arrangements in ways which improve health status is relatively new and little tried. In practice, it means a strong focus on intersectoral mobilization. Initiatives such as World Health Organization–Europe's Healthy Cities program (brought to Canada by Trevor Hancock and the Canadian Public Health Association as the Healthy Communities Program) are a first try at this. Acceptance of a population health perspective ought to be synergistic with the Healthy Communities approach and broaden and deepen the appeal of it.

The work of getting health and transportation authorities as well as town and social planners to adopt a common framework and then getting them to use it in their day-to-day work sounds like a difficult task, but it is a clearly defined one. In British Columbia, regional health boards have been put into operation. They have control of significant health expenditures and, also, have been given a population health mandate. Already the Vancouver–Richmond Health Board has been challenged, through its research advisory committee, to decide whether or not it would be willing to get involved in town planning decisions that may have an impact on population health. Whether or not this challenge is met will help determine whether the board fulfils its mandate or degenerates into yet another health services bureaucracy. Similar challenges need to be made in the context of transportation, town, and social planning in order to stimulate intersectoral activity.

REFERENCES

Baghurst, P.A., McMichael, A.J., Wigg, N.R.,Vimpani, G.V., Robertson, E.F., Roberts, R.J., and Tong, S.L.
1992: Environmental exposure to lead and children's intelligence at the age of seven years: the Port Pirie Cohort Study; The New England Journal of Medicine, v. 327, no. 18, p. 1279–1284.

Bourne, L.S.
1997: Social inequalities, polarization and the redistribution of income within cities: a Canadian example; Department of Geography, University of Toronto, Toronto, Ontario, 9 p.

British Columbia Ministry of Health
1995: Mortality and health status in Vancouver: an analysis by neighbourhood areas; Division of Vital Statistics, Victoria, British Columbia, 7 p.
1996: A report on the health of British Columbians: Provincial Health Officer's Annual Report, 1995; Office of the Provincial Health Officer, Victoria, British Columbia, 11 p.

Dockery, D.W. and Pope, C.A.
1994: Acute respiratory effects of particulate air pollution; Annual Review of Public Health, v. 15, p. 107–132.

Evans, R.G., Barer, M.L., and Marmor, T.R. (ed.)
1994: Why Are Some People Healthy and Others Not? The Determinants of Health of Populations; Aldine de Gruyter, New York, New York, p. 3–26.

Hertzman, C.
1995: Environment and Health in Central and Eastern Europe; The World Bank, Washington, D.C., p. 20–25.

Hertzman, C. and Ostry, A.
1996: Community risk perception and waste management in three communities at different stages in the siting process; *in* Hazardous Waste Siting and Democratic Choice, (ed.) Don Munton; Georgetown University Press, Washington, D.C., p. 273–289.

Hertzman, C. and Wiens, M.
1996: Child development and long-term outcomes: a population health perspective and summary of successful interventions; Social Sciences and Medicine, v. 43, p. 1083–1095.

Hertzman, C., Ward, H., Ames, N., Kelly, S., and Yates, C.
1991: Childhood lead exposure in Trail revisited; Canadian Journal of Public Health, v. 82, p. 385–391.

Jin, A., Hertzman, C., Peck, S.H.S., and Lockitch, G.
1995: Blood lead levels in children aged 24 to 36 months in Vancouver; Canadian Medical Association Journal, v. 152, p. 1077–1086.

Kaplan, G.A., Pamuk, E.R., Lynch, J.W., Cohen, R.D., and Balfour, J.L.
1996: Inequality in income and mortality in the United States: analysis of mortality and potential pathways; British Medical Journal, v. 312, p. 999–1003.

Kawachi, I., Kennedy, B.P., Lochner, K., and Prothrow-Stith, D.
1997: Social capital, income inequality, and mortality; American Journal of Public Health, v. 87, p. 1491–1498.

Kunst, A.E. and Mackenbach, J.P.
1992: An International Comparison of Socioeconomic Inequalities in Mortality; Erasmus University Press, Rotterdam, Netherlands, p. 9–14.

Needleman, H.L. and Bellinger, D.
1991: The health effects of low level exposure to lead; Annual Review of Public Health, v. 12, p. 111–140.
Putnam, R.D.
1993a: The prosperous community: social capital and public life; The American Prospect, v. 13, p. 35–42.
1993b: Making Democracy Work: Civic Traditions in Modern Italy; Princeton University Press, Princeton, New Jersey, p. 63–120.
Statistics Canada
1994: Human Activity and the Environment 1994; Minister of Industry, Science and Technology, Ottawa, Ontario, 187 p.
Wilkinson, R.G.
1992: Income distribution and life expectancy; British Medical Journal, v. 304, p. 165–168.

Atmospheric impacts of urbanization

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Jackson, P.L., 2004: Atmospheric impacts of urbanization; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 123–131.*

Abstract: When humans alter a natural landscape into an urbanized one, a number of atmospheric environmental impacts result. Perhaps the most potentially serious of these impacts is air pollution. In the 'chemical soup' which overlies the Fraser River delta region, people are most concerned about ozone and inhalable particulates because of their effects on the ecosystem (ozone primarily) and human health (ozone and particulates). Steps being taken by the regional government should reduce or at least stabilize air-pollution levels in the region.

Résumé : Lorsque l'on urbanise un milieu naturel, il en découle un certain nombre d'effets sur l'atmosphère, dont la pollution est peut-être le plus sérieux. Parmi les composantes de la « soupe chimique » en suspension au-dessus de la région du delta du Fraser, l'ozone et les particules inhalables sont celles qui portent le plus à l'inquiétude, à cause de leurs effets sur l'écosystème (surtout l'ozone) et sur la santé humaine (l'ozone et les particules). Les mesures prises par l'administration régionale devraient réduire, ou tout au moins stabiliser, le niveau de pollution atmosphérique dans la région.

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INTRODUCTION

Urbanization can have dramatic impacts on the atmospheric environment. Changes in the surface affect mainly the microclimate of a location, whereas emission of pollutants affects the chemical composition of the air itself. The surface changes affecting microclimate and resulting in changes to wind, temperature (urban 'heat-island'), and humidity are described in Jackson (2004). The effects of urbanization of the Fraser River delta region on the chemical composition of air — air pollution — will be discussed here. Government bodies responsible for management and monitoring of outdoor air pollution create administrative divisions termed 'airsheds' which are meant to be the atmospheric analog of 'watersheds'. In a watershed the difference between precipitation and evaporation is confined by gravity to mostly remain in that watershed until it leaves via a river. As an airshed has much more permeable boundaries, significant transport of pollutants can occur outside of the airshed boundaries. Notwithstanding this, for episodes of high pollutant concentrations, the watershed analogy is appropriate, as we shall see.

AIR POLLUTANT EMISSIONS AND AMBIENT CONCENTRATIONS

The primary pollutants of greatest concern in the Fraser River delta region are the oxides of sulphur (SO_x), the oxides of nitrogen (NO_x), volatile organic compounds (VOCs), and fine particulate matter (PM). Oxides of nitrogen and volatile organic compounds under appropriate meteorological conditions are precursors to the secondary pollutant, tropospheric ozone, which is one of the most dangerous pollutants affecting the region from ecosystem and human health perspectives. For many pollutants such as ozone, there are ambient concentration criteria dictated by the National Ambient Air Quality Objectives in three levels ranging from low to high concentrations: level A (desirable): long-term goal for air quality providing the basis for an antidegradation policy in unpolluted areas; level B (acceptable): to protect against effects on natural ecosystems and human well-being; and level C (tolerable): requires abatement without delay to avoid air quality that endangers lifestyle and public health.

Sulphur dioxide (SO_2) has a pungent odour which can be detected at concentrations less than 1 ppm. In high concentrations it can irritate the respiratory tract and aggravate cardiac and respiratory disease. The desirable and acceptable concentration levels are 170 ppb and 340 ppb, respectively, for hourly averages, and 60 ppb and 110 ppb, respectively, for daily averages (Greater Vancouver Regional District, unpub. report, 1996). Estimated SO_2 emissions in the region during 1990 (Greater Vancouver Regional District, unpub. report, 1996) are shown in Figure 1 and indicate that mobile sources (cars, trucks, and marine vessels) contribute approximately half of the emissions in the region with petroleum refining and other sources making up the remainder. Sulphur dioxide levels in the airshed are generally low, given the population density, primarily because natural gas is used for most space heating. A summary of the 1995 ambient concentrations is shown in Figure 2a. The one-hour desirable objective was exceeded only near the oil refineries at Port Moody which are the largest source of sulphur dioxide.

Oxides of nitrogen are produced by high-temperature combustion of fossil fuels and undergo chemical reactions in the atmosphere to produce nitrogen dioxide (NO_2). Nitrogen dioxide is a brown gas with a pungent odour which can cause acute and chronic respiratory disease, and its presence in the atmosphere can result in acid rain. It can take part in photochemical reactions to form ozone. The 'acceptable' concentration levels are 210 ppb for hourly averages and 110 ppb for daily averages. Over three quarters of the emissions of nitrogen oxides estimated for 1990 (Fig. 3) are from mobile sources (cars, trucks, and marine vessels). Nitrogen dioxide levels at all stations in the airshed are low, with no incidences of exceeding the ambient air quality objectives recorded in 1995 (Fig. 4).

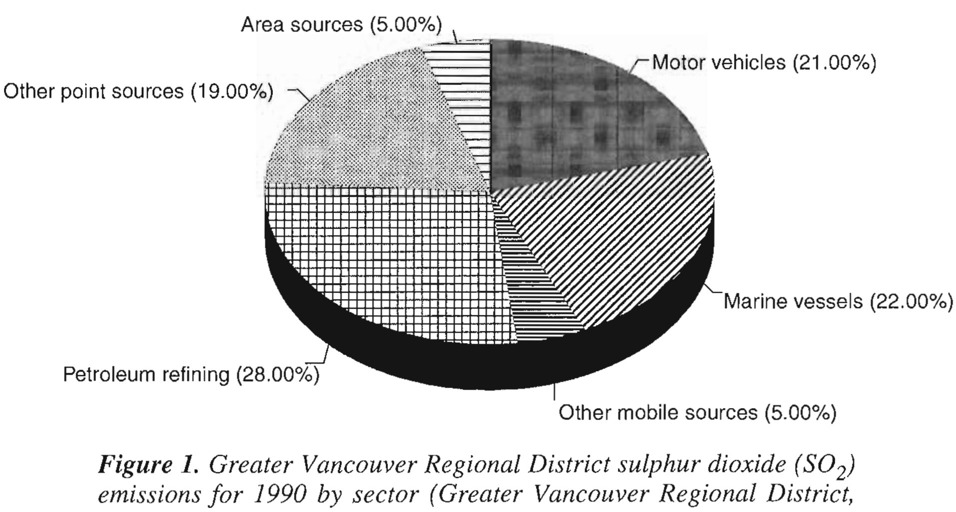

Figure 1. Greater Vancouver Regional District sulphur dioxide (SO_2) emissions for 1990 by sector (Greater Vancouver Regional District, unpub. report, 1996).

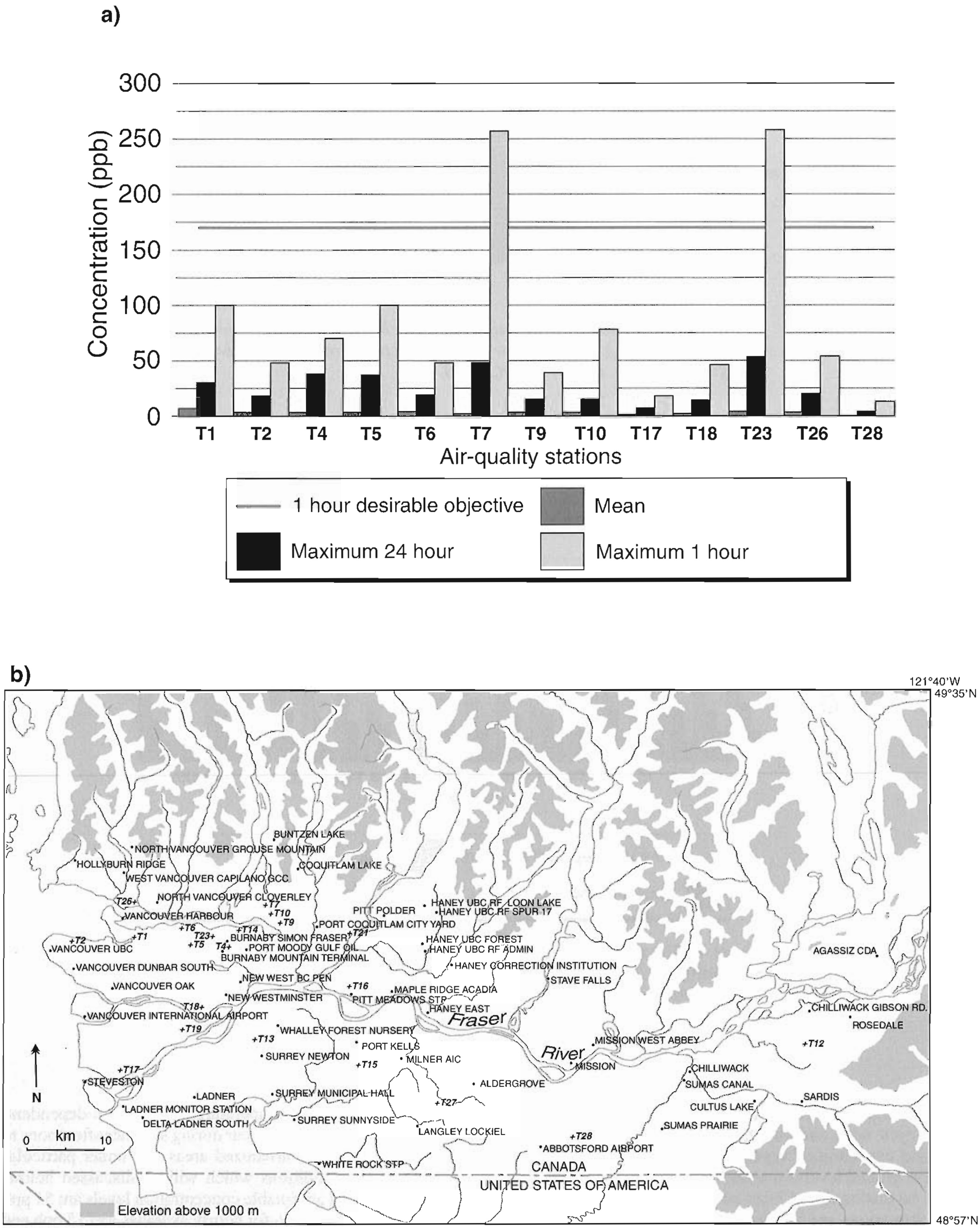

Figure 2. a) Greater Vancouver Regional District sulphur dioxide (SO_2) monitoring, 1995. b) Monitoring station (Txx) locations (Greater Vancouver Regional District, unpub. report, 1996).

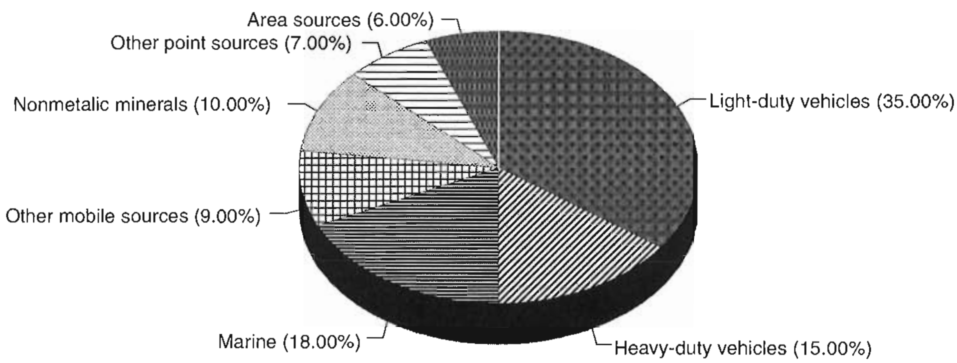

Figure 3. Estimated 1990 Greater Vancouver Regional District oxides of nitrogen (NO_x) emissions for 1990 by sector (Greater Vancouver Regional District, unpub. report, 1996).

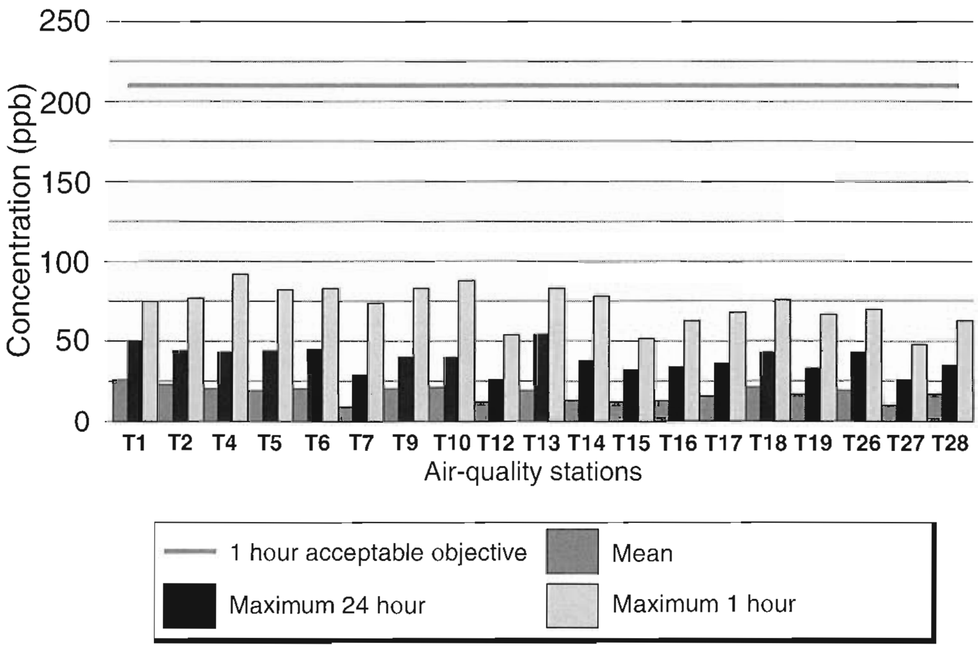

Figure 4. Greater Vancouver Regional District nitrogen dioxide (NO_2) monitoring for 1995. Station (Txx) locations are shown in Figure 2b (Greater Vancouver Regional District, unpub. report, 1996).

Ozone is a highly reactive form of oxygen which can irritate the eyes, nose, and throat; can aggravate respiratory disease; and can damage vegetation and reduce crop yields. Ozone at ground level is a serious environmental hazard but should be distinguished from stratospheric ozone (ozone at 10–50 km above sea level), which is beneficial because it absorbs harmful ultraviolet radiation before it reaches the Earth's surface. Ozone forms when nitrogen oxides and volatile organic compounds react in the presence of sunlight. Because the reaction is temperature- and sunlight-dependent, maximal values typically occur during summer afternoons to the east of the major urbanized areas and under particular meteorological conditions which will be discussed below. The desirable and acceptable concentration levels are 51 ppb and 82 ppb, respectively, for hourly averages and 15 ppb and 25 ppb, respectively, for daily averages. Figure 5 summarizes the ambient ozone concentrations during 1995.

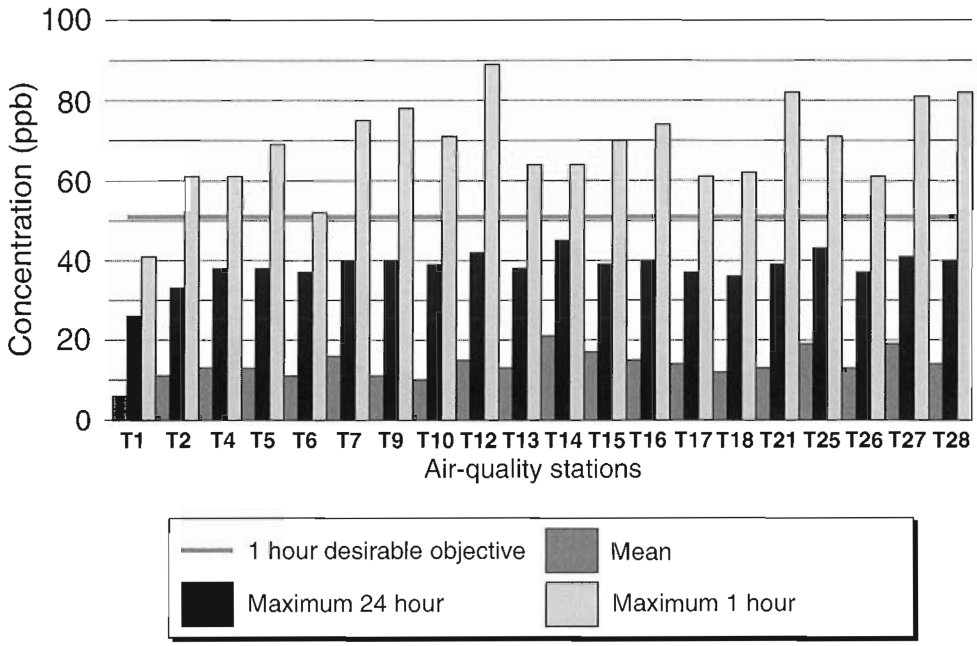

Figure 5. *Greater Vancouver Regional District ozone (O_3) monitoring for 1995. Station (Txx) locations are shown in Figure 2b (Greater Vancouver Regional District, unpub. report, 1996).*

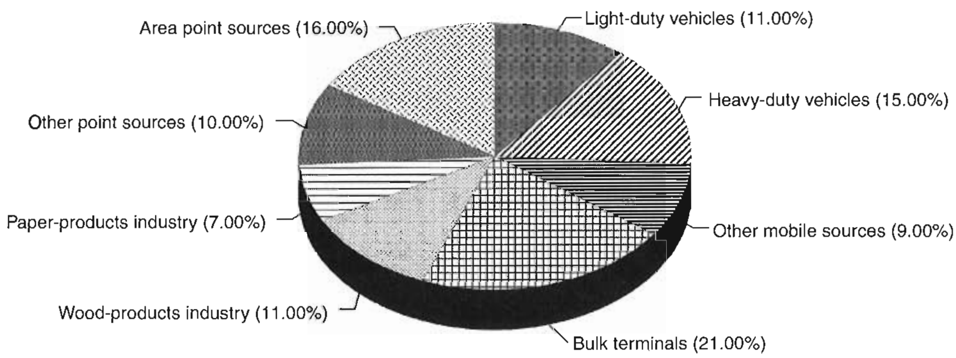

Figure 6. *Estimated 1990 Greater Vancouver Regional District inhalable particulate (PM_{10}) emissions by sector (excluding road dust) (Greater Vancouver Regional District, unpub. report, 1996).*

A pollutant of emerging concern is particulate matter less than 10 μm (PM_{10}) and especially less than 2.5 μm ($PM_{2.5}$) in diameter. Particles larger than 10 μm are not inhalable (by lodging in the nose and throat) and are less of a health concern. Particles smaller than 10 μm can enter the lungs, with finer particles generally penetrating deepest into the lungs and causing potentially more damage. While the exact mechanism allowing particles to damage lungs is not known, there is good epidemiological evidence from many studies that increased PM_{10} concentrations are associated with increases in mortality and hospitalizations from respiratory and cardiac disease (Vedal, 1995).

Particulate matter around 10 μm and larger is normally associated with natural sources (e.g. windblown dust); however, $PM_{2.5}$ arises mainly from human activity such as industrial and residential burning and from motor-vehicle combustion. 'Acceptable' ambient concentrations for PM_{10} are 50 μg/m^3 and 30 μg/m^3 for 24 hour and annual averages, respectively. Recent evidence, however, indicates that there are health effects at concentrations as low as 20 μg/m^3 (Vedal, 1995). Figure 6 shows the inhalable particulate emission inventory for 1990, and Figure 7 shows the mean and maximum concentrations during 1995. The highest concentrations occurred in the Abbotsford and Chilliwack areas during a

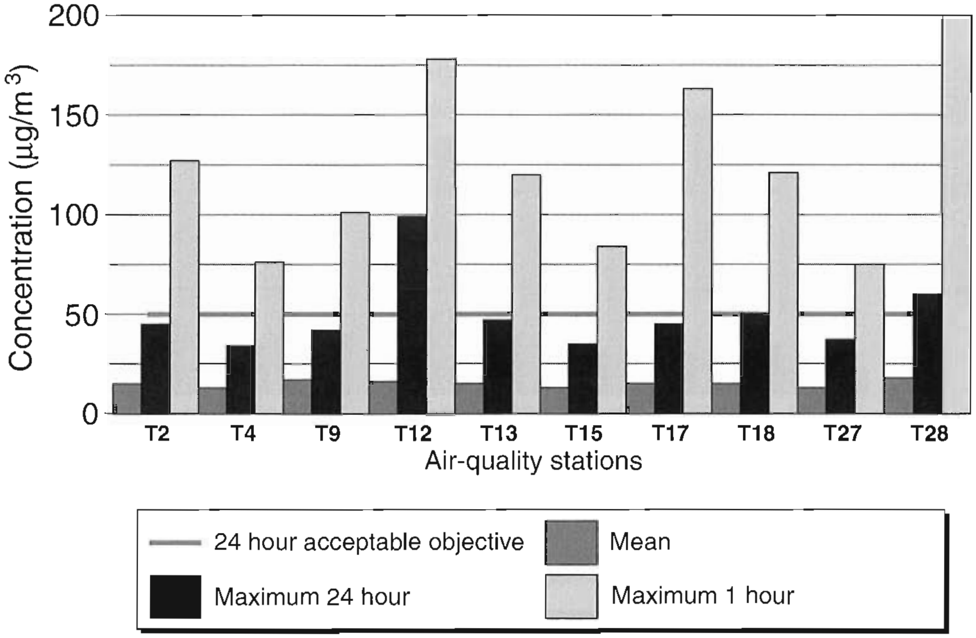

Figure 7. *Greater Vancouver Regional District 1995 inhalable particulate (PM_{10}) monitoring. Station (Txx) locations are shown in Figure 2b (Greater Vancouver Regional District, unpub. report, 1996).*

stagnant period in late summer and during a high-wind episode of windblown dust in winter. A similar pattern occurred during 1994.

Vedal (1995) estimates that there is a 1% increase in daily mortality for each 10 $\mu g/m^3$ increase in ambient PM_{10} above 20 $\mu g/m^3$. He estimates that for the Greater Vancouver Regional District, PM_{10} increases each year account for 10.2 extra deaths, 9.0 extra respiratory hospitalizations, 7.9 extra cardiac hospitalizations, 2.2 extra asthma hospitalizations, 37.0 extra emergency room visits due to asthma, 9.3 extra emergency room visits due to chronic obstructive pulmonary disease, 57 894 extra restricted activity days, 18 306 extra school absences, 21 603 extra child-days with upper or lower respiratory symptoms, and 8787 extra child-days of cough.

In addition to air pollution with immediate impact on the Fraser River delta region, there are considerable greenhouse gas emissions from the area which most scientists agree are contributing to global climate change. Greenhouse gases are radiatively active in the atmosphere — they absorb the infrared radiation emitted by the Earth's surface and re-radiate much of that energy back to the Earth, thus increasing the Earth's surface temperature. This natural process is being inadvertently enhanced by the 'extra' greenhouse gases emitted as a consequence of human activity. The main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and various chlorofluorocarbons (CFCs). Anthropogenic CO_2 and N_2O are emitted primarily by combustion associated with urbanization of the region. Methane is emitted in significant amounts by landfill sites and by wetlands in the delta. The impacts of global climate change are presented by Taylor (2004).

ATMOSPHERIC CONTROLS OF AIR POLLUTION

Pollutants emitted into the atmosphere are transported and dispersed in the downwind direction by the wind and diffused in the vertical and crosswind directions by atmospheric turbulence. The amount of turbulent dispersion increases as the wind speed increases and decreases as the atmosphere's stability increases. The atmosphere's stability is its ability to overturn and is related to the vertical temperature profile. Because cold air is more dense than warm air, situations where the temperature increases with height (called 'inversions') are very stable, with severely limited dispersion of pollutants. One therefore expects the worst pollution on days with light winds and stable and/or inversion conditions. Some pollutants undergo chemical and photochemical reactions in the atmosphere to produce secondary pollutants such as ozone; therefore, the ambient concentration at a particular location is due to a combination of the amount and configuration of the emissions, details of the meteorology (wind direction, wind speed, atmospheric stability, and aerodynamic roughness), and details of any chemical reactions which may occur, including processes of pollutant removal. Because the production of ozone requires sunlight and warm temperatures, it can reach high concentrations during the summer months under anticyclonic meteorological conditions (i.e. weather dominated by high-pressure systems). During these often stagnant conditions, regional winds are light, allowing sea-breeze–land-breeze and mountain-valley local circulations (*see* Jackson, 2004, Fig. 5) to dominate the weather pattern. These local circulations tend to recycle air within the airshed; for example, the sea breeze brings air from

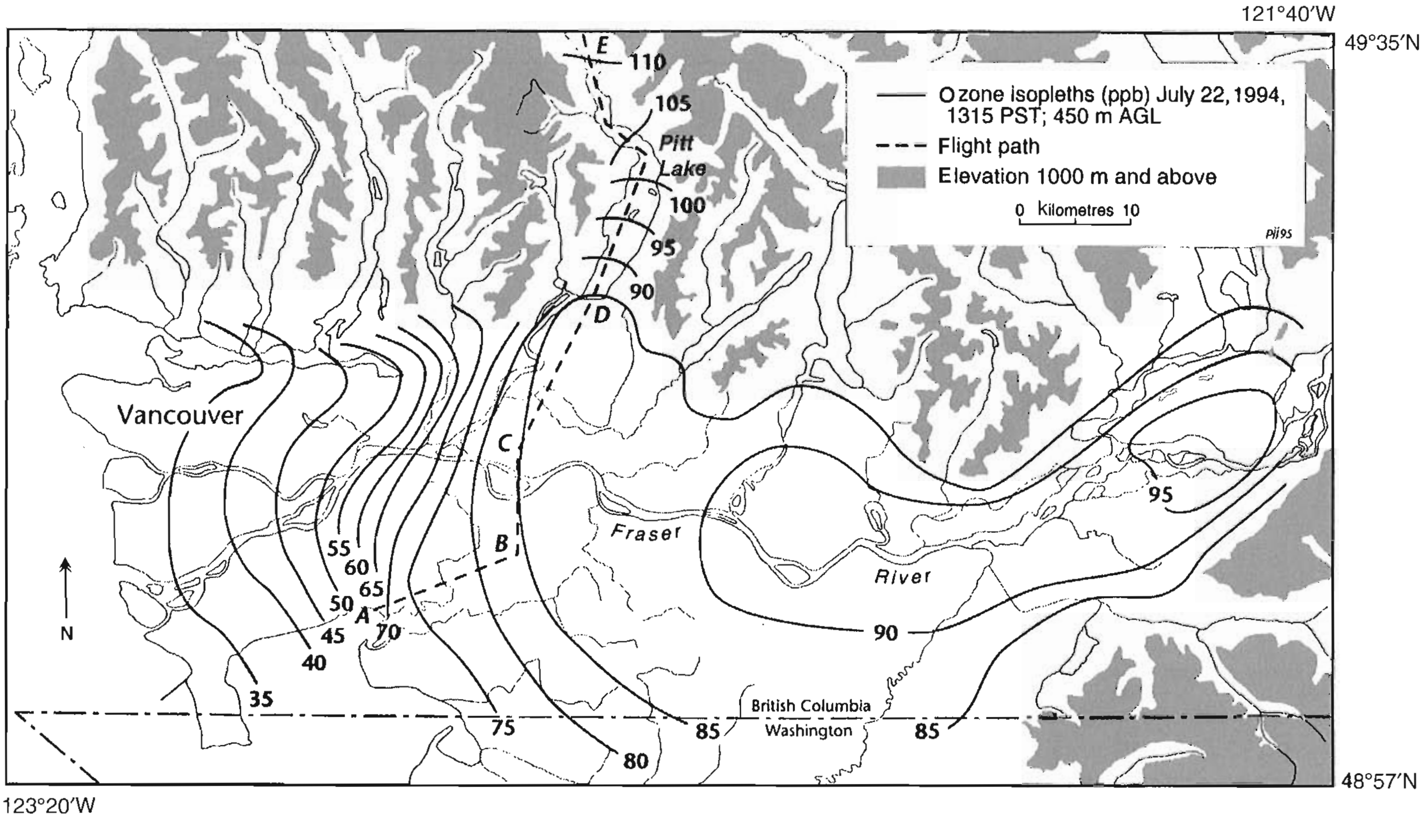

Figure 8. Ozone isopleths measured from an aircraft at 450 m above sea level during an ozone episode on July 22, 1994 (O'Kane, 1997).

Georgia Strait onto the delta by day, but the land breeze brings the same air back out over the delta by night, with the cycle repeated the next day. This 'sloshing' back and forth with limited mixing of fresh air can result over a number of days in a buildup of pollutant concentrations and an ozone episode. This is especially true if these conditions are combined with stable conditions and a shallow mixed-layer depth (the vertical zone in which pollutants emitted near the surface are effectively mixed in the atmosphere). Figure 8 (O'Kane, 1997) shows aircraft-observed ozone concentrations at 450 m above sea level during an ozone episode which occurred on July 22, 1994. Peak ozone values in excess of 100 ppb are noted in the vicinity of Pitt Lake, with elevated values also in the eastern lower Fraser River valley. The highest concentrations are east of the regions of highest population and pollutant emissions. The sea breeze carries the ozone precursors (oxides of nitrogen emitted mostly by vehicles and volatile organic compounds) eastward during the morning and afternoon when the ozone-forming reactions take place, resulting in peak concentrations to the east of most emission sources. Similarly, anabatic (upslope) winds (*see* Jackson, 2004) carry the ozone precursors up side valleys like Pitt Lake, Stave Lake, and Harrison Lake during the day. At night, the ozone-forming reactions that require sunlight do not occur. The remnant ozone-rich air can be moved back to the west by the land breeze and moved downslope by katabatic winds. It also can be left as an elevated polluted layer that is isolated from the ground by an inversion created by nocturnal surface cooling. In both cases the ozone-rich air from the previous day is often left in the airshed to form part of the next day's 'chemical soup'. For this reason, high-ozone episodes occur over several days with ozone concentrations building on each subsequent day. These episodes are terminated when weather conditions change to increase regional winds that 'flush' polluted air from the valley. Ozone trends in the region are downward, as indicated in Figure 9, although this may be an artefact of the monitoring network not adequately sampling ambient conditions in the eastern lower Fraser River valley and up tributary valleys such as Stave Lake, Harrison Lake, and Pitt Lake along the north shore mountains.

An added consequence of urbanization in the Fraser River delta region related to pollutant emission is the reduction in visibility due to air pollution. This is particularly noticeable during summer under calm conditions when photochemical smog forms a brownish layer within the planetary boundary layer (below about 1 km elevation). The haze can reduce horizontal visibility and obscure views of the surrounding mountains. Analysis of light scattering due to particulates from Rocky Point park (location T9, Fig. 2b) between 1986 and 1992 by Pryor et al. (1994) indicates reduced visibility in winter compared to summer that was thought to be due to increased emissions (e.g. wood-fired space heating), increased frequency of inversions during winter, or increased suspension of natural sea-salt aerosols due to winter storm activity.

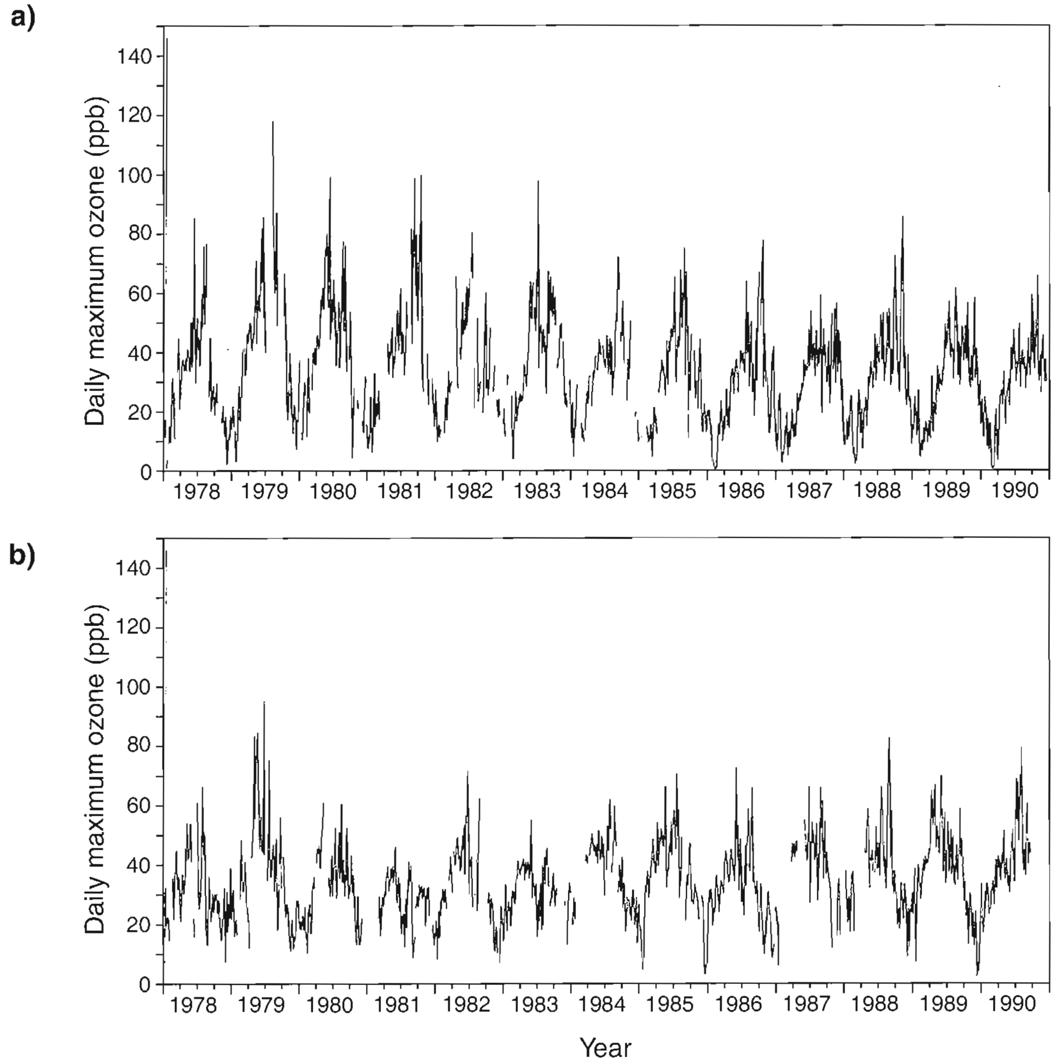

Figure 9. *Seven day moving average of daily maximum ozone at* ***a)*** *Rocky Point park (location T9 from Fig. 2b) and* ***b)*** *Abbotsford airport between 1978 and 1990. Note the higher peak values observed during the summer months and the slight downward trend at Rocky Point park (Steyn et al., 1992, Fig. 3)*

STEPS BEING TAKEN TO CONTROL AIR POLLUTION

As human population and development in the Fraser River delta region continue to grow, the atmospheric impacts of urbanization will become increasingly problematic, especially if these impacts are not taken into consideration during the planning process. Since motor vehicles contribute most significantly to the emissions, continued and strengthened vehicle emission testing, combined with regulations to reduce new vehicle emission could help mitigate the impact of population growth. Improved public transport and development and use of alternative transportation modes could be the key to eventual reduction of air pollution in the region. To be successful, these measures will require participation and lifestyle changes by residents of the region.

In 1994, the Great Vancouver Regional District adopted its Air Quality Management Plan (Greater Vancouver Regional District, 1994) with the mission to "... shape regional land use and transportation, encourage clean air lifestyles, and manage emissions from human activity so as to protect human health and ecological integrity both within the region, in neighbouring jurisdictions in the Lower Fraser Valley airshed, and globally."

The Air Quality Management Plan made 33 recommendations with 54 emission reduction measures. It proposed to reduce by 50% (from 1985 levels) the overall emissions of carbon monoxide (CO), volatile organic compounds, NO_x, SO_x, and particulate matter by the year 2000. By reducing the ozone precursors, volatile organic compounds, and NO_x, it is expected that ozone (smog) problems also will diminish. A number of steps have been taken to reduce automobile-related pollution. A voluntary trip-reduction program ('Go Green'), encouraging use of public transit and carpooling by a variety of means, has been implemented. Regional transportation planning measures are designed to reduce distances people travel, improve vehicle fuel efficiency, introduce cleaner fuels, enhance standards for vehicle emissions, and introduce requirements for zero-emission vehicles like electric cars. A mandatory vehicle emission inspection program also has been introduced ('AirCare'). It is anticipated that AirCare will result in NO_x emission reductions of 10%, volatile organic compound emission reductions of 25%, and CO emission reductions of 30%.

Two studies have attempted to quantify the economic impacts of air pollution in the Greater Vancouver Regional District. SENES Consultants (unpub. report, 1995), in a study conducted for the B.C. Ministry of Transportation and Highways, estimated that the annual cost of the health impact of air pollution was $1 316 000 000, with $1 275 000 000 due to mortality. BOVAR-CONCORD and ARA (unpub. report, 1995) estimated the economic benefits of implementation of the Greater Vancouver Regional District Air Quality Management Plan (Greater Vancouver Regional District, unpub. report, 1994). They estimated benefits of $214 000 000 annually between 1995 and 2004 with benefits of $483 000 000 annually for the years 2005 to 2020. They also found net benefits, after the costs of lowering emissions were taken into account, of $27 000 000 annually until 2004, and $115 000 000 annually between 2005 and 2020. Clean air in the Fraser River delta clearly has economic as well as environmental and health benefits.

ACKNOWLEDGMENTS

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REFERENCES

Jackson, P.L.
2004: Climatological setting of the Fraser River delta and its urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.)B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

O'Kane, S.
1997: An investigation of ozone distribution downwind of Greater Vancouver, B.C. using a novel aircraft measurement system; M.Sc. thesis, University of British Columbia, Atmospheric Science, Vancouver, British Columbia, 97 p.

Pryor, S.C., Steyn, D.G., and Rogak, S.N.
1994: Source apportionment of visibility-degrading aerosols in the lower Fraser valley, B.C.; Atmosphere-Ocean, v. 32, p. 663–683.

Steyn, D.G., Bovis, M., North, M., and Slaymaker, O.
1992: The biophysical environment today; Chapter 9 *in* Vancouver and Its Region, (ed.) G. Wynn and T.R. Oke; University of British Columbia Press, Vancouver, British Columbia, 333 p.

Taylor, E.
2004: Impacts of future climate change on the Fraser River delta and its urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Vedal, S.
1995: Health Effects of Inhalable Particles: Implications for British Columbia; Air Resources Branch, British Columbia Ministry of Environment, Lands and Parks, Victoria, British Columbia, 66 p.

Organic contaminants in suspended sediment upstream of the Fraser River delta

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Abstract: Trace organic contaminants were measured in suspended sediments collected between 1992 and 1994 upstream and downstream of six pulp mills located in the upper and middle Fraser River basin. Sampling was conducted under both fall low-flow and winter base-flow conditions to assess the effect of seasonal hydrological changes on contaminant levels. Results indicate that dioxins, furans, chlorophenolics, and resin acids continue to be detected in higher levels at sites up to 300 km downstream of pulp and paper mills than at unaffected reference sites; however, levels of dioxins and furans were found to have decreased dramatically since the implementation of abatement measures at the mills. Contaminant levels were observed to vary seasonally, with concentrations typically higher during winter base-flow periods than under fall low-flow conditions. No change in contaminant levels was observed over the 1992–1994 sampling period, and none of the contaminants exceeded federal water quality guidelines or provincial criteria for the protection of aquatic life.

Résumé : On a mesuré les concentrations de contaminants organiques présents à l'état de traces dans des sédiments en suspension prélevés de 1992 à 1994 en amont et en aval de six usines de pâtes situées dans les parties supérieure et moyenne du fleuve Fraser. Les prélèvements ont été effectués en automne, dans des conditions de débit d'étiage, et en hiver, dans des conditions de débit de base, afin d'évaluer l'effet des variations hydrologiques saisonnières sur la teneur en contaminants. Les résultats indiquent qu'on continue de détecter des dioxines, des furanes, des dérivés chlorophénoliques et des acides résiniques en concentrations plus élevées dans les échantillons prélevés jusqu'à 300 km en aval des usines de pâtes et papiers que dans ceux prélevés dans des lieux de référence non touchés. On constate cependant que la teneur en dioxines et en furanes a beaucoup diminué depuis la mise en œuvre de mesures de dépollution dans les usines. La teneur en contaminants varie d'une saison à l'autre, les concentrations étant généralement plus élevées en hiver, en période de débit de base, qu'en automne, en période de débit d'étiage. On n'a observé aucune variation de la teneur en contaminants au cours de la période de prélèvement de 1992 à 1994, et aucun contaminant n'était présent en concentrations supérieures aux valeurs seuils indiquées par les directives fédérales sur la qualité de l'eau ou par les critères provinciaux pour la protection de la vie aquatique.

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INTRODUCTION

Sources of organic contaminants to the aquatic environment of the Fraser River basin upstream of Hope include pulp and paper mills, municipal wastewater-treatment facilities, urban runoff, sawmills, wood-treatment facilities, agricultural runoff, and aerial deposition. The largest proportion of industrial effluents discharged to the basin is from pulp-and-paper mills (Schreier et al., 1991).

Contaminants related to pulp-and-paper mills have been of concern, as a number of them have been shown to cause both acute and chronic effects in various organisms (K. Solomon, H. Bergman, R. Huggett, D. Mackay, and B. McKague, unpub. report, 1993). Of primary concern is exposure of the general public to dioxins and furans through food intake (Gilman and Newhook, 1991). In 1988, Mah et al. (1989) identified dioxins and furans in Fraser and Thompson river-bed sediments and fish, thereby prompting the 1989 release of an advisory by Health and Welfare Canada restricting human consumption of muscle tissue from mountain whitefish, large-scale sucker, northern squawfish, and peamouth chub. In April 1990, the advisory was expanded to include muscle tissue from rainbow trout and Dolly Varden and liver tissue from white sturgeon.

In 1991, federal and provincial legislation required bleached kraft pulp mills to make process changes in order to reduce emissions of dioxins and furans and other organochlorine compounds. These regulations resulted in pulp mills modifying their bleaching methods from use of 100% chlorine to 40–100% chlorine dioxide substitution. Following the implementation of pulp-mill regulations and based on results of the 1990–1991 organochlorine trend-monitoring program (L. Dwernychuk, G. Bruce, B. Gordon, and G. Thomas, unpub. report, 1991), consumption advisories were revised by the British Columbia Ministry of Health. Revisions were made for quantities of mountain whitefish that were deemed safe for consumption, and recommendations were made to avoid consumption of liver from large scale sucker, Dolly Varden, rainbow trout, and mountain whitefish. In January

Table 1. Contaminants measured in suspended sediments and their sources and effects.

Contaminants	Major sources	Effects
Dioxins and furans	Pulp-and-paper mills using chlorine bleaching Incinerators Commercial chemicals (PCBs, pentachlorophenol, 2,4-D) Wood and fossil-fuel combustion Sewage-treatment-plant effluents	Teratogenic Carcinogenic Acutely toxic Endocrine-disrupting Bioaccumulative
Chlorophenolics	Pulp-and-paper mills using chlorine bleaching Wood-treatment facilities Incinerators Chlorinated pesticides Sewage-treatment-plant effluents	Immunotoxic Fetotoxic Embryotoxic Fish tainting
Polycyclic aromatic hydrocarbons (PAHs)	Wood and fossil-fuel combustion Creosoted treated products Spills of petroleum products Slash burning Plant material	Carcinogenic Bioaccumulative
Polychlorinated biphenyls (PCBs)	Transformers Lamp ballasts (pre-1980) Global transport and deposition Sewage-treatment-plant effluents Pulp-and-paper-mill effluents	Immunotoxic Endocrine-disrupting Bioaccumulative
Chlorinated pesticides	Agriculture Sewage-treatment-plant effluents Industrial effluents Global transport and deposition	Carcinogenic Endocrine-disrupting Bioaccumulative
Resin acids	Wood-processing industries	Acutely toxic Bioaccumulative
Fatty acids	Wood-processing industries Decaying organic matter Food-processing effluents Sewage-treatment-plant effluents	Acutely toxic

1994, the British Columbia Ministry of Health lifted its advisory on the consumption of mountain whitefish and trout flesh (British Columbia Ministry of Environment, Lands and Parks, information bulletin, January 1994).

This paper is based on results from a three-year study of contaminants in suspended sediments and water in the Fraser River basin (Sekela et al., 1995). The objectives of the study, which was conducted as part of the Fraser River Action Plan, were threefold: 1) to determine levels of contaminants, particularly those associated with pulp-and-paper-mill effluents, in suspended sediments from sampling sites on the Fraser and Thompson rivers; 2) to measure changes in contaminant levels related to different hydrological conditions over the 1992–1994 sampling period; and 3) to relate changes in contaminants associated with pulp-mill effluents to abatement measures implemented by the pulp mills in 1991.

Suspended sediment was selected as a sampling medium because of the relatively high sediment content of the Fraser River (10–1000 mg/L) and because many organic contaminants have a high affinity for sediment particles.

Sampling was conducted at six sites on the Fraser, Thompson, and North Thompson rivers in October 1992, February 1993, November 1993, and November 1994. Although focusing on contaminants originating from pulp-and-paper mills, suspended sediments were analyzed for a number of contaminants associated with both point and nonpoint pollution sources (Table 1).

STUDY AREA

The study area was divided into two main regions: the Fraser River study region included the main stem of the Fraser River between Shelley and Yale, and the Thompson River study region encompassed the area between McLure on the North Thompson River and Savona on the Thompson River (Fig. 1). Four sites were sampled on the main stem of the Fraser River. These were: Shelley (reference site, 18 river kilometres upstream of Prince George), Woodpecker (59 river kilometres downstream of Prince George), Marguerite (65 river kilometres downstream of Quesnel), and Yale (450 river kilometres downstream of Marguerite). The two sites in the Thompson River study region were the unaffected reference site, McLure (41 river kilometres upstream of Kamloops), and Savona (61 river kilometres downstream of Kamloops).

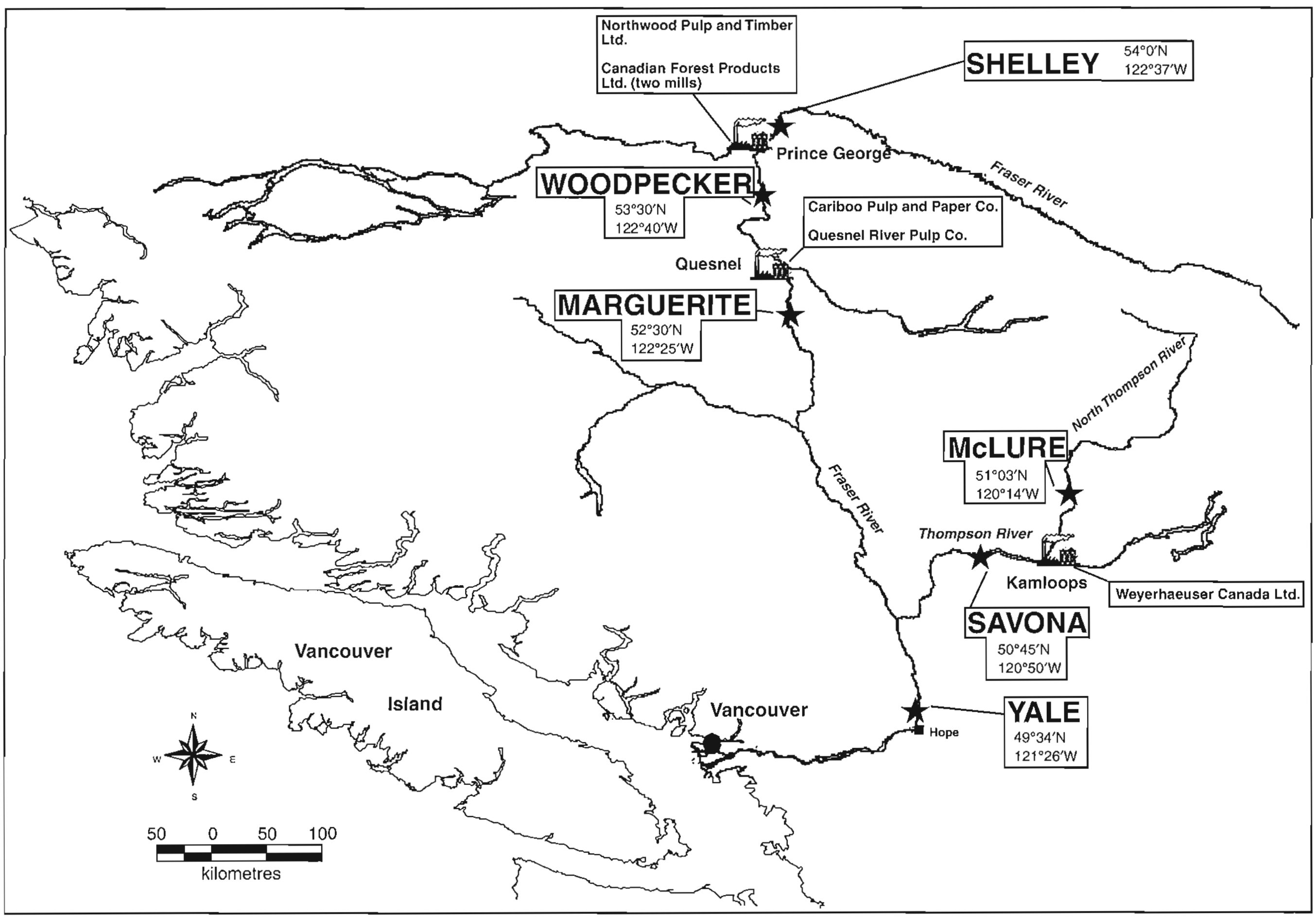

Figure 1. Fraser River basin, including pulp mills located upstream of Hope and sampling sites.

METHODS

Sample timing

To investigate seasonal effects on contaminants associated with suspended sediments, sampling was conducted over two hydrological periods, fall low flow (October 1992, November 1993, November 1994) and winter base flow (February 1993). Figure 2 presents the suspended-sediment concentration at time of sampling, relative to the annual hydrograph, for the North Thompson, Thompson, and Fraser rivers during each of the three sampling periods. As the figures indicate, flow and suspended-sediment concentration are closely linked. Consequently, samples collected during base-flow conditions are expected to represent worst case conditions, as these samples would be least 'diluted' by uncontaminated erosion-derived sediments in comparison to those collected during fall low-flow regimes. Note that flow and suspended-sediment concentrations for the Fraser River were unusually low during the November 1994 low-flow-sampling period and closely approximated the February 1993 base-flow conditions.

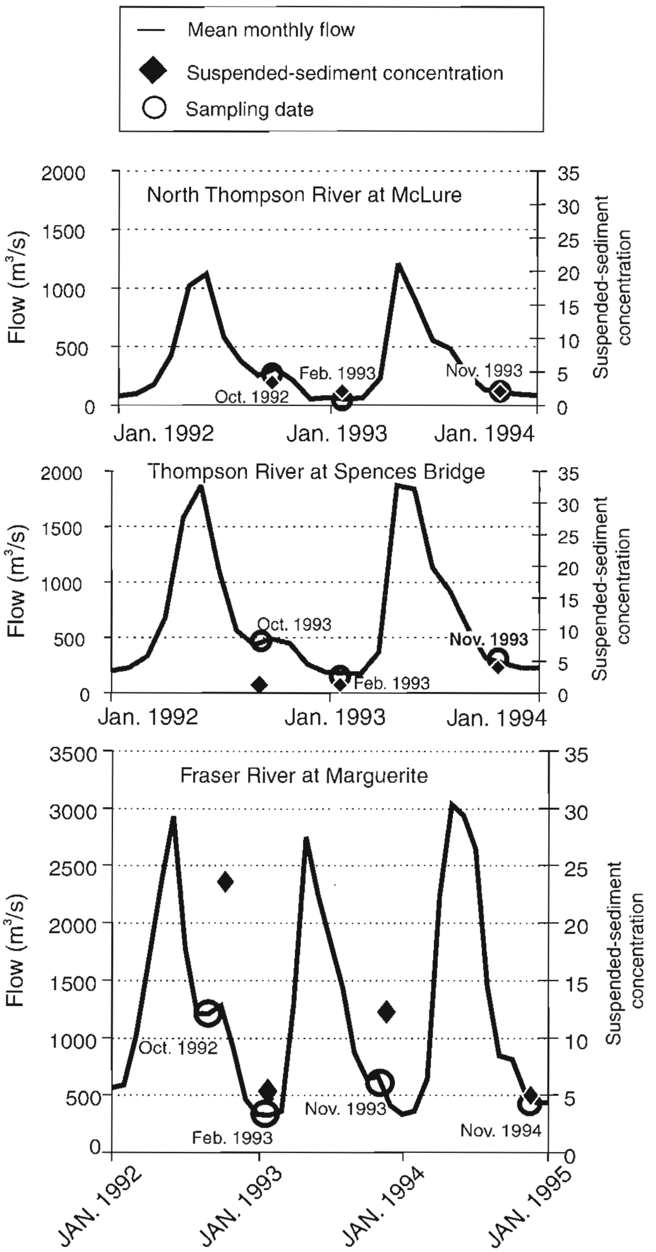

Figure 2. Mean monthly flow of the North Thompson, Thompson, and Fraser rivers, and suspended-sediment concentrations at the time of sampling.

Suspended-sediment collection

Suspended-sediment samples were collected using Westfalia Separator Continuous-flow Centrifuges^{TM} operating at 4 L/min. A single time-integrated sample was collected from each site for each sampling time which ranged from 6.5 h to 96 h. The duration of the sampling periods was dependent on the suspended-sediment concentration in the river water at each site. Details on sampling methods are presented in Horowitz et al. (1989) and Sekela et al. (1995).

Sample analysis

Dioxins and furans were analyzed by high-resolution gas chromatography and high-resolution mass-spectrometric detection. Chlorophenolics, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), resin acids, and fatty acids were analyzed by high-resolution gas chromatography with low-resolution (quadrupole) mass-spectrometric detection. Pesticides were analyzed by high-resolution gas chromatography with low-resolution (quadrupole) mass-spectrometric detection and high-resolution gas chromatography with electron-capture detection. Total organic carbon (TOC) was determined using the Walkley-Black wet oxidation method. Particle size was measured with a Malvern 2600L Laser Particle-size Analyzer^{TM}.

RESULTS AND DISCUSSION

Shelley (upstream of Prince George reach)

Over all sampling periods, six of nine dioxins measured were detected at Shelley, ranging from 0.50 pg/g to 180 pg/g. Of these, the hepta- and octa-chlorinated dioxins, which are associated with pentachlorophenol and combustion sources (Czuczwa and Hites, 1986), were found in the highest concentrations (50 pg/g and 180 pg/g, respectively). A range of furan congeners from tetra- to octa-chlorinated furans were detected in this reach. The tetra-chlorinated congeners were measured near detection levels, whereas penta-, hexa-, hepta-, and octa-chlorinated congeners ranged from nondetectable to 45 pg/g. Aerial deposition of dioxins and furans, originating from combustion sources, likely occurs at this site due to its proximity to the city of Prince George (18 km); however, numerous smaller combustion sources upstream of Prince George also may contribute to the total dioxin and furan load.

Eight out of 48 chlorophenolics were detected at Shelley, ranging in concentration from 0.30 ng/g to 4.1 ng/g. Of these, four belong to the chlorophenol group which has been associated with wood preservation. This is likely related to past operations of a sawmill in the reach which employed pentachlorophenol as a wood preservative until 1990 (J. McGuire, British Columbia Ministry of Environment, Lands and Parks, pers. comm., 1995). Two chlorocatechols (1.3–4.1 ng/g), two chlorosyringaldehydes (1.8–3.1 ng/g), and pentachlorophenol (1.3 ng/g) were also detected in this reach.

Seven out of ten resin acids were detected at Shelley, ranging from 2.5 ng/g to 420 ng/g, and the total resin-acid concentration was 816 ng/g. Dehydroabietic acid comprised 51% of total resin acids. Although resin acids are naturally occurring compounds in the oleoresin of conifers (Windholtz et al., 1983), extensive logging and abandoned piles of sawdust from old sawmills in this reach (R. Fairservice, British Columbia Ministry of Environment, Lands and Parks, pers. comm., 1995) also may be a source of resin acids to the river. The total concentration of fatty acids in this reach was 78.6 μg/g, with palmitic acid contributing 47% of the total.

There were 17 individual PAHs detected at Shelley, with values ranging between 0.50 ng/g and 58 ng/g. Perylene was the most abundant PAH measured (39–58 ng/g), whereas levels of the other PAHs did not exceed 12 ng/g. Total PAH levels ranged between 84 ng/g and 138 ng/g. Although perylene has been associated with terrestrial plant sources (Bouloubassi and Saliot, 1993), many of the PAHs detected in this reach are known to be products of fossil-fuel combustion.

Nine out of 83 PCB congeners were detected at Shelley in the range of 0.010 ng/g to 0.060 ng/g. No PCB aroclors or coplanars were detected in this reach. Polychlorinated biphenyl congener concentrations were near detection limits and represent background levels which are likely perpetuated though long-range aerial deposition.

Two pesticides were detected at Shelley: hexachlorobenzene (0.08 ng/g) and α-hexachlorocyclohexane (0.040 ng/g). Hexachlorobenzene was used in Canada between 1948 and 1972 as a seed dressing to prevent fungal disease in crops. Although it has not been used commercially since 1972, it is widely found in the Canadian environment (Canadian Environmental Protection Act, 1993). As pentachlorophenol is a documented source of hexachlorobenzene (Canadian Environmental Protection Act, 1993), its presence in this reach may be linked to this wood preservative which was used by a sawmill at Shelley until 1990 (J. McGuire, British Columbia Ministry of Environment, Lands and Parks, pers. comm., 1995); however, long-range aerial deposition, which is the largest source of hexachlorobenzene to the Canadian environment (Canadian Environmental Protection Act, 1993), likely contributes a large proportion of this contaminant to this reach. Alpha-hexachlorocyclohexane is an isomer of lindane (γ-hexachlorocyclohexane), which is presently registered for use in Canada as an insecticide for seed treatment (A. Oliver, British Columbia Ministry of Environment, Lands and Parks, pers. comm., 1995). Although not as insecticidal as lindane, α-hexachlorocyclohexane is reported to be highly prevalent in surface waters of western Canada (Inland Waters Directorate, 1986). The presence of α-hexachlorocyclohexane in this reach is suggestive of atmospheric deposition (Lockhart et al., 1992), as insecticide use has historically not been heavy in the Fraser River basin upstream of Prince George (Schreier et al., 1991).

Woodpecker (Prince George to Quesnel reach)

All dioxin congeners, with the exception of total pentachlorodibenzo-p-dioxin (P5CDD), were detected at Woodpecker. Concentrations ranged from 0.30 pg/g for 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) to 130 pg/g for octachlorodibenzo-p-dioxin (O8CDD). The pulp-mill-effluent tracer 2,3,7,8-TCDD was detected here in both October 1992 and February 1993, but was not detectable at Shelley (Fig. 3). Furans were detected in the range 0.10–9.3 pg/g. The compound 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDF), a tracer of pulp-mill effluent, was present in concentrations up to 48 times greater than at Shelley, reflecting pulp-mill-effluent inputs from three bleached-kraft mills at Prince George. Levels of all other dioxins and furans were similar to those measured upstream of Prince George at Shelley. Concentrations of most dioxins and furans were higher in February 1993, during base-flow conditions, compared with October 1992 and November 1993 (low flow). This is attributed to a higher proportion of contaminated sediments in the river during base-flow period when levels of natural, erosion-derived, suspended sediments are at their yearly lowest.

In order to determine the effect of pulp-mill-effluent abatement measures introduced in 1991, dioxin and furan data collected in this study were compared to levels measured in suspended sediments collected in the fall of 1990 by Environment Canada (G. Derksen and G. Mitchell, unpub. report, 1994). Refer to Figure 4 for a comparison of 2,3,7,8-TCDD and 2,3,7,8-TCDF levels measured in October 1990 with levels measured in this study in 1992, 1993, and 1994: concentrations of both 2,3,7,8-TCDD and 2,3,7,8-TCDF measured at Woodpecker decreased dramatically (up to 99%) when compared with levels measured in October 1990. In spite of this dramatic decrease, dioxin and furan levels measured in river-bed sediments downstream of upper Fraser and Thompson river-basin pulp mills are still sufficiently high to exceed interim federal guidelines for dioxin and furan toxicity equivalent values (TEQs) (Brewer et al., 1998).

Twenty-three of 48 chlorophenolics were detected at Woodpecker, ranging from 0.1 ng/g to 670 ng/g. The three most prominent groups of chlorophenolics were chlorocatechols, with a maximum concentration of 670 ng/g, followed by chloroguaiacols (69 ng/g) and chlorovanillins (70 ng/g). All three groups are produced in paper-making during chlorine-bleaching operations and have been detected in bleach-plant wastewater and in water, sediment, and biota from aquatic systems receiving pulp-mill discharges (Carey and Hart, 1988). Chlorophenol levels did not exceed 5 ng/g. A prominent concentration peak was observed for total chlorophenolics measured during winter base flow (February 1993) relative to levels measured during fall low flow (Fig. 5).

Total chlorophenolic levels were up to 367 times higher at Woodpecker than at Shelley, reflecting contributions of three kraft pulp mills at Prince George (Fig. 5).

Resin and fatty-acid levels were not measured at Woodpecker.

Individual PAHs detected at Woodpecker ranged in concentration from 0.40 ng/g to 43 ng/g. With the exception of perylene, none of the other PAHs exceeded levels above 20 ng/g. Total PAH levels ranged from 89 ng/g to 120 ng/g, similar to those measured at Shelley. No differences in PAH levels were noted between winter base-flow and fall low-flow conditions.

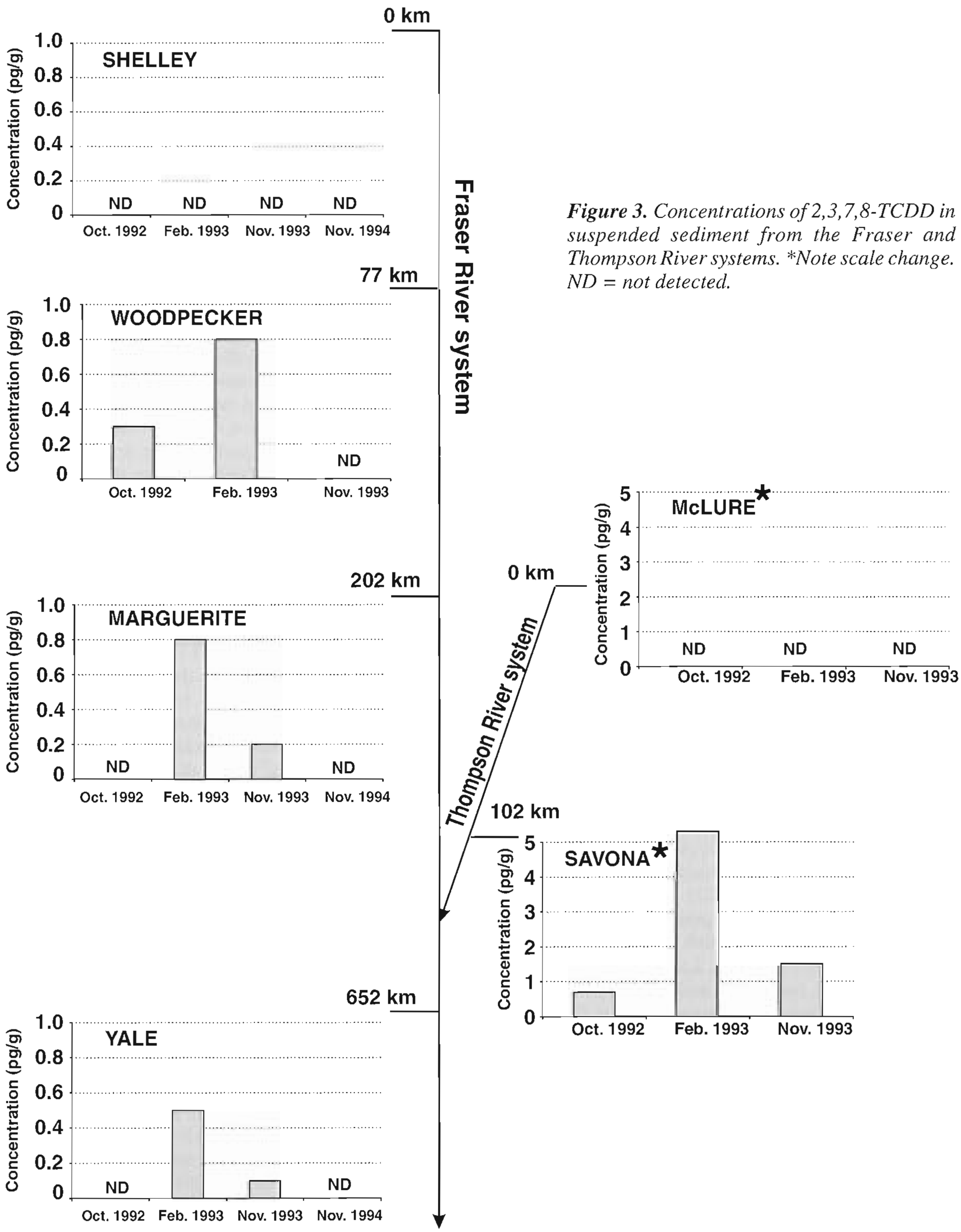

*Figure 3. Concentrations of 2,3,7,8-TCDD in suspended sediment from the Fraser and Thompson River systems. *Note scale change. ND = not detected.*

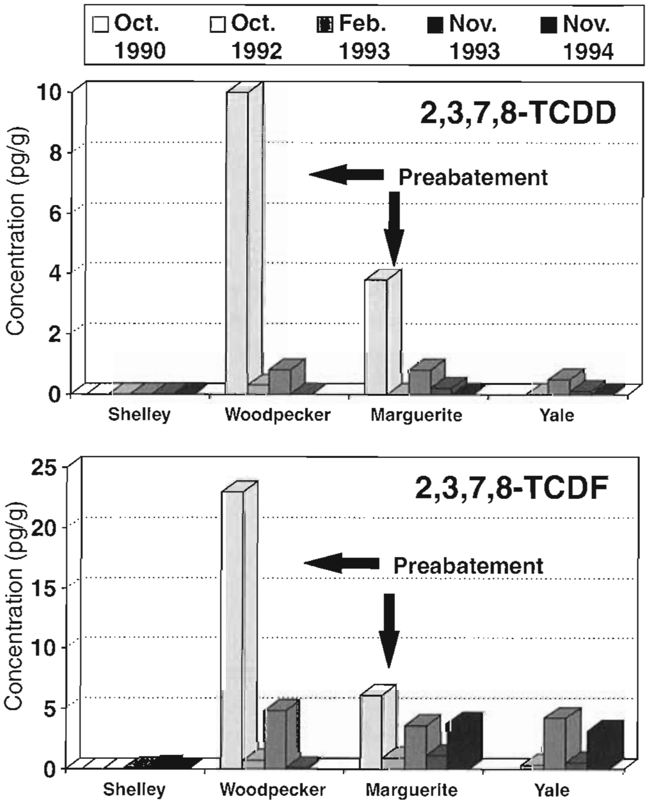

Figure 4. *Concentrations of 2,3,7,8-TCDD and 2,3,7, 8-TCDF in Fraser River suspended sediment (October 1990 data provided by G. Derksen, Environment Canada, written comm., 1994).*

Nevertheless, the PAH sources clearly differed between the two hydrological seasons, as indicated by the ratio of perylene to the remainder of the PAHs. Whereas a predominance of perylene, a PAH derived from terrestrial plant pigments under reducing conditions (Aizenshtat, 1973), has been associated with diagenetic (sedimentary) sources, a low relative abundance has been associated with anthropogenic sources (Bouloubassi and Saliot, 1993). Perylene comprised 36 to 44% of the total PAH concentration in samples collected during the fall, in comparison to only 15% of the total in the winter sample. Conversely, fluorene, pyrene, and chrysene increased in concentration in the winter sample, reflecting the higher contribution of anthropogenically derived PAHs to the river during base-flow conditions.

Three PCB congeners of the 83 measured were detected in this reach: #31 and/or #28 at 0.90 ng/g, #70 and/or #76 at 0.70 ng/g, and #90 and/or #101 at 0.040 ng/g. Three PCB coplanars (#77, #126, and #169) were detected at a concentration of 11 pg/g each. Aroclor 1242 was detected at 4.6 ng/g. These levels, although slightly higher than those measured at Shelley in November 1994, are not indicative of point-source contamination, but rather of background levels found throughout the basin.

Pesticides were not measured at Woodpecker.

Marguerite (downstream of Quesnel)

Dioxins measured in this reach ranged from 0.2 pg/g to 470 pg/g. Levels of the 2,3,7,8-dioxin and 2,3,7,8-furan congeners were 10 times and 21 times higher, respectively, at Marguerite than at Shelley (Fig. 3), reflecting the input of effluents from five pulp-and-paper mills upstream of this site. Relatively similar levels of these two congeners were detected at Marguerite and Woodpecker, suggesting that pulp-mill effluent discharged from the single kraft mill at Quesnel may not be contributing significantly to the overall dioxin and furan concentration in suspended sediments below Quesnel. Alternatively, sediment dilution from tributaries such as the Quesnel River may be effectively reducing the dioxin and furan concentration in this reach of the river. Elevated levels of some of the lower chlorinated dioxins and furans were observed in winter samples relative to fall samples; however, concentrations of both hepta- and octa-chlorinated dioxins were notably higher in the fall of 1994 in comparison to all other sampling periods. Levels of 2,3,7,8-TCDD and 2,3,7,8-TCDF had decreased by 95% at this site since 1990, prior to the introduction of chlorine dioxide substitution by the pulp mills (Fig. 4).

Chlorophenolic levels measured at Marguerite showed a pattern similar to that at Woodpecker, but were somewhat lower. Chlorocatechols were detected in the highest concentrations, with a maximum of 520 ng/g. Samples collected during winter base-flow conditions (February 1993) showed a decrease in the level of total chlorophenolics of over 40% at Marguerite in comparison to Woodpecker (Fig. 5), indicating that the three kraft pulp mills at Prince George are likely contributing a greater load of chlorophenolics than the single kraft mill located at Quesnel. A pronounced concentration peak for total chlorophenolics was observed for samples taken at Marguerite during base-flow conditions (February 1993) relative to fall low-flow conditions (Fig. 5).

All 10 resin acids were detected at Marguerite, in concentrations ranging from 61 ng/g to 32 000 ng/g. Total resin-acid levels were 124 times higher than at Shelley (Fig. 6), indicating that effluents from pulp-and-paper and other wood-processing industries upstream of this site may be adding considerable inputs of resin acids to the river. Dehydroabietic and abietic acids, comprised 62% of total resin acids, followed by pimaric (18%) and isopimaric (15%) acids. All of these resin acids have been identified in kraft-pulp-mill effluents (Leach and Thakore, 1976; Brownlee and Strachan, 1977; Fox, 1977; Knap and Williams, 1982), and dehydroabietic acid has been found at elevated levels downstream of kraft pulp mills compared to upstream sites (Brownlee et al., 1977). Two chlorinated resin acids, 12,14 chlorodehydoabietic and 12,14 dichlorodehydroabietic acids, also were detected at this site, but were nondetectable upstream of Prince George.

Fatty acids were detected at Marguerite in the range of 460 ng/g to 140 000 ng/g. Total fatty-acid levels were 288 669 ng/g, which represents a 3.7-fold increase over levels measured at Shelley (Fig. 7). The observed increase in total fatty acids downstream of Prince George and Quesnel is suggestive of possible contributions from pulp-mill and municipal

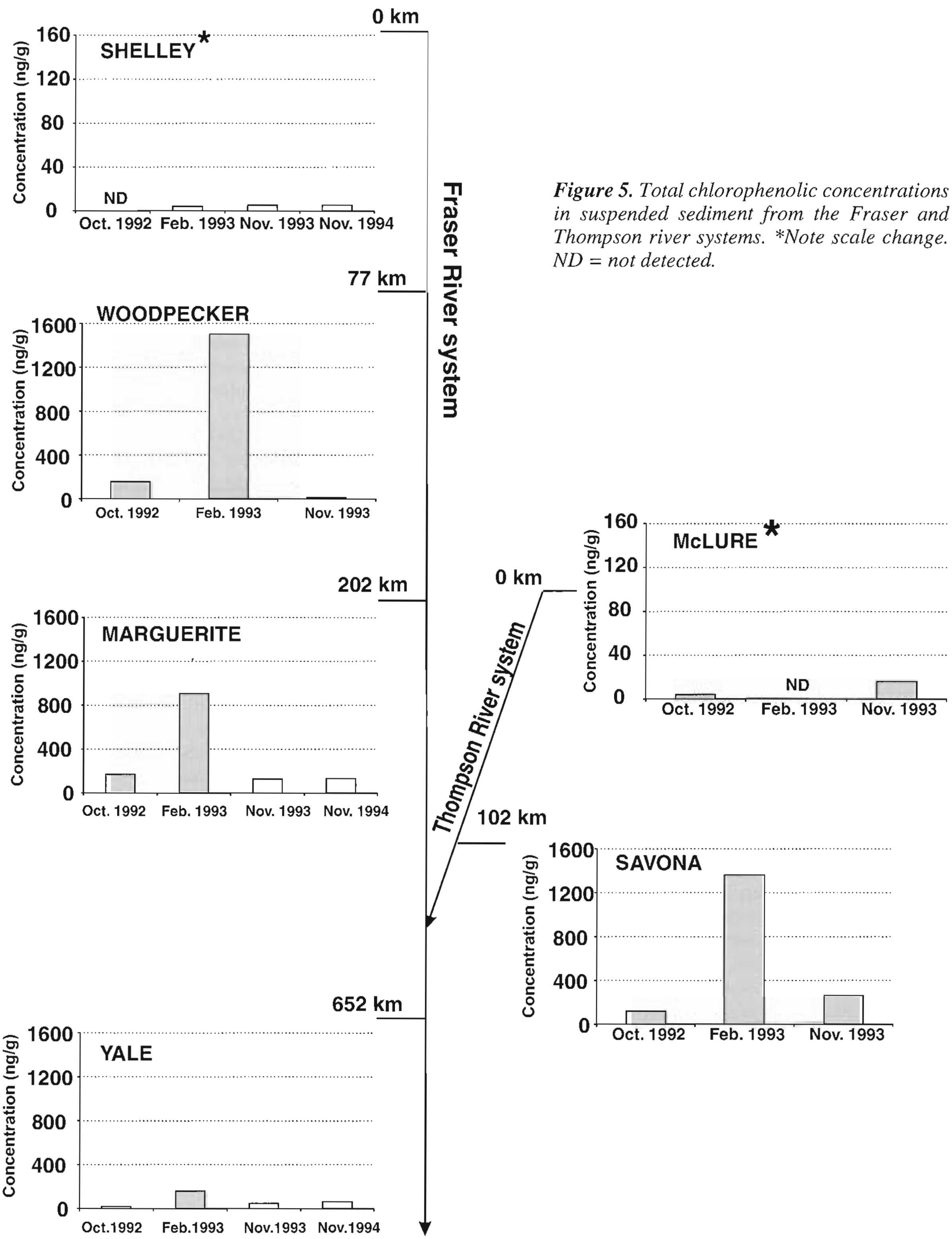

Figure 5. *Total chlorophenolic concentrations in suspended sediment from the Fraser and Thompson river systems. *Note scale change. ND = not detected.*

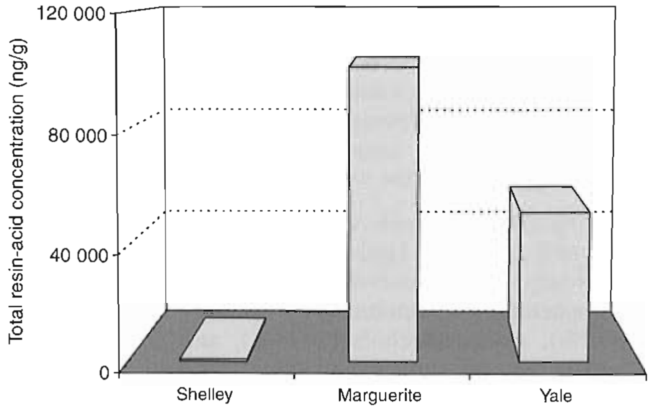

Figure 6. *Total resin-acid concentrations in suspended sediment from the Fraser River system (November 1994).*

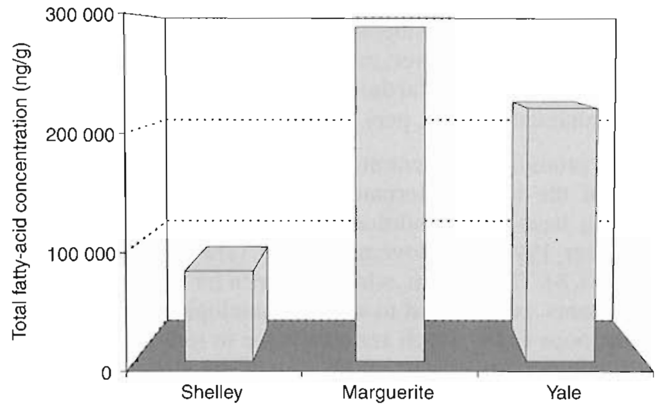

Figure 7. *Total fatty-acid concentrations in suspended sediment from the Fraser River system (November 1994).*

effluents. Indeed, some of the fatty acids found at the highest levels (palmitic, oleic, and myristic acids) have been shown to be major components of pulp-mill effluents (Fox, 1977); however, in the absence of information regarding fatty acid levels in final effluents from Fraser River basin pulp mills, it is difficult to accurately evaluate the source of these compounds.

Polycyclic aromatic hydrocarbon concentrations measured at Marguerite ranged between 0.8 and 55 ng/g, with perylene being consistently most abundant across all sampling dates. Total PAH levels ranged from 128 ng/g to 393 ng/g. The latter concentration, measured in November 1994, is over three times that measured at Shelley during the same time period. In addition to perylene, whose source is sedimentary, the November 1994 sample also had relatively high levels of phenanthrene (55 ng/g), fluoranthene (47 ng/g), and pyrene (50 ng/g). This concentration peak, also seen for the combustion-related hepta- and octa-chlorinated dioxin congeners, suggests that wood-fuel combustion and fossil-fuel combustion may be responsible for the observed increase in these contaminants.

Four PCB congeners were detected at Marguerite in levels ranging from 0.040 ng/g to 0.11 ng/g. No PCB aroclors or coplanars were detected in this reach. Polychlorinated biphenyl congener levels were similar to those detected at Shelley and represent background concentrations.

Two pesticides, hexachlorobenzene and α-hexachlorocyclohexane, were detected in concentrations of 0.30 ng/g and 0.13 ng/g, respectively. These concentrations, which were four and three times higher than at Shelley, respectively, suggest possible nonpoint inputs from historical agricultural practices and commercial chemical sources.

McLure (North Thompson River)

Dioxins were detected at McLure in the range of 1.3 pg/g to 62 pg/g. The majority of detectable dioxins were the hexa-, hepta-, and octa-chlorinated congeners, although 2.2 pg/g of total T4CDD were detected at this site in November 1993. Furan levels ranged from 0.20 pg/g to 6.5 pg/g. As with dioxins, the hepta- and octa-chlorinated furan congeners were measured in the highest concentrations. The predominance of the highly chlorinated dioxin and furan congeners in these samples is consistent with the congener profile associated with pentachlorophenol and combustion sources (Czuczwa and Hites, 1984). This profile is similar to that seen at Shelley, upstream of Prince George.

Five chlorophenolics were detected at this site, with levels ranging between 0.6 ng/g and 9.1 ng/g. Of these, three were di-chlorophenols, one a chloroguaiacol, and one a chlorocatechol. These chlorophenolics had similar concentrations to those found at Shelley, upstream of Prince George, and were likely derived from leaching of preserved wood products (such as railway ties) of nonpoint-source origin.

Polycyclic aromatic hydrocarbon concentrations detected at McLure ranged from 0.90 ng/g to 110 ng/g, with perylene being the most abundant PAH. With the exception of perylene, the rest of the PAHs did not exceed levels of 23 ng/g. Total PAH levels ranged from 134 ng/g to 275 ng/g, higher than those measured at Shelley (84–138 ng/g), possibly as a result of the greater use of fossil fuels in this more populous reach of the river than in the reach upstream of Prince George.

Savona (downstream of Kamloops)

Dioxin levels measured at Savona ranged from 0.70 pg/g to 490 pg/g. These levels were considerably higher than at the reference site, McLure, located upstream of any pulp mills and urban centres. Most notably, 2,3,7,8-TCDD, a marker of pulp-mill effluent, was detected up to a maximum of 5.3 pg/g, while not detectable at McLure (Fig. 3). Moreover, levels of the combustion-related hepta- and octa-chlorinated dioxin congeners were up to 14 times higher than at McLure, with a maximum of 490 pg/g in November 1993. Furans were similarly detected in higher concentrations at Savona than at the reference site, with 2,3,7,8-TCDF and total T4CDF reaching levels of 140 pg/g and 260 pg/g, respectively (Fig. 8). These levels, which are considerably higher than those below pulp mills on the Fraser River, may be linked to failure of an effluent containment pond at the pulp mill in Kamloops (P. Krahn, Environment Canada, pers. comm., 1995).

A prominent concentration peak was observed for a number of the lower chlorinated dioxin and furan congeners during base-flow conditions in February 1993 relative to October 1992 and November 1993 (low-flow conditions) (Fig. 3, 8). This pattern, which was seen for a number of contaminants, is attributed to winter limnological conditions in Kamloops Lake, which are conducive to reduced mixing of effluent-rich river water with lake water (Bothwell et al., 1992). Conversely, fall flow conditions result in a thorough mixing of the more dense river water with the warmer lake water, leading to enhanced effluent dilution.

An additional factor contributing to the higher levels of dioxins and furans in suspended sediments sampled during the winter was the relatively high TOC of suspended sediment collected in February 1993 (18.5%) versus that collected during fall sampling (1.5–4.9%). Numerous laboratory studies have linked increased sorption of hydrophobic contaminants to sediments with high TOC levels (Karickhoff et al., 1979; Knap and Williams, 1982), and recent field studies at this site have shown a similar pattern (Sekela et al., 1995). This observed TOC increase at Savona is likely due to a higher algal biomass associated with an enhancement of nutrient levels during the winter (St. John et al., 1976).

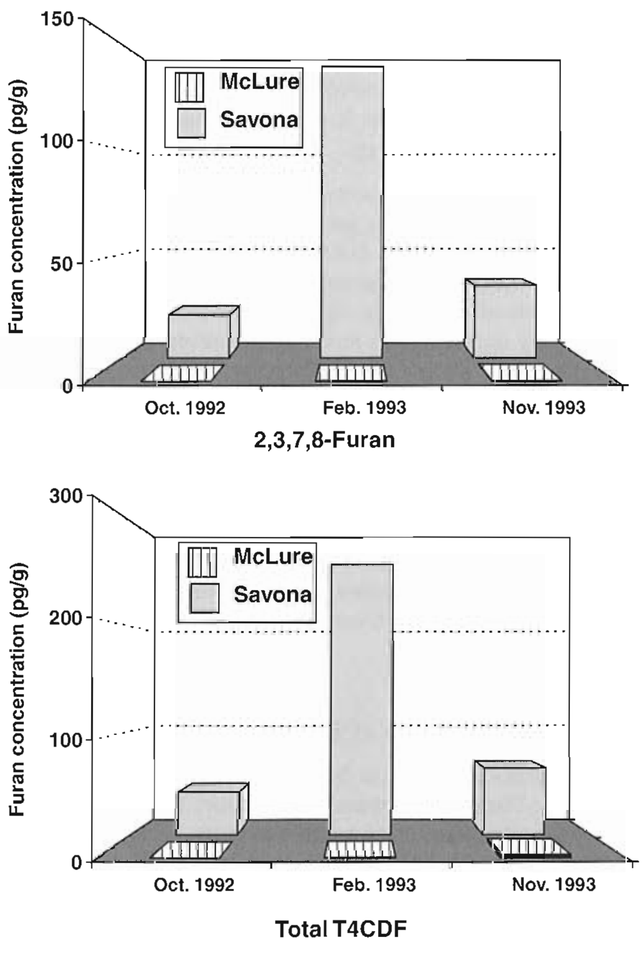

Figure 8. Furan concentrations in suspended sediment from the Thompson River system.

Chlorophenolic levels were measured at Savona in the range of 0.20 ng/g to 1100 ng/g. Chlorovanillins accounted for the largest concentrations observed (49–84% of the total chlorophenolic concentration), followed by chloroguaiacols (7–37%), chlorocatechols (2–14%), and chlorophenols (0–1%). This chlorophenolic pattern, although proportionally different from that observed in sediments downstream of pulp mills in the upper Fraser River, is clearly suggestive of pulp-mill origins. In fact, the high predominance of chlorovanillins has been related to the degree of chlorine dioxide substitution employed by the pulp mills (Liebergott et al., 1991). At the time of sampling, the pulp mill at Kamloops employed 100% chlorine dioxide substitution, which is known to generate approximately 90% chlorovanillins. Conversely, pulp mills in the upper Fraser River basin employed 40–100% chlorine dioxide substitution, which has been shown to generate approximately 46% catechols and guaiacols (Liebergott et al., 1991). A concentration peak similar to that observed for dioxins was observed for total chlorophenolics in February 1993 (Fig. 5).

Individual PAH congeners detected at Savona ranged in concentration between 1.6 ng/g and 500 ng/g, and total PAH levels ranged between 266 ng/g and 2287 ng/g. The latter represents a 17-fold increase in PAH concentration compared to that measured at McLure during base-flow conditions (Fig. 9). This increase is attributed to Savona's location 61 river kilometres downstream of Kamloops, a major urban centre, which is expected to contribute a considerable load of PAHs from fossil-fuel combustion through urban runoff. The difference in PAH sources between the two sites was demonstrated by the ratio of perylene, a PAH of sedimentary origin, to the remainder of the PAHs, which are largely derived from combustion sources. Perylene comprised 30–34% of the total PAH concentration at McLure, compared to only 4–12% of the total at Savona in October 1992 and February 1993.

The total PAH concentration measured at Savona in February 1993 was nearly nine times higher than that measured in fall flow conditions (Fig. 9). Two factors are thought to influence this PAH peak: first, the reduced dilution of contaminants during this time of the year, as was discussed above, and second, the effect of high TOC levels on PAH phase partitioning. The TOC concentration in suspended sediment collected in February 1993 was up to 12 times higher than during fall sampling. This factor had a distinct effect on the PAH phase-partitioning profile at Savona. Whereas PAH partitioning into the suspended solid phase was 0.83–24% in October 1992, it increased to 30–52% in February 1993 (Sekela et al., 1995).

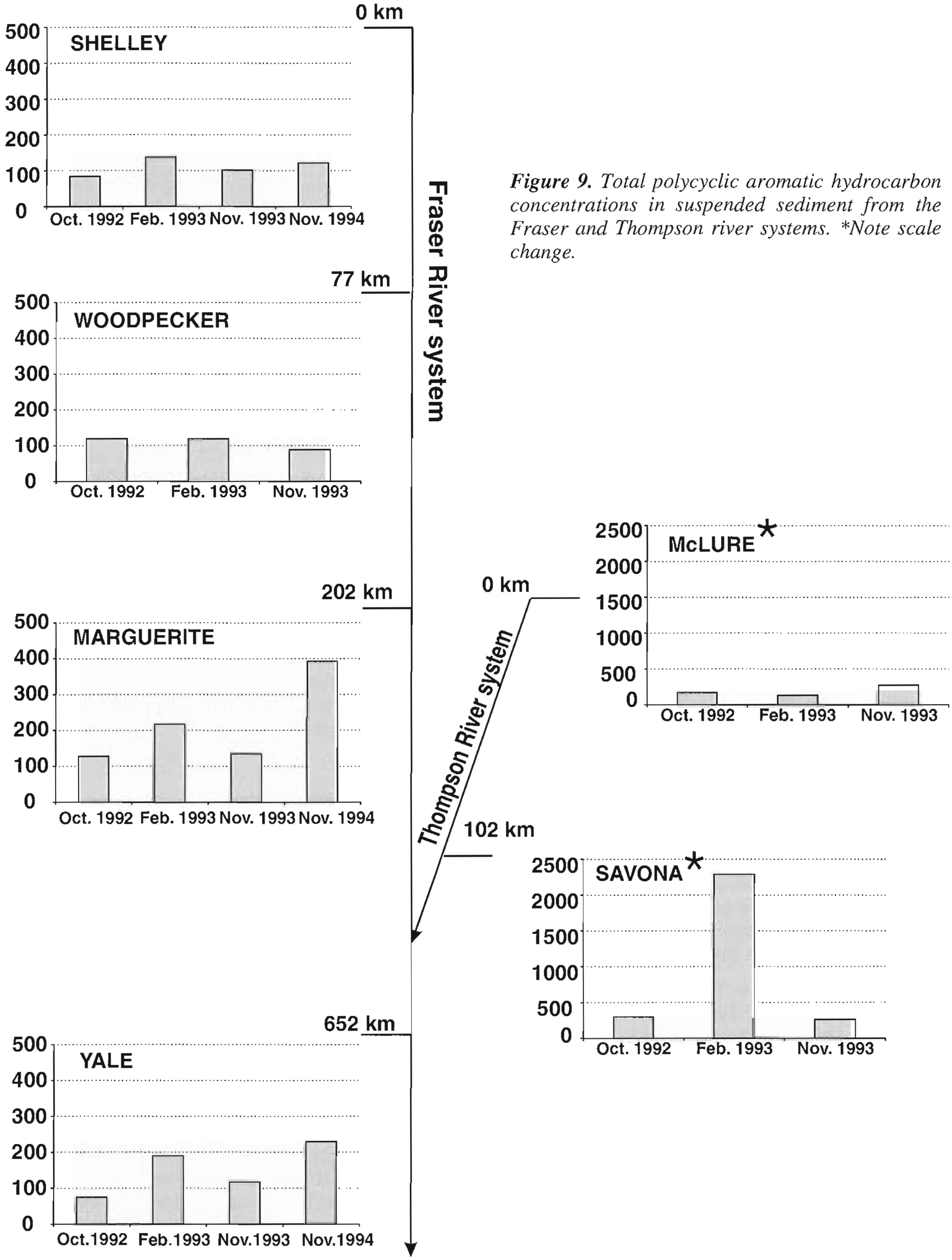

Figure 9. Total polycyclic aromatic hydrocarbon concentrations in suspended sediment from the Fraser and Thompson river systems. *Note scale change.

Yale (downstream of Thompson River confluence with the Fraser River)

Dioxins were detected at Yale in the range of 0.1 pg/g to 230 pg/g, with the hepta- and octa-chlorinated congeners having the highest concentrations. Furans were detected in the range of 0.17 pg/g to 36 pg/g. The highest furan levels were observed for the total di- and tri-chlorinated congeners (34 pg/g and 36 pg/g, respectively), both tracers of pulp-mill effluents in sediment samples (Pastershank and Muir, 1995). Dioxin levels at Yale were lower than those measured at Marguerite, upstream of the confluence with the Thompson River. This reflects contaminant 'dilution' by uncontaminated sediments, originating primarily from Fraser River bank erosion and associated with higher flow regimes; however, factors such as contaminant degradation and volatilization also may contribute to the lower contaminant levels observed at Yale. In contrast, concentrations of some furan congeners exceeded levels measured at Marguerite in the two low-flow sampling periods, February 1993 and November 1994, likely reflecting the relatively high furan inputs from the Thompson River. It is notable that contaminant contributions from the Thompson River are detectable, considering the large dampening effect resulting from the widely different suspended-sediment regimes of the two rivers: 10–1000 mg/L for the Fraser River in comparison to 5–250 mg/L for the North Thompson River (Northwest Hydraulic, 1993).

Chlorophenolics were detected at Yale at levels of 0.20–37 ng/g. These levels are considerably lower than those detected upstream at both Marguerite and Savona. Total chlorophenolic levels were six and eight times lower than at Marguerite and Savona, respectively, during base-flow conditions (Fig. 5). Levels of 6-chlorovanillin, detected at 1100 ng/g at Savona, were considerably lower in the Fraser River at Yale (32 ng/g), but similar to the concentration measured at Marguerite. As discussed above, this consistent decrease in contaminant levels at this site is attributed to a considerable amount of sediment dilution occurring between Marguerite and Yale. Nevertheless, catechols, guaiacols, and vanillins, all markers of pulp-mill effluent, still constituted the largest proportion of the total chlorophenolic concentration, indicating that the pulp-mill effluent signal is still clearly detectable more than 265 river kilometres from the nearest pulp mill.

Individual resin acid levels at Yale were 33–17 000 ng/g, with total resin acid levels at 52 083 ng/g. Total resin acid levels were 64 times higher at Yale relative to Shelley while dropping by approximately 50% in comparison to Marguerite (Fig. 6). This observed pattern is believed to be a consequence of the abundance of wood-processing industries, including five pulp mills, in the area of the river between Prince George and Marguerite, in comparison to the reach of the river between Marguerite and Yale. Sediment dilution likely accounts for the observed 50% decrease in total resin acids at Yale in comparison to Marguerite. Resin acid contributions from the Thompson River are likely negligible, based on levels detected in whole-water samples from Savona (Sekela et al., 1995). The resin acid profile was similar to that observed at Marguerite, with dehydroabietic and abietic acids comprising 61% of the total resin acid concentration.

Fatty acid levels at Yale were 110–100 000 ng/g, and the total fatty acid concentration was 219 410 ng/g. Although similar to levels measured at Marguerite, total fatty acid concentrations at Yale were approximately three times higher than at Shelley (Fig. 7). Palmitic acid was the most abundant fatty acid, making up 48% of the total fatty acid concentration.

Polycyclic aromatic hydrocarbons were detected at Yale at levels ranging from 0.3 ng/g to 40 ng/g. Total PAH levels ranged from 75 ng/g to 230 ng/g. Total PAH concentrations were up to 12 times lower at Yale than at Savona, reflecting the large sediment-dilution effect of the Fraser River (Fig. 9). In contrast, with the exception of November 1993, total PAH levels did not differ considerably from those measured at the other upstream sites on the Fraser River. Total PAH levels measured at Yale and Marguerite were three times higher in November 1994 compared to the other fall sampling dates, possibly a consequence of the extensive forest fires affecting the Kamloops forest district area earlier that year (British Columbia Ministry of Forests, unpub. internal report, 1995).

Five PCB congeners were detected at Yale in the range of 0.10 ng/g to 0.21 ng/g; PCB aroclors and coplanars were below detection limits. Differences in PCB congener concentrations between Shelley, Marguerite, and Yale were within the range of analytical variability. Woodpecker had slightly higher PCB levels than the other Fraser River sites; however, concentrations (converted to nanograms per litre) were well below water-quality guidelines.

Only two pesticides, hexachlorobenzene (0.21 ng/g) and α-hexachlorocyclohexane (0.17 ng/g) were detected at Yale. Their levels did not substantially differ from those at Marguerite, but were 2.6 times and 4.8 times higher, respectively, than levels measured at Shelley.

CONCLUSIONS

This three-year survey of suspended sediments in the upper and middle Fraser and Thompson rivers has clearly shown that pulp-mill-associated contaminants such as dioxins, furans, chlorophenolics, and resin acids continue to be detected downstream of the mills; however, the data show a dramatic reduction in dioxin and furan levels in suspended sediments from those measured in 1990, prior to implementation of chlorine dioxide substitution by the pulp mills. This decrease also has been observed in other basin-wide studies which assessed dioxin and furan levels in river-bed sediments (Brewer et al., 1998) and in mountain whitefish and peamouth chub (Hatfield Consultants, unpub. report, 1997; Raymond et al., 2001). Similarly, levels of pulp-mill-related chlorophenolics measured in river-bed sediments in the upper Fraser River basin (Brewer et al., 1998) also have decreased from levels measured by L. Dwernychuk (unpub. report, 1990) prior to the initiation of pulp-mill-effluent abatement measures.

Levels of polycyclic aromatic hydrocarbons were similarly found to be higher downstream of pulp and paper mills, although the major source of these contaminants is likely to be urban runoff and atmospheric deposition. Their prominence in reaches of the river adjacent to major transportation arteries points to automobile emissions as an important source of these contaminants to the aquatic environment. Polychlorinated biphenyls and organochlorine pesticides were detected in trace levels and do not appear to be of concern.

As guidelines do not presently exist for contaminants associated with suspended sediments, comparisons to guidelines were made by converting concentrations in suspended sediments to concentrations in water. None of the contaminant levels measured in this study exceeded federal guidelines or provincial water-quality criteria for the protection of aquatic life; however, it should be noted that guidelines or criteria do not exist for many organic contaminants measured at elevated levels downstream of pulp-and-paper mills.

Seasonal hydrological changes clearly influenced contaminant concentrations in suspended sediments, as an increase in concentration was evident for many contaminants measured during the winter base-flow period when compared to the fall low-flow period. This increase in contaminant concentrations during the winter base-flow period clearly reflects the effect of flow and natural suspended-sediment reduction associated with winter months. The higher contaminant levels observed during winter base-flow conditions indicate that organisms within the riverine ecosystem may be exposed to a higher degree of contaminant-related stress during the winter in comparison to other times of the year.

The seasonal effect on contaminant levels also was observed in the Thompson River; however, contaminant concentrations in the Thompson River were primarily influenced by seasonally induced limnological cycling of Kamloops Lake, resulting in a definite peak in contaminant levels during winter sampling. This peak also was likely augmented by the relatively high total organic carbon of the suspended sediment collected from the Thompson River during winter sampling.

Whereas winter low flow has been demonstrated to increase the contaminant concentration associated with suspended sediments and water (Sekela et al., 1995), the spring freshet flush has been shown to be a time of contaminant resuspension and transport. Sekela et al. (1994) have demonstrated that suspended sediments showed a measurable increase in contaminant concentration during the onset of freshet and concluded that this increase was likely due to the resuspension of river-bed sediment material deposited during the previous winter base-flow period. This rapid flushing action effectively transports sediments to the Fraser River estuary and beyond into the Strait of Georgia (Fraser River Estuary Management Program, 1996). This contaminant path was traced by Carey and Hart (1988) through their tracking of chlorophenolics released from pulp-and-paper mills in the upper and middle Fraser River to the estuary.

These upstream contaminant inputs may have an impact on the health of the vulnerable Fraser River delta ecosystem, already threatened by heavy industrialization in certain areas and loss of habitat resulting from a rapidly growing population. Many of these contaminants, such as dioxins, furans, chlorophenolics, and PCBs have been shown to bioaccumulate in Fraser River estuary biota such as benthic invertebrates (Richardson and Levings, 1996), peamouth chub and starry flounder (Raymond et al., 2001), herons, cormorants, and eagles (Wilson et al., 1996), and river otters (L. Harding, Environment Canada, pers. comm., 1995). Furthermore, the cumulative effects of exposure to several contaminants, even at low concentrations, is not known.

The results of the current study have established a base line of contaminant levels in the Fraser River basin upstream of Hope, have demonstrated the effect hydrological changes have on contaminant levels, and have shown that dramatic declines in levels of some contaminants have occurred in response to abatement measures implemented in the 1980s and early 1990s.

In general, the environmental quality of the Fraser River basin upstream of Hope is considered to be good, based on the levels of contaminants in suspended sediments; however, it is recommended that periodic monitoring be undertaken to ensure that the environmental quality of the upper and middle river basin does not degrade as a result of increasing stress from population growth.

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REFERENCES

Aizenshtat, Z.
1973: Perylene and its geochemical significance; Geochimica et Cosmochimica Acta, v. 37, p. 559–567.

Bothwell, M., Derksen, G., Nordin, R., and Culp, J.
1992: Nutrient and grazer control of algal biomass in the Thompson River, British Columbia: a case history of water quality management; *in* Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management, (ed.) R.D. Robarts and M.L. Bothwell; National Hydrology Research Institute Symposium Series 7, Environment Canada, Saskatoon, Saskatchewan, p. 253–266.

Bouloubassi, I. and Saliot, A.
1993: Dissolved, particulate and naturally derived polycyclic aromatic hydrocarbons in a coastal environment: geochemical significance; Marine Chemistry, v. 42, p. 127–143.

Brewer, R., Sekela, M., Tuominen, T., and Moyle, G.
1998: Contaminants in bed sediments from 15 reaches of the Fraser River Basin; Aquatic and Atmospheric Sciences Division, Environmental Conservation Branch, Pacific and Yukon Region; Environment Canada, Vancouver, British Columbia, DOE FRAP 1997-37, 68 p.

Brownlee, B. and Strachan, W.
1977: Distribution of some organic compounds in the receiving waters of a kraft pulp and paper mill; Journal of the Fisheries Research Board of Canada, v. 34, p. 830–837.

Brownlee, B., Fox, M., Strachan, W., and Joshi, S.
1977: Distribution of dehydroabietic acid in sediments adjacent to a kraft pulp and paper mill; Journal of the Fisheries Research Board of Canada, v. 34, p. 838–843.

Canadian Environmental Protection Act
1993: Priority substance list assessment report: hexachlorobenzene; Environment Canada, Health and Welfare Canada, 52 p.

Carey, J. and Hart, J.
1988: Sources of chlorophenolic compounds to the Fraser River estuary; Water Pollution Research Journal of Canada, v. 23, p. 55–68.

Czuczwa, J. and Hites, R.
1984: Environmental fate of combustion-generated polychlorinated dioxins and furans; Environmental Science and Technology, v. 18, p. 444–450.
1986: Airborne dioxins and dibenzofurans: sources and fates; Environmental Science and Technology, v. 20, p. 195–200.

Fox, M.
1977: Persistence of dissolved organic compounds in Kraft pulp and paper mill effluent plumes; Journal of the Fisheries Research Board of Canada, v. 34, p. 798–804.

Fraser River Estuary Management Program
1996: Fraser River Estuary Management Program; Burnaby, British Columbia (ISBN 0-7726-3038-0), 164 p.

Gilman, A. and Newhook, R.
1991: An updated assessment of the exposure of Canadians to dioxins and furans; Chemosphere, v. 23, p. 1661–1667.

Horowitz, A., Elrick, K., and Hooper, R.
1989: A comparison of instrumental dewatering methods for the separation and concentration of suspended sediment for subsequent trace element analysis; Hydrological Processes, v. 2, p. 163–189.

Inland Waters Directorate
1986: Detailed surface water quality data — Alberta, Manitoba, Northwest Territories and Saskatchewan; Environment Canada, Inland Waters Directorate, Western and Northern Regions, Water Quality Branch, Regina, Saskatchewan, 276 p.

Karickhoff, S., Brown, D., and Scott, T.
1979: Sorption of hydrophobic pollutants on natural sediments; Water Research, v. 13, p. 241–248.

Knap, A. and Williams, P. Le B.
1982: Experimental studies to determine the fate of petroleum hydrocarbons from refinery effluent in an estuarine system; Environmental Science and Technology, v. 16, p. 1–4.

Leach, J. and Thakore, A.
1976: Toxic constituents in mechanical pulping effluents; Tappi, v. 59, p. 129–132.

Liebergott, N., van Lierop, B., Nolin, A., Faubert, M., and Laflamme, J.
1991: Modifying the bleaching process to decrease AOX formation; Pulp and Paper Canada, v. 92, p. T70–T75.

Lockhart, W., Wagemann, R., Tracey, B., Sutherland, D., and Thomas, D.
1992: Presence and implications of chemical contaminants in the freshwaters of the Canadian Arctic; The Science of the Total Environment, v. 122, p. 165–243.

Mah, F., MacDonald, D., Sheehan, S., Tuominen, T., and Valiela, D.
1989: Dioxins and furans in sediment and fish from the vicinity of ten inland pulp mills in British Columbia; Environment Canada, Pacific and Yukon Region, Inland Waters Directorate, Water Quality Branch, 77 p.

Northwest Hydraulic
1993: Determination of Sediment Deposition Zones — Fraser River Basin; prepared for Environment Canada, Conservation and Protection, North Vancouver, B.C.; Northwest Hydraulic Consultants, Vancouver, British Columbia, DOE FRAP 1994-32, 65 p.

Pastershank, G. and Muir, D.
1995: Contaminants in environmental samples: PCDDs and PCDFs downstream of bleached kraft mills — Peace and Athabasca rivers, 1992; Northern Rivers Basins Study, Edmonton Alberta, Project Report No. 44, 80 p.

Raymond, B.A., Shaw, D.P., Kim, K., Nener, J., Baldazzi, C., Brewer, R., Moyle, G., Sekela, M., and Tuominen, T.
2001: Fraser River Action Plan Resident Fish Contaminant and Health Assessment; Aquatic and Atmospheric Sciences Division, Environmental Conservation Branch, Pacific and Yukon Region; Environment Canada, Vancouver, British Columbia, DOE FRAP 1998-20.

Richardson, J. and Levings, C.
1996: Chlorinated organic contaminants in benthic organisms of the lower Fraser River, British Columbia; Water Quality Research Journal of Canada, v. 31, p. 153–162.

Schreier, H., Brown, S., and Hall, K.
1991: The land-water interface in the Fraser River Basin; *in* Water in Sustainable Development: Exploring Our Common Future in the Fraser River Basin, (ed.) H.J. Dorcey, and G. Griggs; Westwater Research Centre, University of British of Columbia, Vancouver, British Columbia, p. 77–100.

Sekela, M., Brewer, R., Baldazzi, C., and Moyle, G.
1994: Change in contaminant concentration in Fraser River suspended sediments and water during the onset of freshet (Marguerite — 1993); Science Division, Environmental Conservation Branch, Pacific and Yukon Region, Environment Canada, North Vancouver, British Columbia, DOE FRAP 1994-29, 94 p.

Sekela, M., Brewer, R., Baldazzi, C., Moyle, G., and Tuominen, T.
1995: Survey of contaminants in suspended sediments and water in the Fraser River Basin; Aquatic and Atmospheric Sciences Division, Environmental Conservation Branch, Pacific and Yukon Region, Environment Canada, Vancouver, British Columbia, DOE FRAP 1995-21, 170 p.

St. John, B., Carmack, E., Daley, R., Gray, C., and Pharo, C.
1976: The limnology of Kamloops Lake, British Columbia; Environment Canada, Inland Waters Directorate, Pacific and Yukon Region, Vancouver, British Columbia, 167 p.

Wilson, L., Elliot, J., and Whitehead, P.
1996: Chlorinated compounds in wildlife from the Fraser River Basin; Environment Canada, Environmental Conservation Branch, Canadian Wildlife Service, Delta, British Columbia, DOE FRAP 1996-09, 73 p.

Windholtz, M., Budavari, S., Blumetti, R., and Otterbein, E. (ed.).
1983: The Merck Index. An Encyclopedia of Chemicals, Drugs and Biologicals; 10th edition, Merck and Co., Inc., Rahway, New Jersey, 2179 p.

Tidal marshes of the Fraser River estuary: composition, structure, and a history of marsh creation efforts to 1997

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Adams, M.A. and Williams, G.L., 2004: Tidal marshes of the Fraser River estuary: composition, structure, and a history of marsh creation efforts to 1997; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 147–172.*

Abstract: Tidal marshes support important habitat for the fish and wildlife of the Fraser River estuary. The presence and distribution of plant species within these marshes are governed by salinity and tidal inundation. These parameters are in turn related to the location of the salt wedge within the estuary. Distinct salt-, brackish-, and fresh-marsh species assemblages occur throughout the estuary as a result of these influences.

Past human activities have resulted in the net loss of tidal marsh, impacting the estuary's ability to sustain fish and wildlife.

Tidal-marsh creation is a technical tool to achieve environmentally sustainable development within the estuary. Early marsh-creation efforts achieved limited success. Deficiencies in project performance were primarily a result of poor quality assurance and control during site preparation and planting. Recent efforts have achieved excellent success in establishing tidal marshes through an intense focus on compliance with sound design criteria.

Résumé : Les marais littoraux fournissent un habitat important pour la faune de l'estuaire du Fraser. La présence et la distribution des espèces végétales dans ces marais sont régies par la salinité et par l'inondation due à la marée, lesquelles dépendent à leur tour de la position du coin salé dans l'estuaire. Ces influences donnent lieu à des assemblages distincts d'espèces qui vivent dans les marais d'eau salée, saumâtre ou douce de l'estuaire.

L'activité humaine à ce jour a entraîné une perte nette de marais littoraux, ce qui a affecté la capacité de l'estuaire à assurer la subsistance de la faune.

La création de marais littoraux est un outil technique qui contribue au développement écologiquement durable de l'estuaire. Les premières tentatives de création de marais ont eu peu de succès. Les lacunes dans le rendement des projets étaient principalement dues à des déficiences de l'assurance et du contrôle de la qualité lors de la préparation du site et de la plantation. Grâce à une rigoureuse adhésion à de solides critères de conception, des efforts plus récents ont été couronnés de succès.

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INTRODUCTION

The Fraser River estuary supports a tidal wetland resource that is an integral and critical component of the ecology of the Pacific coast of North America. Centrally located along the Pacific flyway, it annually provides staging and feeding areas for millions of migratory birds during the spring breeding and fall wintering migrations. It also annually provides valuable nursery habitat for hundreds of millions of juvenile salmonid fish and sustains a myriad of ecological functions for resident fish and wildlife throughout the year.

The lowlands of the estuary and surrounding areas sustain a human population of over 1.5 million. Residential, commercial, and industrial developments and associated uses constantly interact with the natural environments of the estuary, and often limit the extent to which these environments can sustain fish and wildlife. Impacts include the loss of nearshore subtidal environments associated with port expansion on the delta front, net loss of sediment supply associated with dredging of the lower distributary channels, accumulation of mill-generated woody debris on intertidal marshes, and development of recreational beaches within shoreline environments.

Conflicting uses within the estuary have required special resource-management initiatives. The Fraser River Estuary Management Program (FREMP), a co-operative agreement amongst provincial and federal government agencies and administrations to facilitate a co-ordinated project review process, was initiated in 1986. To achieve environmentally sustainable development within the estuary, FREMP depends strongly upon the legislative clout afforded by the federal *Fisheries Act*. The Department of Fisheries and Oceans enforces this legislation. To facilitate achievement of its own departmental objectives, the Department of Fisheries and Oceans introduced in 1986 its national fish habitat policy and the guiding principle of 'no-net-loss' of the productive capacity of fish habitat. The Fraser River Estuary Management Program and the national fish habitat policy of the Department of Fisheries and Oceans are key ingredients for sustainable natural resource management within the Fraser River estuary.

One of the important natural resources of the estuary is its tidal marshes. These emergent plant communities consist of assemblages of salt, brackish, and fresh species. Despite the importance of tidal marshes as fish and wildlife habitat, relatively little study has been conducted upon the species composition and structure of these communities. Furthermore, the majority of the studies have been conducted within the lower estuary, at the delta front, and within the lower reaches of the main distributary channels. Study of tidal fresh marshes of the upper distributary channels has been cursory.

Despite the paucity of knowledge and understanding of the ecology of tidal marshes of the Fraser River estuary, natural resource management agencies have utilized tidal-marsh creation as a means to achieve environmentally sustainable development within the estuary. Marsh creation, a highly visible indication of active management, has been and continues to be one of the primary technical tools exploited by these agencies.

This paper presents a summary of literature regarding plant-species composition and structure of tidal marshes within the Fraser River estuary. It introduces a hypothesis as to the primary factors that may account for the presence and organization of species within tidal fresh marshes of the upper estuary. A history of tidal-marsh creation within the estuary is presented, and suggestions for future research are provided.

FRASER RIVER HYDROLOGY AND SALINITY

The Fraser River estuary is located at the western edge of the Fraser Lowland in southwestern British Columbia (Fig. 1). The lowland is a triangular area bounded on the west by the Strait of Georgia, on the north by the Coast Mountains, and on the south and southeast by the Cascade Mountains.

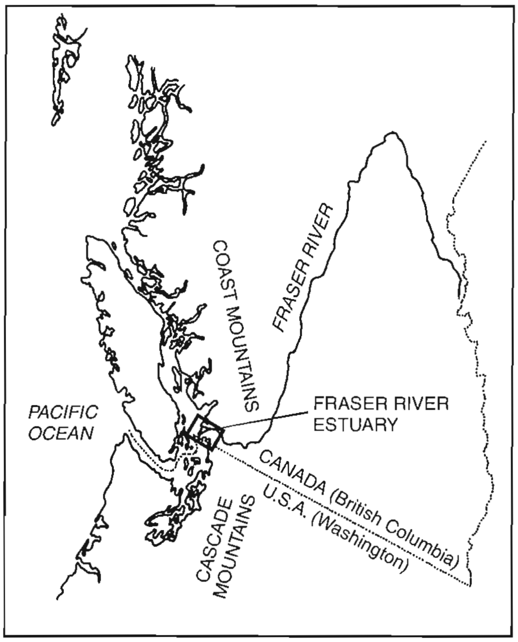
The Fraser River drainage basin encompasses approximately 233 000 km^2. About two thirds of the precipitation within the basin falls as snow (Ages and Woollard, 1976). During freshet, when melting of the snowpack in late spring and early summer causes a rapid rise in discharge, the average discharge is typically 9600 m^3/s. Discharges during freshet may reach 15 600 m^3/s. Discharges during winter may be as low as 340 m^3/s.

The oceanographic characteristics of the Fraser River estuary are strongly affected by the quantity, quality, and timing of freshwater discharge and by the tides and winds of the Strait of Georgia. Surface current patterns, especially in those portions of the river that are partially trained by jetties and groins, are strongly dominated by river flows. These fresh waters are less dense than the saline waters of the Strait of Georgia, and as a result, a halocline occurs within the lower estuary. The halocline persists, as the water column is not sufficiently mixed by tidal and wind action to adequately intergrade these two layers.

The denser saline waters tend to flow upstream underneath the downstream-flowing fresh waters until an equilibrium of the vertical pressures is reached (Tamburi and Hay, 1978). When this equilibrium is achieved, a curved interface between the salt water and the fresh water is formed, creating a salt wedge (Fig. 2). Salt water flows upstream along the river bottom until it reaches an area of zero velocity. This is where the interface touches the bottom. The upstream flow of salt water along the bottom replaces the salt water that is carried off by turbulent mixing with fresh water at the interface. The position of the interface and the zero-velocity point vary with both tide and freshwater discharge.

When freshwater discharge is low, the penetration of the salt wedge within the main distributary channel, the 'South Arm', extends to approximately 32 km upstream of the mouth of the channel (A. Tamburi and D. Hay, unpub. report, 1978); this corresponds to approximately the upstream end of Annacis Island. As the freshet commences, the location of the salt water–fresh water interface moves downstream due to increasing vertical pressures. Above a freshwater discharge of approximately 10 000 m^3/s, the salt wedge moves completely out of the 'South Arm'.

The halocline delineating the two layers of water can be dramatic. Salinity at 3.1 m below surface at the mouth of the 'South Arm' (at Sand Heads) in August can be 0.0 ppt, whereas at 9.0 m below surface, the salinity can be 25 ppt (Ages and Woollard, 1976). Detailed salinity distributions in the Fraser River estuary for 1976 and 1977 were determined by Ages (1979). Surface waters in the lower river, to at least Steveston, were almost invariably fresh during the period of mid-May to mid-August. Salinity as far as Sand Heads seldom exceeded 0.0 ppt during this same period. Slightly brackish surface waters occasionally penetrated the outer estuary during August and September, and by December, the month of lowest discharge, surface salinities in the range of 0 to 4 ppt were recorded upstream as far as Ladner Marsh.



The tides of the Strait of Georgia and those of the Fraser River estuary are characterized by a mixture of diurnal and semidiurnal inequality that affects both the time and the height of the tide. This inequality occurs principally in the time and in the height of succeeding low tides. Tidal ranges have a cycle of approximately two weeks, as well as a seasonal cycle. In the Fraser River estuary, the lowest tide occurs near midnight in the winter months and during midday in the summer months.

DISTRIBUTION OF PLANT SPECIES WITHIN THE FRASER RIVER ESTUARY

Current knowledge

The plant species that occur in tidal marshes along the Pacific coast of North America are typically found in recurring and well described patterns, zoned by a conspicuous gradient of tidal inundation (Yamanaka, 1975; Moody, 1978; del Moral and Watson, 1978; Disraeli and Fonda, 1979; Burg et al., 1980; W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw,

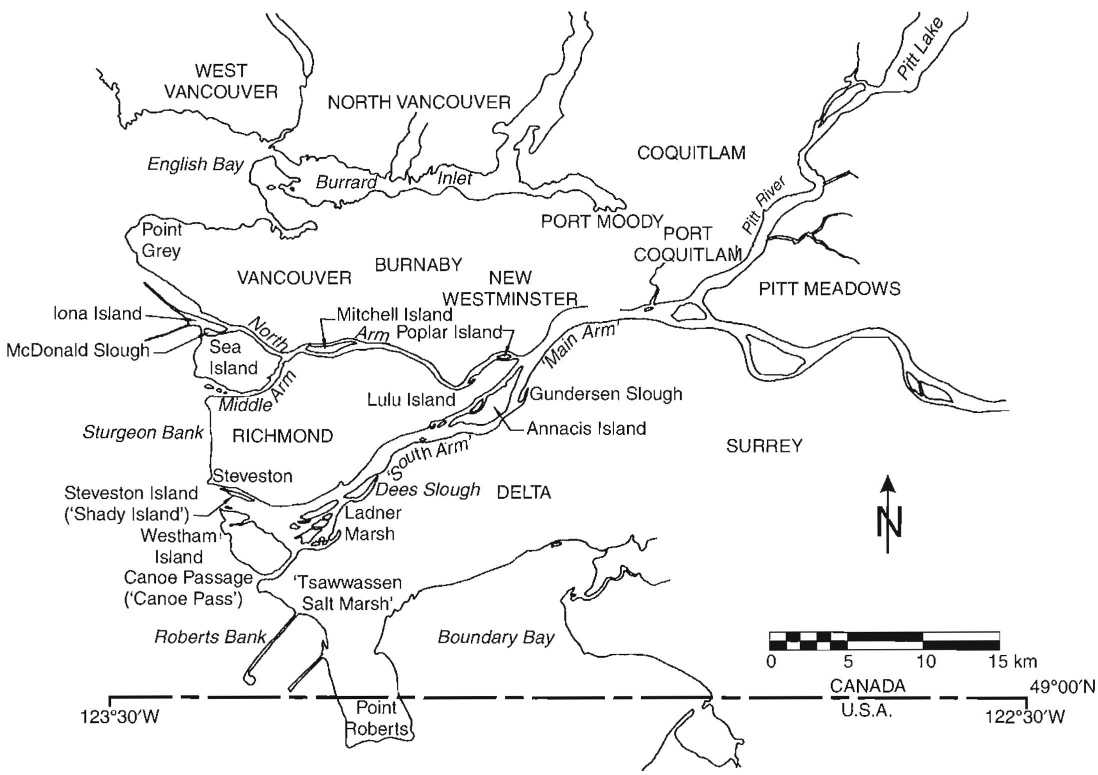


Figure 1. Map of the Fraser River estuary showing locations mentioned in the text.

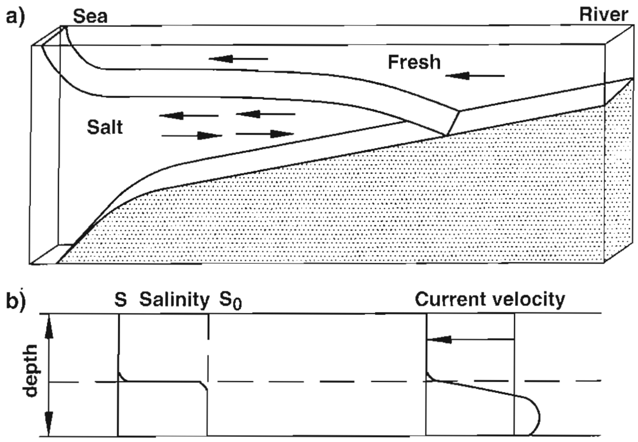


Figure 2. A salt wedge: ***a)*** *longitudinal section along an estuary;* ***b)*** *typical salinity and velocity profiles* (after *Bowden, 1967).*

and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980; Dawe and White, 1982, 1986; Hutchinson, 1982; Vince and Snow, 1984; M.A. Adams and P. Paterson, unpub. report, 1988). This pattern is not restricted to the Pacific coast of North America. It has been well described for tidal marshes on the Atlantic coast of North America, Britain, and northern Europe (Chapman, 1960; Adams, 1963; Ranwell, 1972; Redfield, 1972).

This conspicuous pattern has led researchers to investigate the role of physical factors in determining plant-species vigour and zonation. Several physical factors influenced by tidal inundation have been suggested as playing a key role in the distribution of plant species. These have included soil oxygen concentrations (Howes et al., 1981; Mendelssohn et al., 1981), flooding and drainage (Disraeli and Fonda, 1979; Mendelssohn and Seneca, 1980; Armstrong et al., 1985), nutrient limitation (Valiela and Teal, 1974), and soil sulphide accumulation (King et al., 1982). Salinity has been found to affect both the horizontal and vertical distribution of plant species within a tidal marsh (Burg et al., 1980; Hutchinson, 1982; Ewing, 1983, 1986). The horizontal distribution of plant species is often a function of the proximity to freshwater discharge. The vertical distribution is typically a result of the extent of inundation by saline waters. Zonation is likely a manifestation of a combination of parameters that impose a complex cumulative effect on plant-species vigour (Ewing, 1986).

The roles of interspecific plant competition, herbivory, and physical disturbance in determining the spatial distribution of plant species have not been afforded much attention by researchers. Interspecific plant competition has rarely been investigated (Silander and Antonovics, 1982; Ellison, 1987; Pidwirny, 1990), although it has been suggested that it is important in structuring tidal-marsh communities (Pielou and Routledge, 1976; Gray and Scott, 1977; Snow and Vince, 1984). Several researchers have suggested that herbivory is not an important determinant of plant distribution (Smalley, 1960; Teal, 1962; Denno, 1977; Vince et al., 1981; Bertness et al., 1986; Bertness and Ellison, 1987); however, several growing populations of Canada geese (*Branta canadensis*) within the Fraser River estuary have been observed by the present authors to selectively graze upon sedge and grass species to such an extent as to exclude forage species from the species assemblage of affected marshes.

When the influence of physical disturbance on the spatial distribution of plant species has been investigated (Reidenbaugh and Banta, 1980; Hartman et al., 1983; Bertness and Ellison, 1987), the vector of disturbance has appeared to be primarily the deposition of wrack (i.e. dead plant material) upon the above-ground parts of emergent species. Wrack buries and smothers the vegetation, eventually killing it. Adams (1993) suggested that the colonization of tidal marshes by purple loosestrife (*Lythrum salicaria*) is facilitated by disturbance. Although wrack may be a significant agent of disturbance, the primary agent of disturbance within the Fraser River estuary appears to be wood debris, especially in tidal freshwater portions of the distributary channels. The primary industrial user of the Fraser River estuary is the lumber industry; both mills and log-storage facilities are located in close proximity to tidal marshes. Interestingly, the most vigorous stands of loosestrife appear to be within those tidal marshes with substantial log debris.

The earliest detailed floristic description of estuarine marshes in the Fraser River estuary was provided by Burgess (1970), who investigated the emergent communities of tidal marshes seaward of Iona Island, Sea Island, and Lulu Island within the island complex that includes Woodward Island, Ladner Marsh, and Brunswick Point. He mapped the distribution of prevalent marsh species, calculated seed-production indices, and separated the tidal marshes into upper and lower zones according to species composition. Fourteen species were identified within two zones, of which five sedge (Cyperaceae) species, *Carex lyngbyei*, *Scirpus validus*, *Scirpus americanus*, *Scirpus maritimus*, and *Eleocharis palustris*, encompassed 93% of the total area of marsh within the study area. *S. americanus* and *C. lyngbyei*, the dominant species within the upper and lower intertidal zones, respectively, accounted for 70% of the total area of marsh.

Yamanaka (1975) measured primary productivity and mapped zones of species dominance of tidal marshes located at the seaward end of the estuary. His study area included Sturgeon Bank, Roberts Bank, and Boundary Bay. With the exception of a transect at Iona Island where little emergent vegetation was encountered, the general sequence of dominant species for Sturgeon Bank, in order of decreasing elevation, was *Typha latifolia*, *Carex lyngbyei*, *Scirpus validus*, *Scirpus maritimus*, and *Scirpus americanus*. The sequence of occurrence was often repetitive, and at times one species was absent from the community surveyed. For the Roberts Bank transects, a transect at Reifel Island in proximity to the main discharge channel of the river was similar in structure to that of the Sturgeon Bank communities; the general sequence of dominant species was *T. latifolia* to *C. lyngbyei* to *S. americanus*. Farther from the discharge channel to the south within 'Tsawwassen Salt Marsh', the dominant species were halophytes such as *Distichlis spicata* and *Salicornia virginica*.

Parsons (1975) mapped six plant communities that occurred within a salt marsh at Boundary Bay. The plant communities were delineated according to the fidelity of species presence and elevation as well as soil conductivity. *Distichlis spicata* appeared to transcend the range of elevations occupied by emergent vegetation; it was a codominant of the high marsh with *Grindelia integrifolia*, and it was a codominant of the low marsh with *Salicornia virginica*.

The 'Tsawwassen Salt Marsh', within the intercauseway area of Roberts Bank, was described further by Hillaby and Barrett (1976). They did not emphasize the delineation of distinct vegetation communities across the landscape, but rather the description of species assemblages and corresponding elevations within quadrats sampled systematically along transects that dissected the marsh. The marsh was partially enclosed by a dyke along its seaward boundary and did not encompass the range of elevations inhabited by halophytes within the intercauseway area. The marsh in essence was a high-elevation marsh with the species assemblages dominated by *Distichlis spicata*.

Moody (1978) investigated the primary productivity, decomposition, and spatial and temporal distributions of emergent plant species within a tidal marsh at Brunswick Point. As described by Yamanaka (1975), the species were distributed along both an elevational gradient and a salinity gradient that runs approximately north to south along Roberts Bank. Dominant species throughout Brunswick Point, in close proximity to Canoe Passage (locally known as 'Canoe Pass'), were *Carex lyngbyei*, *Scirpus americanus*, and *Scirpus maritimus*. The southern portions of the marsh further away from the influence of Canoe Passage were dominated by *Triglochin maritimum*, *Distichlis spicata*, and *Salicornia virginica*.

As part of a program that assessed the use of dredge spoil for marsh creation, W.S. Boyd and co-workers (W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980) collected biophysical data pertaining to 14 tidal marshes, ranging from low-salinity brackish (0–4 ppt, measured from May through August, 1979) to fresh marshes. The low-salinity brackish marshes in proximity to Steveston Island (locally known as 'Shady Island') exhibited classic maritime structure; zones of vegetation of relatively low species diversity occurred at lower elevations, whereas vegetation zones of relatively higher species diversity occurred at higher elevations. The dominant species of lower elevations, often forming near-monospecific stands, were *Carex lyngbyei*, *Scirpus validus*, *Scirpus americanus*, and *Eleocharis palustris*. Prevalent species of higher elevations were *Typha latifolia*, *Phalaris arundinacea*, *Glyceria grandis*, *C. lyngbyei*, *Juncus balticus*, *Potentilla pacifica*, and *Lythrum salicaria*. Tidal fresh marshes near the mouth of the estuary upstream of Steveston Island ('Shady Island') exhibited the same relationship between elevation and species diversity. *Scirpus americanus* was not observed within these marshes, its absence apparently related to the lack of persistent saltwater intrusion within the lower intertidal zone.

Boyd and co-workers (W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980) observed that further upstream in the estuary, in proximity to Annacis Island, where tidal influence is less dramatic and the salt wedge is rarely encountered, the structure of tidal fresh marshes departed from that of the classic maritime marshes of the lower river. Stratified zones of near-monospecific stands of vegetation were not as frequently encountered. In general, plant-species diversity was relatively constant within each individual marsh. The upstream limit of *Carex lyngbyei* occurred near the upstream end of Annacis Island.

Shepperd (1981), as part of a study investigating the development of a late Holocene salt marsh at Boundary Bay, distinguished the vegetation zones of a present-day salt marsh. The landward portion of the marsh consisted of a species assemblage dominated by grasses. Along the banks of a small tidal channel that traversed this zone occurred a second assemblage that included *Grindelia integrifolia*, *Distichlis spicata*, and *Salicornia virginica,* and a third assemblage immediately beyond the top-of-bank that included *Aster subspicatus*, *Rumex crispus*, and *Achillea millefolium*. Seaward of these zones an assemblage dominated by *S. virginica*, *G. integrifolia*, *Atriplex patula*, and *Vicia sativa* occurred. The seaward boundary of this zone was demarcated by a wrack corridor within which *A. patula* dominated. The next zone was marked by an assemblage dominated by *Spergularia marina*, *Triglochin maritimum*, and *S. virginica*, where the subdominant assemblage included *G. integrifolia*, *D. spicata*, and *Plantago maritima* at the landward edge of the zone. The seaward edge of this zone was characterized by *S. virginica* and *T. maritimum*.

Hutchinson (1982) conducted an investigation of the plant-environment relations of foreshore marshes located on Sturgeon Bank fronting Lulu Island. Three elevational zones of vegetation were described: a low-elevation marsh dominated by *Scirpus americanus* and *Scirpus maritimus*; a middle-elevation marsh dominated by *Carex lyngbyei*, *Triglochin maritimum*, and *S. maritimus*; and a high-elevation marsh community of *Agrostis exarata*, *Distichlis spicata*, and *Typha latifolia*. Hutchinson (1982) interpreted this as a successional sequence. The spatial distribution of all seven species was mapped. The distribution of *T. latifolia*, *D. spicata*, and *Potentilla pacifica* appeared to be influenced only by marsh surface elevation, while the distribution of *S. americanus*, *S. maritimus*, *C. lyngbyei*, and *T. maritimum* appeared to be influenced by both elevation and salinity. Substrate texture and moisture were associated with species abundance.

Bradfield and Porter (1982) investigated the vegetation structure of portions of Ladner Marsh. Cluster analysis of vegetation-cover data identified seven community subgroups within three main community groups that had been subjectively described in the field. The main groups consisted of a *Carex lyngbyei* zone within regularly flooded, well drained areas; a *Festuca arundinacea–Salix lasiandra* zone associated with the crests of levees; and a mixed forbs zone, characterized by *Menyanthes trifoliata,* that occurred within regularly flooded, but poorly drained areas. Ordination results suggested relationships between trends in compositional variation and particular environmental gradients. The principal ordination axes appeared to be related to substrate drainage and to total period of inundation, suggesting that these two components of the hydrological regime operate independently to control vegetation pattern. Elevation above local low water was not found to be a reliable predictor of vegetation.

Porter (1982) investigated the quantitative relationships between species performance and distribution and several environmental parameters at marshes located at Ladner Marsh, Brunswick Point, and Boundary Bay. The environmental parameters included soil texture (per cent sand, silt, and clay), elevation, and soil concentrations of nitrogen, potassium, calcium, magnesium, and sodium. The marshes separated conspicuously into two types according to floristic and environmental criteria: a fresh-to-brackish type at Ladner Marsh and in northern and western Brunswick Point; and a saline type in southeastern Brunswick Point and at Boundary Bay. Within both types, four main species-environment sample groups were identified. Within the fresh-to-brackish type, the groups were dominated by *Carex lyngbyei* and *Agrostis alba*; *A. alba* and *Scirpus maritimus*; *Scirpus americanus;* and *Equisetum fluviatile*, *Scirpus validus*, *A. alba*, and *Alisma plantago-aquatica*. Within the saline type, the groups were dominated by *Atriplex patula*; *C. lyngbyei* and *Distichlis spicata*; *Salicornia virginica* and *Triglochin maritimum*; and *Spergularia canadensis*.

M.A. Adams and P. Paterson (unpub. report, 1988) conducted a survey of intertidal marshes throughout the estuary on a reach-by-reach basis. Reaches were delineated by 0.4 m intervals in low-water elevation, as indicated by Public Works Canada Annual Survey Maps of the estuary. At least three representative transects per reach were sampled. A total of 56 transects within 14 reaches were sampled. All marshes sampled were either brackish or fresh. A typical sequence of vegetation-elevation zones near the mouth of the estuary, in order of decreasing elevation and according to a single dominant emergent species, was *Typha latifolia*, *Carex lyngbyei*, *Scirpus validus*, and *Eleocharis palustris*. These zones were characterized by relatively low species diversity. Marshes near the upstream limit of the salt wedge displayed a wide variation in vegetation-elevation species sequences. Some marshes roughly paralleled the sequence exhibited near the mouth of the estuary, whereas others exhibited a sequence where the dominants of the lower estuary were either complemented or replaced by other emergent species such as *Equisetum fluviatile*, *Phalaris arundinacea*, and *Carex* species other than *C. lyngbyei*. Marshes upstream of the upper limit of the salt wedge typically exhibited vegetation-elevation zones characterized by several species rather than a single species, and by relatively high species diversity. *C. lyngbyei* was absent from these marshes. Species typical of nontidal wetlands within southwestern British Columbia, such as *Carex rostrata*, were common.

The salt wedge and tidal-marsh structure

As described in the literature, low-elevation tidal marshes at the delta front, immediately above unvegetated tidal flats, are dominated by near-monospecific stands of *Scirpus americanus*. Patches of *Scirpus maritimus* occasionally occur within these stands. As one approaches the distributary channels, at locations such as Canoe Passage ('Canoe Pass'; Westham Island), Steveston Island ('Shady Island'; 'South Arm'), Siwash Island (Middle Arm), and 'Musqueam Marsh' (North Arm), the low marsh is composed of several species in addition to *S. americanus* and *S. maritimus*, including *Scirpus validus*, *Carex lyngbyei*, and *Eleocharis palustris*. Both species assemblages may be considered low-elevation tidal marshes, the former being high-salinity brackish (4–28.5 ppt) and the latter low-salinity brackish (0–4 ppt) marsh. Farther upstream within the distributary channels, at locations such as Bridgeport (immediately upstream of the split of the North and Middle arms) and Ladner Marsh, *S. americanus* and *S. maritimus* disappear from the low-elevation marsh assemblage and are replaced by typical fresh-marsh species such as *Equisetum fluviatile* and *Juncus articulatus*.

The stratified nature of the water column within the lower Fraser River estuary has manifested itself upon the structure of tidal marshes throughout most of Sturgeon and Roberts banks and the seaward reaches of the distributary channels. The low- to middle-elevation marshes are occupied by modestly salt-tolerant species such as *Scirpus americanus*, *Scirpus maritimus*, and *Carex lyngbyei*, whereas the high-elevation marsh is characterized by the salt-intolerant *Typha latifolia*. It is apparent that even low-salinity brackish waters rarely inundate high tidal elevations.

The majority of descriptive studies of tidal marshes within the lower estuary have noted that marked transitions between salt, brackish, and fresh marshes are accompanied by marked changes in the composition of species. Throughout all of the marshes described, irrespective of the salinity regime, the classic maritime structure is prevalent. Tidal fresh marshes within the distributary channels of the lower Fraser River estuary, well upstream of the delta front, exhibit this structure. It is apparent that tidal inundation, and not salinity, is the primary contributing factor in the expression of the classic maritime structure. At some point within the estuary, however, other hydraulic processes must interfere with tidal processes sufficiently to cause the abandonment of this structure. There has yet to be a study that specifically investigates at what point within the estuary the classic maritime structure disappears, and what factors contribute to this change in structure.

It is proposed that, for salt-wedge estuaries such as the Fraser River estuary, a relationship exists between the upstream limit of the salt wedge and the upstream limit of marshes exhibiting the classic maritime structure. As the classic maritime structure is often depicted by zones of a single dominant species, the distribution of dominant species throughout the estuary should provide some insight as to where within the estuary the classic maritime structure is abandoned. The dominant species of tidal marshes throughout the distributary channels and the lower 'Main Arm' of the

Fraser River and the Pitt River downstream of Pitt Lake are presented in Tables 1 and 2. The locations of these tidal marshes are depicted in Figure 3.

A review of data collected by Boyd and co-workers (W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980) and M.A. Adams and P. Paterson (unpub. report, 1988) for the 'South Arm' of the Fraser River suggests a relationship between the salt wedge and the tidal marshes exhibiting the classic maritime structure. Distinct zones of vegetation consistently occur in sequence on an elevational gradient within the 'South Arm' and become increasingly infrequent upstream of Annacis Island. This phenomenon concurs approximately with the upstream extent of the salt wedge within the 'South Arm'. The salt wedge apparently does not have to bathe the intertidal elevations inhabited by a marsh exhibiting the classic maritime structure; it simply has to be a consistent component of the water column.

A hypothetical model is proposed to explain this apparent relationship between community structure and the salt wedge. In this model, the upper boundary of the wedge acts as a false channel bottom, with fluvial fresh waters flowing above the denser marine salt waters. As the wedge moves upstream during a flood tide, it displaces fluvial waters vertically, flooding the tidal marshes of the distributary channels. The flooding is relatively dramatic, with the downstream flow of fluvial water not directly opposing its vertical displacement. This flooding regime would account for the classic maritime structure of tidal marshes within the distributary channels.

In contrast, for those reaches of the river upstream of the wedge, tidal flooding is relatively gradual. The rise in water levels is due to the false channel bottom of the salt wedge at its upstream limit acting as a temporary weir. As any weir does, the elevated bottom acts as an impediment to fluvial flows, resulting in a decrease in the hydraulic head of the river channel. Backflooding (i.e. the reversal of surface flows with a concurrent rise in water level) occurs as the false channel bottom rises with the upstream movement of the salt wedge. The vertical displacement is mitigated by downstream-flowing waters that directly oppose backflooding waters. There is a constant opposing interaction between tidal and fluvial processes that results in a flooding regime that is shorter in duration and narrower in elevational range than the flooding regime directly associated with the wedge. Classic maritime structure cannot be sustained by this flooding regime.

The physiological stress imposed upon marsh plants by the relatively severe tidal inundation regime directly associated with the salt wedge limits the number of species that can inhabit the intertidal zone and contributes to the classic maritime structure observed within tidal fresh marshes of the 'South Arm' downstream of Annacis Island. These tidal fresh marshes are characterized by up to five distinct zones of vegetation, each dominated by a single species. These species are tolerant of extended periods of tidal inundation. Other species, many of which are typical of nontidal fresh marshes, are poorly adapted to extended periods of tidal inundation, and accordingly are poorly represented in the species assemblages of these tidal fresh marshes. In contrast, the relatively less dramatic and less severe inundation regime of those portions of the estuary upstream of Annacis Island precludes few species that typically occur within nontidal wetlands. The result is the abandonment of the classic maritime structure, with the assemblage of species characterized by few dominant species and greater species diversity.

MARSH CREATION

The mandate for the management of tidal marshes within the Fraser River estuary primarily rests with the federal Department of Fisheries and Oceans. Although the provincial Ministry of Environment, Lands and Parks and the federal Department of Environment do participate in the management of tidal marshes within the estuary, only the Department of Fisheries and Oceans possesses legislation (i.e. the federal *Fisheries Act*) that can accomplish effective enforcement of its policies.

Within the Fraser River estuary, the management of social, economic, and environmental resources is conducted under the auspices of the Fraser River Estuary Management Program (FREMP), which was created to improve the co-ordination of the various regulatory agencies active within the estuary. A co-ordinated review process is facilitated for all development project applications within the estuary. The review process is primarily managed by a lead agency and the FREMP Environmental Review Committee. Lead agencies, which are authorized to regulate the right to occupy or lease land or water lots not privately owned, serve as the prime contact throughout the project review process. The Environmental Review Committee is responsible for reviewing all projects from an environmental perspective; a strong emphasis is placed on fish and wildlife habitat issues. The member agencies of the Environmental Review Committee are the Department of Fisheries and Oceans, the Ministry of Environment, Lands and Parks, and the Department of Environment.

The mandate of the Department of Fisheries and Oceans is applied under the auspices of FREMP. The guiding principle of the fish-habitat policy of the Department of Fisheries and Oceans is the 'no-net-loss' of fish habitat. The design of the proposed works must demonstrate the mitigation of impacts to habitat to the fullest extent possible. In the event of unmitigable impacts to fish habitat, the impacts must be compensated by the creation of replacement habitats. The creation of tidal marshes has often been used as compensation.

Until recently, the creation of tidal marsh as compensation has been undertaken without a concurrent commitment to post-construction monitoring. Early projects did not include the collection of quantitative data to assess the adequacy of marsh-creation efforts in achieving design criteria. As a result, quantitative information regarding the biophysical parameters of created tidal marshes is scarce. Today, quantitative data are collected as part of multi-year monitoring programs; however, monitoring protocols are not standardized, rendering comparison of data from different projects difficult.

1. Reifel #1
2. Reifel #2
3. Shady Island #1
4. Shady Island #2
5. Canoe Pass #1
6. Canoe Pass #2
7. Steveston
8. Gilbert Road
9. Ewen Slough
10. Finn Slough
11. Rose Island
12. Kirkland Island
13. Dees Slough
14. Trimac #1
15. Trimac #2
16. Chatterton #1
17. Chatterton #2
18. Dow Island
19. Dow Chemical
20. Cypress
21. Gundersen Slough #1
22. Gundersen Slough #2
23. Annieville Channel #1
24. Annieville Channel #2
25. Annieville Channel #3
26. Annacis Channel #1
27. Annacis Channel #2
28. Annacis Channel #3
29. Annacis Channel #4
30. Wreck Beach #1
31. Wreck Beach #2
32. Wreck Beach #3
33. Musqueem
34. Iona Island
35. McDonald Slough
36. Woods Island Slough #1
37. Woods Island Slough #2
38. Terra Nova
39. McCallen Road
40. Telegraph Cove
41. Bridgeport
42. Crown Forest
43. No. 6 Road #1
44. No. 6 Road #2
45. No. 8 Road #1
46. No. 8 Road #2
47. Byrne Road Park #1
48. Byrne Road Park #2
49. Tree Island
50. Poplar Island #1
51. Poplar Island #2
52. Timberland #1
53. Timberland #2
54. Timberland #3
55. Sapperton Bar
56. Lafarge #1
57. Lafarge #2
58. Lafarge #3
59. Coquitlam River #1
60. Coquitlam River #2
61. Douglas Island
62. Rivlow
63. Kanaka Island
64. Chatham Reach
65. Kennedy Island
66. Goose Island #1
67. Goose Island #2
68. McIntyre Creek

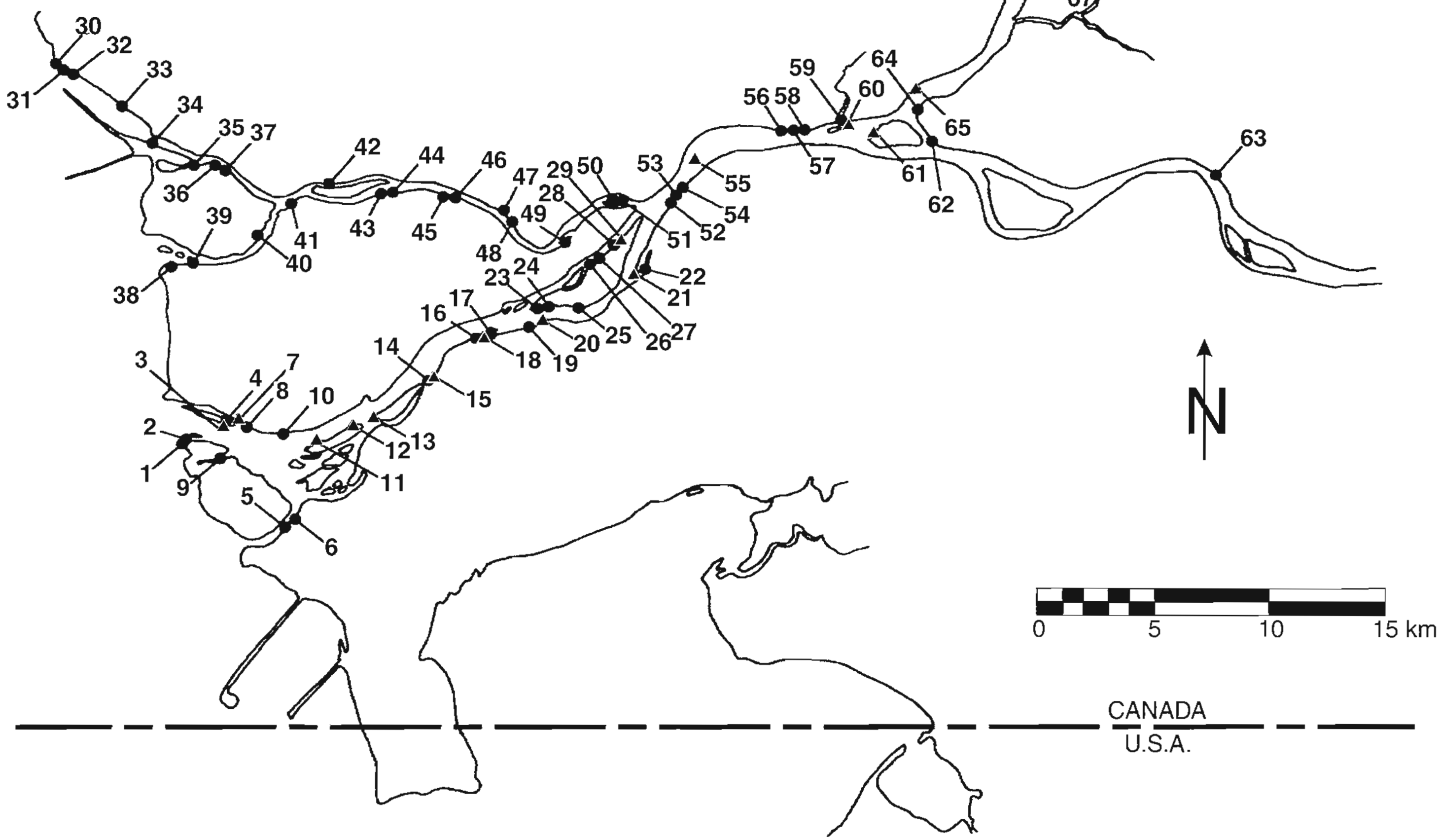


Figure 3. *Locations of surveyed tidal marshes. Triangles:* data from *W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980; dots:* data from *M.A. Adams and P. Paterson, unpub. report, 1988.*

Table 1. Dominant emergent species of tidal marshes of the Pitt River and the main and southern distributary channels of the Fraser River estuary. *See* Figure 3 for survey-site locations. *Data from* W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980; M.A. Adams and P. Paterson, unpub. report, 1988.

Survey sites	cl	co	cr	sa	sm	sv	smi	scy	sce	ep	jb	ja	je	jo	jc	pa	dc	gg	tl	ta	ml	la	ef
Reifel Island #1	•									•	•								•				
Reifel Island #2	•										•								•				
Shady Island #1	•			•		•					•						•		•				
Shady Island #2	•					•				•									•				
Canoe Pass #1	•									•									•				
Canoe Pass #2	•					•				•									•				
Steveston	•					•				•							•						
Gilbert Road	•			•		•				•	•							•					
Ewen Slough	•										•								•				
Finn Slough	•																		•				•
Rose Island	•					•				•	•						•		•				•
Kirkland Island	•					•					•						•	•	•				
Deas Slough	•					•				•	•								•				
Trimac #1	•																	•					•
Trimac #2	•					•				•									•				•
Chatterton	•					•				•		•											•
Dow Island	•					•				•							•						•
Dow Chemical	•					•				•							•						•
Cypress	•					•				•		•											•
Gundersen Slough #1						•				•		•						•					
Gundersen Slough #2										•								•					
Annieville Channel #1	•					•																	
Annieville Channel #2																			•				

cl = *Carex lyngbyei*
co = *C. obnupta*
cr = *C. rostrata*
sa = *Scirpus americanus*
sm = *S. maritimus*
sv = *S. validus*
smi = *S. microcarpus*
scy = *S. cyperinus*
sce = *S. cernuus*
ep = *Eleocharis palustris*
jb = *Juncus balticus*
ja = *J. articulatus*
je = *J. effusus*
jo = *J. oxymeris*
jc = *J. canadensis*
pa = *Phalaris arundinacea*
dc = *Deschampsia caespitosa*
gg = *Glyceria grandis*
tl = *Typha latifolia*
ta = *T. angustifolia*
ml = *Myosotis laxa*
la = *Lycopus americanus*
ef = *Equisetum fluviatile*

Table 1 (cont.).

Survey sites	cl	co	cr	sa	sm	sv	smi	scy	sce	ep	jb	ja	je	jo	jc	pa	dc	gg	tl	ta	ml	la	ef
Annieville Channel #3	•									•													
Annacis Channel #1	•									•						•			•				•
Annacis Channel #2	•									•		•							•				
Annacis Channel #3	•									•						•			•				
Annacis Channel #4			•																				
Annacis Channel #5	•						•									•	•		•				•
Timberland #1			•									•				•			•				
Timberland #2		•																					
Timberland #3													•										
Sapperton Bar													•			•			•				
Lafarge #1								•	•	•			•						•				•
Lafarge #2	•															•			•				
Lafarge #3	•															•			•				
Coquitlam River #1							•	•		•						•			•				
Coquitlam River #2																•		•					•
Douglas Island																•			•				•
Rivtow							•	•				•				•							•
Kanaka Creek												•				•							
Chatham Reach														•			•						•
Kennedy Island		•							•							•				•	•	•	
Goose Island #1								•		•				•		•							
Goose Island #2		•	•							•				•									•
McIntyre Creek															•	•							•

cl = *Carex lyngbyei*; co = *C. obnupta*; cr = *C. rostrata*; sa = *Scirpus americanus*; sm = *S. maritimus*; sv = *S. validus*; smi = *S. microcarpus*; scy = *S. cyperinus*; sce = *S. cernuus*; ep = *Eleocharis palustris*; jb = *Juncus balticus*; ja = *J. articulatus*; je = *J. effusus*; jo = *J. oxymeris*; jc = *J. canadensis*; pa = *Phalaris arundinacea*; dc = *Deschampsia caespitosa*; gg = *Glyceria grandis*; tl = *Typha latifolia*; ta = *T. angustifolia*; ml = *Myosotis laxa*; la = *Lycopus americanus*; ef = *Equisetum fluviatile*

Table 2. Dominant emergent species of tidal marshes of the northern distributary channels of the Fraser River estuary. *See* Figure 1 for site locations. *Data from* M.A. Adams and P. Paterson, unpub. report, 1988.

Survey sites	cl	co	cr	sa	sm	sv	ep	jb	ja	pa	tl	ta	ls	ip	as	ef
Wreck Beach #1	•			•		•										
Wreck Beach #2	•			•								•				
Wreck Beach #3	•			•								•				
Wreck Beach #4					•											
Musqueam	•											•				
Iona Island	•					•		•			•				•	
McDonald Slough	•					•	•	•					•	•		
Woods Island Slough #1	•			•				•			•					
Woods Island Slough #2	•					•	•				•					
Terra Nova	•						•				•					
McCallum Road	•					•	•	•			•					
Telegraph Cove	•					•	•	•			•		•			
Bridgepoint	•					•	•				•					•
Crown Forest	•										•					
No.8 Road #1	•								•							
No.8 Road #2	•										•					
Byrne Road Park #1		•				•										
Byrne Road Park #2		•				•	•			•	•					
Tree Island	•					•			•	•			•			
Poplar Island #1	•		•						•		•					
Poplar Island #2	•		•						•		•					

cl = *Carex lyngbyei*; co = *C. obnupta*; cr = *C. rostrata*; sa = *Scirpus americanus*; sm = *S. maritimus*; sv = *S. validus*; ep = *Eleocharis palustris*; jb = *Juncus balticus*; ja = *J. articulatus*; pa = *Phalaris arundinacea*; tl = *Typha latifolia*; ta = *T. angustifolia*; ls = *Lythrum salicaria*; ip = *Iris pseudacorus*; as = *Aster subspicatus*; ef = *Equisetum fluviatile*

The primary source of plant material for marsh creation has been, and continues to be, natural tidal marshes of the estuary. Marsh vegetation is transplanted from the donor site (i.e. natural marsh) to the recipient site (i.e. created marsh). Plant material is typically extracted utilizing a golf-cup cutter, with the transplant propagule being a 10 cm diameter by 20 cm deep cylindrical plug composed of plant material and sediments (Fig. 4).

A total of 42 marsh transplants have been documented for the Fraser River estuary (*see* Table 3 for project summaries). Early transplants were primarily experimental, conducted as part of studies to assess the feasibility of marsh creation. Despite the limited applicability of the results from these preliminary studies, early development projects were permitted by environmental agencies to utilize relatively large-scale marsh transplants as compensation for development-associated impacts.

Many of the early marsh-transplant projects achieved limited success in establishing tidal marsh. A review of pertinent project data and the inspection of many of the project sites suggest that the limited success of these projects was due primarily to poor quality assurance and control of site preparation and planting of vegetation, and secondarily to inadequate design criteria. Later projects included a higher standard of quality assurance and control, ensuring that construction and planting conformed to sound design criteria. As a result, these projects have achieved far greater success in creating tidal marshes. The following projects highlight some of the failures in construction and design and some of the remedies instituted to enhance project success.

Figure 4. *Golf-cup cutter transplant plug. Photo by M. Adams. GSC 2003-496*

The majority of marsh-creation efforts have sought to establish *Carex lyngbyei* marshes. The clonal, perennial sedge is the dominant emergent species of low- to middle-elevation tidal marshes, from the delta front in proximity to the mouths of the distributary channels upstream to the divergence of the 'Main Arm' into the North and 'South' arms. It occurs within estuaries throughout most of the Pacific coast of North America, from northern California (Mason, 1957) to the Bering Strait of Alaska (Northern Plant Documentation Center, University of Alaska Museum, unpub. distribution map and documentation for the distribution of *Carex lyngbyei* in Alaska, 1984).

Table 3. History of marsh-transplant projects, Fraser River estuary. *See* Figure 1 for site locations.

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
1[a,b]	January –March 1979	Steveston Island ('Shady Island'), 'South Arm'	450	*Carex lyngbyei* (n/a); *Scirpus americanus* (n/a)	Golf-cup cutter plugs (cylindrical, 10 cm diameter and 20 cm high) extracted from a natural tidal marsh at Steveston Island ('Shady Island'), 'Main Arm' and transplanted at the recipient site at 1.0 m intervals	One transplant plot (40 m x 15 m) was planted with the two species on a moderately sloping beach with substrate elevations of 1.4 – 3.2 m above local low water	Two growing seasons: end of 1979 growing season survivorship for *Scirpus americanus* and *Carex lyngbyei* was 69% and 65%, respectively; plugs started to coalesce by the end of the 1980 growing season
2[a,b]	January –March 1979	'Albion Flats', Roberts Bank	525	*Carex lyngbyei* (n/a); *Scirpus americanus* (n/a)	Golf-cup cutter plugs extracted from a natural tidal marsh at Steveston Island ('Shady Island'), 'Main Arm' and transplanted at the recipient site at 1.0 m intervals	One transplant plot (35 m x 15 m) was planted with the two species at a uniform substrate elevation of approximately 2.4 m above local low water	Two growing seasons: end of 1979 growing season survivorship for *Scirpus americanus* and *Carex lyngbyei* was 71% and 84%, respectively; plugs started to coalesce by the end of the 1980 growing season
3[a,b]	January –March 1979 February 1980	Iona Causeway, Sturgeon Bank	**1979:** 3100 **1980:** 704	**1979:** *Carex lyngbyei* (n/a); *Scirpus americanus* (n/a); *Scirpus maritimus* (n/a) **1980:** *Salicornia virginica* (n/a); *Distichlis spicata* (n/a)	Transplant propagules extracted with a golf-cup cutter from natural tidal marshes (*see* below) and transplanted to the recipient site at 1.0 m intervals **1979:** from, and in proximity to, Steveston Island ('Shady Island'), 'Main Arm' **1980:** from Boundary Bay	**1979:** two transplant plots (50 m x 50 m; 40 m x 15 m) were planted with the two species at substrate elevations 2.5 – 3.5 m above local low water **1980:** two transplant plots (32 m x 12 m; 32 m x 10 m) were planted with the two species at substrate elevations more than 3.5 m above local low water	**1979:** less than one growing season; monitoring discontinued after 1979 growing season due to high mortality of transplanted propagules **1980:** less than one growing season; monitoring discontinued after 1980 growing season due to high mortality of transplanted propagules
4[c]	February –May 1979	Deas Slough, 'South Arm'	1115	Mixed species (n/a)	Sediment containing root and rhizome material was salvaged (January 1979) from a development site at Sunbury Landing, Annieville Channel, 'Main Arm', stored several months (until May 1979), and transplanted to the recipient site using a front-end loader	Downstream of Deas Marina on south shore of Deas Slough	Monitoring of transplanted vegetation not documented
5[d]	March –April 1980	Steveston Bend, 'South Arm'	2684	*Carex lyngbyei* (718); *Scirpus americanus* (1366)	Golf-cup cutter plugs extracted from a natural tidal marsh on Steveston Island ('Shady Island') and transplanted to the recipient site at 1.0 m intervals	40 000 m^3 of dredge spoil was disposed of (February–March 1980) on the leeward side of a river training structure (Steveston north jetty) to substrate elevations 2.3 m geodetic	One growing season: burial and exposure of plugs due to dredge spoil drift, cupping around plugs, and high salinities relative to donor sites resulted in 100% mortality for *Carex lyngbyei* and low vigour for *Scirpus americanus*

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
6[d]	March –April 1980	Sapperton Bar, 'South Arm'	650	*Carex lyngbyei* (163); *Scirpus americanus* (163); mixed high marsh assemblage of which *Phalaris arundinacea* was a subdominant (325)	Golf-cup cutter plugs extracted from natural tidal marshes (*see* below) and transplanted to the recipient site at 1.0 m intervals *Carex lyngbyei* and *Scirpus americanus*: from a marsh on Steveston Island ('Shady Island') Mixed high marsh assemblage: from a marsh at the confluence of the Coquitlam and Fraser rivers	At the downstream end of Sapperton Bar, within the 'South Arm' of the Fraser River, all species were transplanted to substrate elevations approx. 0.3 m above local low water	Less than one growing season: all marsh plugs died prior to the end of the first growing season; mortality likely as a result of severe grazing by Canada geese (*Branta canadensis*)
7[e,f]	May 1983	Blind end of Gundersen Slough, Annieville Channel, 'South Arm'	625	*Carex lyngbyei* (n/a)	Sod apparently salvaged from a narrow strip marsh during rock riprap (armament) placement along the bank of the slough; mode of transplant not documented	An oval bench was created by placing fill within a rock riprap containment berm; a log boom surrounds the bench to prevent the accumulation of water-borne debris; surface substrate elevations were constructed at approximately 2.0 m above local low water	Monitoring of transplanted vegetation undocumented: one of the authors observed during a site visit (August 1994) a mixed assemblage of emergent species, the most prevalent being *Typha latifolia*, *Carex lyngbyei*, *Lythrum salicaria*, *Juncus articulatus*, and *Juncus effusus*
8[e,f]	March 1986	Fraser River Park, North Arm	1750	*Carex lyngbyei* (2125); *Scirpus validus* (450); *Juncus balticus* (4375)	Golf-cup cutter plugs extracted from natural tidal marshes within 'Woods Island Slough' and transplanted to the recipient site at 0.5 m intervals	Two intertidal benches fronting the park (riverward) were transplanted with the three species to areas designated for monospecific plantings; the range substrate elevations transplanted ranged from 0.10 m to 1.60 m geodetic	One growing season: a subjective assessment of the transplant conducted during August 1986 concluded that plug survivorship was poor; poor substrate (coarse sand) and elevations too high for transplanted species were implicated as causes for plug mortality
9[e,f]	March 1986	Sandbar at Gravesend Reach, downstream of Tilbury Slough	n/a	*Carex lyngbyei* (n/a)	Golf-cup cutter plugs extracted from a natural tidal marsh immediately across a small side channel that separates the sandbar from the mainland, and a marsh at the downstream end of Tilbury Island; nursery-grown seedlings were also planted at the site	The transplant and planting of nursery stock occurred on the southeast portion of the sandbar on predominantly unvegetated mudflat at elevations consistent with those inhabited by *Carex lyngbyei* in adjacent marshes	Severe grazing by approximately 80–100 Canada geese (*Branta canadensis*) eliminated all transplanted propagules by August 1986; except for several seedlings protected by a wire enclosure, the seedlings were also consumed by the geese

[a] Pomeroy et al., 1981a
[b] Pomeroy et al., 1981b
[c] Pomeroy, 1980
[d] W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980
[e] Department of Fisheries and Oceans files
[f] ECL Envirowest Consultants Limited files
[g] G.L. Williams and Associates Ltd. file information
[h] Fraser River Estuary Management Program file information
n/a = not available

Table 3 (cont.).

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
10[f,h]	March 1987	Fraser River Park, North Arm	1084	*Carex lyngbyei* (1660); *Juncus balticus* (1040)	Plugs extracted with a golf-cup cutter from tidal marshes of 'Woods Island Slough' and north foreshore of Iona Island; plugs transplanted to the recipient site at 0.5 m intervals	As per the 1986 transplant, myriad irregular plots on an intertidal bench and along the margins of an intertidal channel were transplanted; surface substrate elevations ranged from approximately 0.10 m to 1.60 m above local low water	Monitoring of transplanted vegetation is not documented: observations made by one of the authors during repeated annual visits (1988–1994) to the site suggest that survivorship of propagules was likely less than that of the 1986 transplant; poor substrate conditions had not been remediated within those areas in which the 1986 transplant had failed and where the 1987 transplant occurred
11[e,f]	March –April 1988	Mitchell Island, North Arm	15 000	*Carex lyngbyei*, *Scirpus validus*, *Typha latifolia* (16 000 combined)	Large sods of marsh vegetation were salvaged from a tidal marsh on Lulu Island to be impacted by development; the sods were cut into plugs (10 cm^2 x 10 cm high) at the recipient site for planting; for most of the site, plugs were transplanted at 1 m intervals; 10 m^2 test plots transplanted with plugs at both 0.5 m and 1.0 m intervals	Approximately 100 000 m^3 of dredge material was placed on the south shore of Mitchell Island to increase substrate elevations to a range of 2.2 – 2.6 m above local low water; the dredge spoil was not contained within a berm; the site design incorporates log boom storage riverward of the marsh to mitigate the impact (erosion) of breaking wakes	Three growing seasons: wakes caused the riverward edge of the dredge spoil pad to recede 18 m (1988–1991) and the development of sand berm within the transplanted area; establishment of log storage riverward of the site has decreased the incidence of wakes breaking on the spoil pad and associated erosion and berm formation; by 1991, half of the transplanted area did not sustain transplants; factors implicated for plug mortality include burial of plugs by moving sands, saturated soil conditions, and grazing by geese
12[e,g]	February –March 1988	Westminster Quay, Main Arm	150	*Carex rostrata* (232); *Carex lyngbyei* (38); *Scirpus cyperinus* (53); *Scirpus microcarpus* (113); *Juncus articulatus* (42); *Iris pseudacorus* (26); *Typha latifolia* (34)	Transplant propagules extracted from a tidal marsh on the north foreshore of Poplar Island; *Carex*, *Scirpus*, and *Juncus* propagules consisted of golf-cutter plugs; *Typha* and *Iris* propagules consisted of cut sods approximately 20 cm^2	The recipient site was an intertidal bench approximately 80 m long and 3 m wide consisting of a riprap berm containing earthen fill of upland origin; substrate elevations were consistent with the high marsh at the donor site	Monitoring of transplanted vegetation not documented: observations made by one of the authors during repeated annual visits (1988–1994) reveal a vegetation assemblage more typical of a tidal alder/willow swamp than marsh; the site suffers from chronic wood-debris accumulation
13[e,f]	March 1988	Sandbar at Gravesend Reach, downstream of Tilbury Slough	570	*Carex lyngbyei* (1475); *Juncus articulatus* (230); *Juncus balticus* (30); *Iris pseudacorus* (15); *Typha latifolia* (120)	*Carex* and *Juncus* propagules extracted using a golf-cup cutter; *Typha* and *Iris* propagules consisted of cut sods (20 cm^2); propagules extracted from a tidal marsh immediately across a small side channel that separates the sandbar from the mainland; plugs and sods transplanted at approximately 0.5 m and 0.75 m spacings centre-to-centre, respectively	The transplant occurred on the southeast portion of the sandbar on predominantly unvegetated mudflat at elevations consistent with those inhabited by *Carex lyngbyei* in adjacent marshes	Monitoring of transplanted vegetation not documented

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
14[e,f]	April 1988	Foreshore flats at confluence of stream "A" with the Fraser River, 'Main Arm' (downstream end of 'Surrey Bend')	4000	*Typha latifolia* (n/a)	*Typha latifolia* rhizomes were extracted from nontidal wetlands within south Langley	The recipient site is located adjacent to the confluence of Stream "A" with the Fraser River, at the downstream end of Surrey Bend; sidecast material from railway construction was excavated down to intertidal elevations and planted with the rhizomes	Monitoring of transplanted vegetation not documented
15[f,h]	Spring 1988	Adjacent to railway bridge on mainland downstream of Gundersen Slough, 'Main Arm'	498	*Juncus articulatus* (n/a)	Transplant propagules, consisting of sods (30 cm^2), were extracted from low–elevation tidal marshes in proximity to the recipient site	Two rock riprap berms, one upstream and the other downstream of a small creek that discharges into the 'Main Arm' (traversed by a railway bridge), contain sand fill at elevations of approximately 0.8–1.0 m geodetic	Monitoring of transplanted vegetation not documented: observations made by one of the authors during a site visit in May 1992 noted the approximate areal cover of *Juncus articulatus* on the marsh benches to be 60–70% of the area of the benches
16[f,h]	February –March 1989	Immediately downstream of Deering Island, north foreshore of North Arm	3461	*Carex lyngbyei* (13 844)	Golf-cup cutter plugs extracted from a tidal marsh at the blind end of McDonald Slough, North Arm, and transplanted at 0.5 m centre-to-centre intervals to the recipient site	Approximately 6000 m^3 of dredge material was placed within a rock riprap containment berm; substrate elevations range from 0.5 m to 1.0 m geodetic	Two seasons: 1991–1992; plugs started to coalesce by the end of the second growing season; the site displayed two vegetation zones, one dominated by monospecific *Carex lyngbyei* and the other dominated by both *Carex lyngbyei* and *Scirpus validus*; in general, by the end of the third growing season (1992) biomass and areal cover were comparable to those of natural marshes
17[f,h]	March 1989	Garry Point Park, 'South Arm'	1680	*Carex lyngbyei* (6720)	Golf cup cutter plugs extracted from a natural tidal marsh along the south shoreline of Canoe Passage ('Canoe Pass'), 'South Arm', immediately upstream of the Westham Island bridge, and transplanted to the recipient site at 0.5 m centre-to-centre intervals; substrate elevations of the donor site ranged from 0.35 m to 0.80 m geodetic	The recipient site consisted of three small intertidal basins excavated out of dredge spoil; substrate elevations were within the range of adjacent natural *Carex lyngbyei* marshes; the basins occurred in sequence along the entrance channel to 'Scotch Pond' at the west end of Garry Point Park	Monitoring of transplanted vegetation not documented: observations made by one of the authors during repeat annual visits (1989–1994) note, for 1994, the average areal coverage of emergent species within the two larger basins at greater than 90%; the most upstream ('Scotch Pond' channel) basin marsh is co-dominated by *Carex lyngbyei* and *Scirpus validus*, while the most downstream marsh is dominated by *C. lyngbyei*, with *Scirpus maritimus* as a conspicuous subdominant; the middle basin sustained only approximately 50% areal cover of *C. lyngbyei*, apparently as a result of shifting substrates (coarse sand)

[a] Pomeroy et al., 1981a
[b] Pomeroy et al., 1981b
[c] Pomeroy, 1980
[d] W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980
[e] Department of Fisheries and Oceans files
[f] ECL Envirowest Consultants Limited files
[g] G.L. Williams and Associates Ltd. file information
[h] Fraser River Estuary Management Program file information

Table 3 (cont.).

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
18[f,h]	March 1989	North end of No. 6 Road, Lulu Island, North Arm	635	*Carex lyngbyei* (2000); *Scirpus validus* (105)	*Carex lyngbyei*: golf-cup cutter plugs extracted from several small natural tidal Lulu Island marshes upstream of the recipient site and transplanted to the recipient site at 0.5 m intervals centre-to-centre *Scirpus validus*: 30 cm^2 sods were cut from a tidal Lulu Island marsh downstream of the recipient site adjacent to a railway trestle bridge and transplanted at 0.75 m intervals	*Carex lyngbyei*: a pump station discharge pipe was extended through an existing drainage channel within the Fraser River foreshore and buried in dredge spoil to surface substrate elevations consistent with those of adjacent natural *C. lyngbyei* marshes *Scirpus validus*: a second fill area was retained by a riprap berm along the eastern edge of the berth, of which substrate elevations were consistent with those of adjacent natural *S. validus* marshes	Monitoring of transplanted vegetation not documented: areal coverage of transplanted species within their respective areas, as noted by one of the authors during a May 1993 site visit, was greater than 90%
19[f,h]	March 1989	Dredge spoil bench approximately 1 km upstream of Tilbury Island on mainland foreshore	180	*Carex lyngbyei* (720)	Golf-cup cutter plugs extracted from adjacent natural tidal marsh	Prop scour hole immediately riverward of a natural tidal *Carex lyngbyei* marsh, and adjacent to a log handling facility, was filled with dredge spoil to elevations consistent with those of adjacent natural *Carex lyngbyei* marshes	Monitoring of transplanted vegetation not documented: as noted by one of the authors during a May 1993 site visit, many of the original plugs were not evident, apparently impacted by the grounding of logs on the marsh; the compensation marsh had been colonized extensively by *Juncus articulatus*; approximately 70% (300 m^2) of area originally planted supports a plant community co-dominated by *Carex lyngbyei* and *J. articulatus*
20[f,h]	March 1989	North foreshore of Richmond Island at downstream end, North Arm	4053	*Carex lyngbyei* (16 212)	Golf-cup cutter plugs extracted from natural tidal marshes of Sea and Iona islands within McDonald Slough	An intertidal basin was excavated out of upland along the northern shore of the downstream end of Richmond Island; surface substrate design elevations were approximately 0.0 m geodetic	Monitoring of transplanted vegetation not documented: during a May 1993 site visit, one of the authors noted that less than 10% of the entire basin sustained marsh vegetation; basin elevations were apparently too low
21[f,h]	Spring 1990	South foreshore of Deas Island within Deas Slough, 'Main Arm'	3080	Mixed-species high marsh consisting predominantly of *Phalaris arundinacea*	Large sections of sod were mechanically salvaged from a high-elevation natural tidal marsh on the south foreshore of Lulu Island to be impacted by port development; much as with the placement of commercial lawn turf, the sod was placed completely throughout the recipient site	The site consists of two linear intertidal benches, each consisting of fill and a rock riprap containment berm; the downstream bench is approximately 200 m long with a mean width of approximately 7 m, while the upstream bench is approximately 280 m long with a mean width of approximately 6 m	Monitoring of transplanted vegetation not documented: during a May 1993 site visit, one of the authors noted that each bench sustained greater than 90% areal cover of predominantly *Phalaris arundinacea* marsh

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
22[f,h]	March 1990	South foreshore of Ladner channel within Ladner Harbour	410	*Carex lyngbyei* (1640)	Golf-cup cutter plugs extracted from a natural tidal marsh located within at the downstream end of 'Ladner Island'	The site consists of a linear intertidal bench, consisting of dredge spoil fill and a rock containment berm; the bench is approximately 120 m long with a mean width of approximately 3 m	Monitoring of transplanted vegetation is not documented: one of the authors noted, during repeated annual visits (1990–1994), that transplanted vegetation started to coalesce during the second growing season; by the end of the fourth growing season, areal cover of emergent vegetation was greater than 90%; *Carex lyngbyei* was the dominant species
23[f,h]	Spring 1990	North foreshore of Steveston Island ('Shady Island'), Cannery Channel	1625	Mixed species marsh consisting predominantly of *Carex lyngbyei*	Large sections of sod were mechanically salvaged from a natural tidal marsh within a small-craft harbour, as the foreshore was to be cut and filled to form clean lines and grades; much as with the placement of commercial lawn turf, the sod was placed upon the recipient site	The recipient site consisted of high intertidal mudflat on the north foreshore of Steveston Island ('Shady Island')	Monitoring of transplanted vegetation not documented: one of the authors noted, during a January 17, 1992 site visit, that much of the sod had "sunk" into the mudflat below elevations conducive to *Carex lyngbyei* persistence; approximately 488 m^2 of mixed sedge marsh (*C. lyngbyei*, *Scirpus validus*, and *Eleocharis palustris*), as indicated by exposed rhizomes and late winter shoots, was observed
24[f,h]	March 1991	'Ladner Slough', 'South Arm'	250	*Carex lyngbyei* (1000); *Typha latifolia* (100)	*Carex lyngbyei*: golf-cup cutter plugs were extracted from Ladner Marsh and transplanted to the recipient site at 0.75 m centre-to-centre intervals; *Typha latifolia*: 30 cm^2 sods were extracted from Ladner Marsh and transplanted at 1.0 m centre-to-centre intervals	The recipient site, former farmland, was excavated to elevations consistent with adjacent natural marshes; the site is divided into two units, a blind channel and a small lagoon; substrate elevations are approximately 0.50 m to 0.75 m GSC	Monitoring of transplanted vegetation not documented: one of the authors observed during an August 1994 site visit that the transplanted plugs and sods had coalesced; within each of their respective planted areas, *Carex lyngbyei* and *Typha latifolia* were the dominant species; within the *C. lyngbyei* zone, subdominants included *Scirpus validus* and *Bidens cernua*
25[f,h]	May 1991	Immediately downstream of the No. 2 Road Bridge along the north foreshore of Lulu Island, Middle Arm	4500	*Carex lyngbyei* (7020)	Transplant plugs (approximately 10 cm^2 and 20 cm high) excavated utilizing a fencepost spade were extracted from natural tidal marshes adjacent to the recipient site; plugs were transplanted to the recipient site at 0.75 m intervals	The recipient site is an historic dredge spoil site (ca. late 1930s); the site was excavated to create an intertidal basin partially protected by a barrier island; wooden screens across the two openings of the island prevent wood debris from entering the marsh; surface substrate elevations are 0.50–0.75 m geodetic	Five growing seasons: third year monitoring data for *Carex lyngbyei* revealed that the transplant marsh, for several vigour variables (areal cover, dry weight biomass, stem density), was consistently lower in value(s) than a comparable natural *C. lyngbyei* marsh; fourth year data documented the transplant marsh as sustaining greater areal cover of *C. lyngbyei* than the comparable natural marsh

[a] Pomeroy et al., 1981a
[b] Pomeroy et al., 1981b
[c] Pomeroy, 1980
[d] W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980
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Table 3 (cont.).

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
26[f,h]	May 1991	Lulu Island, upstream of Annacis Highway bridge, north shore Annacis Channel	1866	*Carex lyngbyei* (9600)	Transplant plugs (approximately 10 cm^2 x 20 cm high) were extracted from natural marshes approximately 200–300 m downstream of the recipient site on the north shore of Annacis Island; nursery stock sprigs were also planted (numbers of transplant and nursery stock not available)	Dredge spoil fill contained within a riprap containment berm; surface substrate elevations are 0.35–0.50 m geodetic	Three growing seasons: by the third growing season, three vegetation zones were evident, the first consisting of *Carex lyngbyei*, *Juncus effusus*, *Phalaris arundinacea*, and *Scirpus cyperinus*; the second consisting of *J. effusus*, *Juncus oxymeris* and *Juncus articulatus*; and the third consisting of *Scirpus validus* and *Typha latifolia*; areal cover within the zones ranged from 25% to 100%
27[f,h]	March 1992	North shore of slough enclosed by Richmond Island, North Arm	625	*Carex lyngbyei* (2500)	30 cm^2 sods were extracted from the blind end of McDonald Slough (foreshore of Iona Causeway) and transplanted to the recipient site	A marsh bench consisting of fill of upland origin contained within a rock riprap berm located on the north foreshore of slough adjacent to a fill causeway; the bench dimensions were 2.5 m x 250 m; substrate elevations are 0.50–0.75 m geodetic	Monitoring of transplanted vegetation not documented
28[g,h]	March 1992	Downstream of the Morey Channel Bridge, on Sea Island, Middle Arm	77	*Carex lyngbyei* (308)	Golf-cup cutter plugs were extracted from an adjacent natural tidal marsh and transplanted to the recipient site	The recipient site consists of dredge spoil contained within a riprap containment berm	Monitoring of transplanted vegetation not documented
29[f,h]	March –April 1992	Adjacent to south pier of Alex Fraser Bridge, 'South Arm'	2000	*Carex lyngbyei* (n/a)	Using garden spades, small sods, approx. 10 cm^2 and less than 10 cm high, were excavated from a natural tidal marsh located on the north foreshore of Annacis Channel, immediately upstream of the Annacis Highway bridge	The recipient site consists of a circular basin excavated within dredge spoil	Monitoring of transplanted vegetation not documented
30[f,h]	March –April 1992	Upland immediately adjacent to downstream end of Deas Slough	*Carex lyngbyei*: 2500 *Typha latifolia*: 2475	*Carex lyngbyei* (10 000); *Typha latifolia* (4400)	*Carex lyngbyei*: golf-cup cutter plugs were extracted from Ladner Marsh and transplanted to the recipient site at 0.5 m centre-to-centre intervals *Typha latifolia*: 30 cm^2 sods were excavated from nontidal wetlands within old fields adjacent to recipient site and transplanted to the recipient site at 0.75 m centre-to-centre intervals	Historically, the recipient site was high intertidal cottonwood swamp; dredge spoiling activities over several decades had degraded the site; habitat restoration creation consisted of excavating an intertidal wetland system consisting of sloughs and marsh benches; high-elevation benches (1.25–1.50 m geodetic) were transplanted with *Typha latifolia*; a low-elevation (0.50–0.75 m geodetic) 8100 m^2 basin was partially transplanted (2500 m^2) with *Carex lyngbyei*	Monitoring of transplanted vegetation has not been conducted: one of the authors noted, during repeated site visits (1992–1994), that the *Typha latifolia* transplants have achieved limited success, with most of the area encompassed by the benches supporting wet-meadow emergents; as of September 1994, the low-elevation basin supported a diverse species assemblage that included *Carex lyngbyei*, *Lythrum salicaria*, *Scirpus validus*, *Typha latifolia*, *Bidens cernua*, *Alisma plantago-aquatica*, and *Sagittaria latifolia*; areal coverage by this assemblage was more than 90%

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
31[g,h]	March 1993	'Tugboat Landing', north foreshore of North Arm	3568	*Carex lyngbyei* (14 272)	Golf-cup cutter plugs were extracted from natural tidal marshes throughout the North Arm and transplanted to the recipient site at 0.5 m centre-to-centre intervals	The recipient site consists of three marsh benches, each consisting of dredge spoil contained by a rock riprap berm; surface substrate elevations range from 0.5 m to 0.8 m geodetic	Three growing seasons: at the end of the 1995 growing season, areal coverage by emergents throughout the marsh benches approached 100%; the dominant species was *Carex lyngbyei*, with other prevalent species being *Eleocharis palustris* and *Juncus articulatus*
32[g,h]	March –April 1993	'Fraser Lands', north foreshore of North Arm	8000	*Carex lyngbyei* (14 160)	Golf-cup cutter plugs were extracted from natural tidal marshes throughout the North Arm and transplanted to the recipient site at 0.75 m centre-to-centre intervals	The recipient site consists of two marsh benches, each consisting of soil of upland origin contained by a rock riprap berm; surface substrate elevations range from 0.5 m to 0.8 m geodetic	Three growing seasons: at the end of the 1995 growing season, areal coverage by emergents throughout the marsh benches approached 100%; the dominant species was *Carex lyngbyei*, with other prevalent species being *Eleocharis palustris* and *Typha latifolia*
33[f,h]	May – June 1993	Roberts Bank intercauseway area, north foreshore of Tsawwassen Causeway	8460	*Scirpus americanus* (3384); *Scirpus maritimus* (3384); *Distichlis spicata* (3384); *Salicornia virginica* (3384); *Triglochin maritimum* (3384)	Using fencepost spades, plugs 10 cm^2 and 20 cm high were extracted from Roberts Bank tidal marshes located south of Canoe Passage ('Canoe Pass') and north of the Tsawwassen Causeway; plugs were transplanted to the recipient at 0.5 m and 0.75 m spacings within plots located throughout the recipient site	The recipient site consists of a 4 ha basin consisting of dredge spoil contained by a large cobble berm; surface substrate elevations range from 3.25 m to 4.25 m local low water	Two growing seasons: the monitoring program was suspended by environmental agencies after the second year of an original 5 year tenure; the initial transplant program was experimental, the objective being to determine the suitability of selected species to the basin environment; the species were planted within plots distributed throughout the basin; *Scirpus maritimus* plugs suffered 100% mortality by the end of the first growing season; in general, the other species were distributed along an elevational gradient, with *Salicornia virginica* at higher elevations, *Distichlis spicata* at middle elevations, and *Triglochin maritimum* at lower elevations
34[f,h]	March –April 1994	'Burnaby Bend', north foreshore of North Arm	2865	*Carex lyngbyei* (11 460)	Golf-cup cutter plugs were extracted from natural tidal marshes located within the North and Middle arms and Sturgeon Bank, and transplanted to the recipient site at 0.5 m centre-to-centre intervals	The recipient site consists of six marsh benches, ranging from 203 m^2 to 594 m^2, each constructed of fill of upland origin contained by a rock riprap berm	One growing season: preliminary monitoring results indicate close to 100% survivorship of plugs from all donor sites; areal cover by *Carex lyngbyei* for each bench was less than 25% after 1 year

[a] Pomeroy et al., 1981a
[b] Pomeroy et al., 1981b
[c] Pomeroy, 1980
[d] W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980
[e] Department of Fisheries and Oceans files
[f] ECL Envirowest Consultants Limited files
[g] G.L. Williams and Associates Ltd. file information
[h] Fraser River Estuary Management Program file information

Table 3 (cont.).

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
35[g,h]	March 1994	Vancouver fire ramp, north foreshore of North Arm	412	*Carex lyngbyei* (1648)	Golf-cup cutter plugs were extracted from natural tidal marshes in the North Arm, and transplanted to the recipient site 0.5 m centre-to-centre intervals	The recipient site consists of a marsh bench of sandy soil of upland origin contained by a riprap berm; surface substrate elevations range from 0.08–0.43 m geodetic	Two growing seasons: *Carex lyngbyei* displayed 100% survivorship with limited vegetative expansion; high species diversity with *Agrostis alba*, *Potentilla pacifica*, *Polygonum persicaria*, and others
36[f,h]	March 1994	'Woods Island', south foreshore of the North Arm	5694	*Carex lyngbyei* (22 776)	Golf-cup cutter plugs were extracted from natural tidal marshes within the lower North Arm and Middle Arm	The recipient site consists of an oval basin, with an island at its centre, excavated within historical dredge spoil; surface substrate elevations range from 0.5–0.75 m geodetic	Three growing seasons: the monitoring program is entering the fourth year of a 5 year monitoring program; close to 100% survivorship of transplanted plugs; areal cover by *Carex lyngbyei* less than 75%
37[g,h]	May 1994	Lulu Island, foot of Gilbert Road, 'South Arm'	550	*Carex lyngbyei* (1800); *Juncus balticus* (400)	Golf-cup plugs were extracted from adjacent natural tidal marshes on Lulu Island, 'South Arm'	The recipient site consists of a rectangular marsh bench of dredged material contained by a riprap berm; berm dimensions: approximately 11 m wide and 55 m long; substrate elevations were consistent with adjacent natural marshes	Three growing seasons: the monitoring program is entering the fourth year of a 5 year program; berm failure resulted in the loss of substrates and some transplant vegetation; berm repair (spring 1996) included re-transplant of 70% of bench
38[h]	October 1994	Queensborough Bridge, north foreshore of Lulu Island, North Arm	120	*Carex lyngbyei* (360)	Golf-cup plugs extracted from tidal marshes located within the North Arm and transplanted to the recipient site at 0.5 m centre-to-centre intervals	Narrow bench 7 m x 55 m long (385 m^2) of which 120 m^2 was transplanted and remainder left to colonize naturally	Observations made in August 1995 note 75% survivorship; *Juncus articulatus* was actively colonizing area
39[f,h]	March 1995 March – May 1996 March – May 1997	Marsh and slough restoration at 'Burnaby Bend', North Arm	**1995:** 6000 **1996:** 6100 **1997:** 4000	**1995:** *Carex lyngbyei* (10 220); *Carex obnupta* (100); *Scirpus validus* (100); *Scirpus microcarpus* (200) **1996:** *Carex lyngbyei* (transplant 9300; nursery 1500) **1997:** *Carex lyngbyei* (transplant 7250; nursery 4100); *Scirpus cyperinus* (120); *Scirpus microcarpus* (150); *Juncus effusus* (80)	**Transplant:** for all years for transplant *Carex lyngbyei*, golf-cup cutter plugs were extracted from natural tidal marshes located within the Middle and North arms and transplanted to the recipient site at 0.75 m centre-to-centre intervals; for 1995, species other than *C. lyngbyei* obtained from project site; for 1997, species other than *C. lyngbyei* obtained from non-tidal drainage ditches **nursery stock:** for 1996, no.1 pot planted at 0.75 m centre-to-centre spacings; for 1997, 1100 no.1 pot planted at 0.50 m and 0.75 m centre-to-centre spacings, and 3000 sprigs in clumps of five at 0.25 m spacings	All phases of the project, the recipient sites are characterized by bench marshes fringing tidal sloughs excavated within historic floodplain; the benches are bordered by fresh swamp shrubs and trees retained as part of the overall design; to restore tidal flows, culverts within a dyke were placed at several locations; open breaches were not feasible due to the presence of a sanitary main immediately landward of the dyke	Monitoring of transplant and nursery stock performance is currently not being conducted; preliminary observations by the author suggest that shading by bordering shrubs and trees has decreased the vigour of planted vegetation in some areas; 1996 nursery stock displayed vigour similar to that of transplant stock

Project no.	Date	Recipient site location	Transplanted area (m^2)	Transplanted species and no. of propagules	Transplant methodology and donor site location	Recipient site description	Transplant monitoring duration and results
40[f,h]	October 1995	Poco Trail upgrade, Pitt River	154	*Scirpus microcarpus* (520); *Scirpus cyperinus* (40); *Juncus effusus* (40)	15 cm^2 plugs were extracted from marshes of non-tidal drainage ditches and transplanted to the recipient site at 0.5 m centre-to-centre intervals	Semicircular basin located on west foreshore of Pitt River, between two bridges	Five growing seasons: results of first year monitoring note that vegetative expansion of plugs has been slow; 1996 areal coverage less than 40%
41[f]	April 1997	Captain's Cove Marina upgrade, Deas Slough, 'South Arm'	2780	*Carex lyngbyei* (4920)	Golf-cup plugs were extracted from natural tidal marshes located within Ladner Reach of the lower 'South Arm' and transplanted at the recipient site at 0.75 m centre-to-centre intervals	Wide bench 20 m wide x 139 m long constructed at upstream end of marina	Five growing seasons: monitoring program to commence during summer 1997
42[h]	April 1997	Canadian Pacific Barge Facility, Tilbury Island, 'South Arm'	1525	*Carex lyngbyei* (6100)	Golf-cup plugs were extracted from natural tidal marshes located in immediate proximity to the project site and transplanted at 0.50 m centre-to-centre intervals	Bench constructed along shoreline	Five growing seasons: monitoring program to commence during summer 1997

[a] Pomeroy et al., 1981a
[b] Pomeroy et al., 1981b
[c] Pomeroy, 1980
[d] W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. summary report on site conditions for the Fraser River Estuary Habitat Development Program, 1980
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In terms of above-ground net annual production, it is the most productive emergent species of estuarine marshes on the Pacific coast of North America (Keefe, 1972; Hutchinson, 1986).

A notable early attempt to evaluate wetland-creation techniques was initiated by the Department of Fisheries and Oceans and the Canadian Wildlife Service during the early 1980s. Boyd and co-workers (W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. addendum to the criteria summary report for the Fraser River Estuary Habitat Development Program, 1980) conducted experimental transplants at a dredge-spoil pad located at the bend of the Steveston north jetty (Table 3, project no. 5). The original design of the spoil pad utilized 100 000 m^3 of material. Only approximately 40 000 m^3 of dredge-spoil material was actually placed at the site. The pad had a maximum height of 2.3 m above geodetic zero and was characterized by an approximate slope of 1:20. The design called for the transplant of 6000 plugs of marsh, consisting evenly of *Scirpus americanus* and *Carex lyngbyei*. Due to both the decreased volume of dredge material placed at the site and the initial instability of placed material, only 718 plugs of *C. lyngbyei* and 1366 plugs of *S. americanus* were transplanted. The plugs were harvested from two donor sites located at nearby Steveston Island ('Shady Island') and transplanted to the creation site in rows at 1 m intervals.

The decision to decrease the number of *Carex lyngbyei* relative to the number of *Scirpus americanus* plugs was made where the instability of the spoil pad became obvious. *Scirpus americanus* is known to colonize barren sand substrates on the leading edge of the estuarine marshes of the Fraser River (Moody, 1978). Accordingly, the investigators considered this species better able to survive the unstable conditions prevalent on the spoil pad.

Preliminary observations (W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. addendum to the criteria summary report for the Fraser River Estuary Habitat Development Program, 1980) of the performance of the transplanted plugs revealed that *Carex lyngbyei* plugs were subject to cupping (erosion of substrate from around the plug). It was hypothesized that cupping was attributable to the cohesive nature of the *C. lyngbyei* plugs; unconsolidated substrates surrounding the plugs eroded as waves and currents focused upon the perimeter of the relatively well consolidated plugs. *Scirpus americanus* did not exhibit such cupping. The *S. americanus* plugs were composed of a loose matrix of roots and rhizomes infilled with sand; a well defined interface between the plug and surrounding substrates did not exist. As a result, there was not a focal point for erosion. Five days after transplanting, approximately 25% of the *C. lyngbyei* plugs were absent or exposed; sand surrounding the majority of remaining plugs had been partially eroded, resulting in the plugs protruding above the surface of the substrate. The *S. americanus* plugs exhibited little erosion.

The migration of sand throughout the site caused further loss of marsh plugs due to burial and exposure. Twenty days after the completion of transplant activities, all of the *Carex lyngbyei* plugs had died. Plant vigour of surviving *Scirpus* *americanus* plugs was poor; shoots did not exceed 3 cm in height. Although it was apparent that the migration of sand throughout the site significantly contributed to marsh-plug mortality, the difference between sediment salinities of the donor and recipient sites was also likely a contributing factor. Sediment salinities at the recipient site were 10 to 15 ppt higher than at the donor site for the 28 day period following transplant.

A second marsh-creation effort performed as part of the same program (Table 3, project no. 6) involved the transplant of 163 plugs of each of *Carex lyngbyei* and *Scirpus americanus* and 325 plugs of high marsh that was comprised of a mix of species including *Phalaris arundinacea*, *Deschampsia caespitosa*, and *Equisetum fluviatile* (W.S. Boyd, E.R. White, G.J. Holowatiuk, J.S. Readshaw, and P.G. Harrison, unpub. addendum to the criteria summary report for the Fraser River Estuary Habitat Development Program, 1980). The donor site for the two sedges was a marsh at Steveston Island ('Shady Island'), whereas the donor site for the high-elevation marsh species was a marsh located on the small delta of the Coquitlam River at its confluence with the Fraser River. The recipient site was Sapperton Bar at New Westminster, an elevated river bar upstream of the divergence of the 'Main Arm' of the river into the North and 'South' arms. All the transplanted marsh plugs died prior to the end of the first growing season. All plugs were severely grazed by Canada geese (*Branta canadensis*). Most of the plugs were clipped to ground level immediately after transplanting.

The first non-experimental marsh transplant implemented as part of a fish-habitat enhancement project occurred at Fraser River Park in south Vancouver (Table 3, project no. 8). The site is located on the north shore of the North Arm of the Fraser River. Marsh vegetation was transplanted on two occasions, the first during February 1986 and the second in March 1987.

The donor site for both transplants was a marsh near the upstream end of 'Woods Island Slough' (locally used name), located on the south shore of the North Arm opposite the recipient site. The 1986 transplant involved approximately 2125 plugs of *Carex lyngbyei*, 450 plugs of *Scirpus validus*, and 4425 plugs of *Juncus balticus*. The 1987 transplant involved 1040 plugs of *C. lyngbyei* and 1660 plugs of *J. balticus*.

Some propagule failure occurred during the first two growing seasons of each of the transplants. This failure was primarily attributable to poor substrate quality in specific areas of the recipient site. One area was characterized by shifting sand that periodically buried and exposed marsh plugs. A second area was characterized by cobble, broken concrete, and clay bricks; plugs planted in this area slowly broke down, exposing the root-and-rhizome matrix. Plug success approached 100% in areas characterized by substrates consisting of mixed sand and clay. Within such areas, plugs coalesced by the end of the second growing season.

The first large-scale marsh-creation program implemented as compensation for the loss of tidal marsh associated with shoreline development occurred on the south shore of Mitchell Island within the North Arm (Table 3, project no. 11; Fig. 5). In early 1988, 100 000 m^3 of dredge spoil were placed on low intertidal and subtidal mudflat. Surface elevations ranged from 1.9 m to 2.2 m above local low water. A total of 1.5 ha was transplanted with approximately 16 000 marsh plugs obtained from the development-site marsh. Marsh vegetation was removed in 1.5 m^2 mats from the development site utilizing an excavator. Approximately 175 mats were transported to the recipient site. The mats were cut into plugs, approximately 10 cm square and 20 cm deep, and transplanted into the dredge spoil at 1 m centre-to-centre (of plug) intervals. Test plots (10 m^2) incorporating inter-plug intervals of either 0.5 m or 1.0 m were conducted to assess the effect of planting densities on the rate of plug coalescence. Transplanted species included *Carex lyngbyei*, *Scirpus validus*, and *Typha latifolia*.

The Mitchell Island marsh-creation project was the first marsh-habitat compensation project implemented within the Fraser River estuary that included the annual collection of quantitative biophysical data over several growing seasons to assess compliance with design criteria (Williams, 1993). Physical stability was monitored using surface-elevation

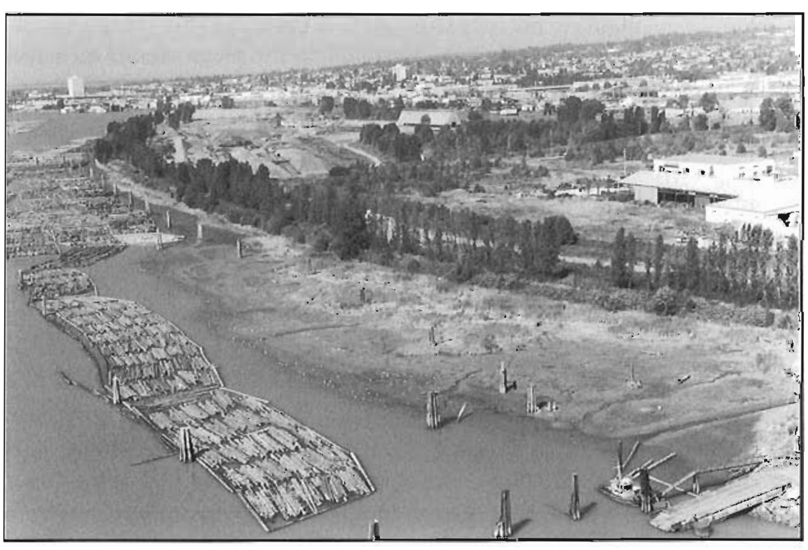

Figure 5.

Constructed marsh at Mitchell Island, North Arm, looking downstream. Photo by G. Williams. GSC 2003-497 surveys for the intertidal marsh and soundings for the subtidal portion of the dredge-spoil fill. Vegetation monitoring consisted of estimates of areal coverage.

Comparison of physical monitoring data for a typical cross-section of the dredge spoil revealed that the spoil surface elevation increased slightly along the landward portion of the site, likely as a result of sediment deposition during freshet. In contrast, the riverward edge of the spoil, defined as the local low-water contour, receded approximately 18 m during a three-year period (1988–1991). An engineering assessment of the marsh in June 1991 attributed the main erosional forces affecting the spoil slope to boat-generated waves, some of which could reach 0.7 m in height. The energy generated by the waves also transported fine sand landward to form a berm or dune along the shoulder of the spoil pad.

To reduce the size of waves impacting the spoil pad and the associated erosion and movement of sand, log-boom storage was established within subtidal waters immediately riverward of the dredge-spoil pad. The berm was subsequently removed, as it had a tendency to occasionally migrate into the transplanted area and smother emergent vegetation. The booms were effective in reducing the size of waves impacting the spoil pad: pad erosion ceased and a second berm has yet to develop.

By August 1991, approximately half of the marsh area sustained emergent vegetation. It had been anticipated during the design phase of the project that at least 70% of the area apparently capable of supporting emergent vegetation would be vegetated by the end of the 1991 growing season. Several factors appeared to limit areal cover by emergents. First, the sand berm migrated into transplanted areas, smothering and killing some plugs and preventing the areal expansion of others. Second, transplanted vegetation within the western and eastern sections of the marsh not impacted by the sand berm did not survive. Although empirical data were not collected for soils within these areas, the soils were observed to drain poorly, which in turn could have contributed to anaerobic conditions within the upper soil horizon, leading to plant death. Third, after the transplant of vegetation, portions of the site were heavily grazed by Canada geese. The intensity of grazing, often resulting in the removal of both above- and below-ground portions of the two sedge species, obviously contributed to plug mortality.

Figure 6. *Constructed marsh at Deering Island, North Arm, looking downstream. Photo by M. Adams. GSC 2003-498*

The results of monitoring indicate that there was little observable difference in areal coverage between plantings at 0.5 m and 1.0 m spacings after three growing seasons. An unplanted control plot developed a species assemblage similar to that sustained within the transplant plots; however, areal cover was less than that of the transplant plots.

Lessons learned from the Mitchell Island project were applied to a marsh-creation effort further downstream in the North Arm within the Southlands region of the City of Vancouver, immediately downstream of Deering Island (Table 3, project no. 16; Fig. 6). The project was implemented to offset losses of intertidal marsh and mudflats associated with residential development of the island. During the late winter and early spring of 1989–1990, 3400 m^2 of low intertidal flats, substrates of which were in large part composed of demolition debris, were enclosed within a large riprap berm and log boom. Dredge spoil was placed within the beamed area during October–November of 1989. The spoil was permitted to settle, compress, and consolidate prior to transplanting. By March 1990, a sand dune, encompassing approximately 500 m^2, had developed on the site. This dune was removed during mid-March 1990 as part of the final stage of site construction that graded the spoil material to surface-substrate elevations conducive to sedge establishment and persistence. After grading, the enclosed area was transplanted with plugs of *Carex lyngbyei* at 0.5 m centre-to-centre intervals.

The transplanted plugs started to coalesce by the end of the second growing season. Furthermore, two distinct zones of vegetation were apparent at this time. Approximately 1500 m^2 of marsh at the upstream end of the site supported a vegetation assemblage that was dominated by *Scirpus validus*, whereas the remaining downstream portion of the site was characterized by an assemblage dominated by *Carex lyngbyei*. The site is not characterized by an elevational gradient to account for this difference. The dredge spoil placed at the site was relatively homogeneous in terms of substrate size gradation and, therefore, a relationship between edifice factors and dominant vegetation was not readily apparent. Rather, it appears that the presence of *S. validus* at the upstream end of the site is related to its proximity to a patch of natural *S. validus* marsh immediately upstream of the site. The site was designed to incorporate elevations that occur within the lower range of *C. lyngbyei* typically inhabited by the sedge in the lower North Arm. The upper range of *C. lyngbyei* was avoided as *Lythrum salicaria*, an undesirable species from a fish-and-wildlife-habitat perspective, typically occurs within high-elevation *C. lyngbyei* marshes. The lower elevational range of *C. lyngbyei* overlaps with the higher elevation range of *S. validus* within the North Arm. It may be that some environmental factor conferred a competitive advantage to *S. validus* over *C. lyngbyei*, and the ready source of seeds provided the means for the bulrush to colonize the site.

Figure 7. Debris screen at channel opening of constructed marsh, Middle Arm, downstream of No. 2 Road Bridge. Photo by M. Adams. GSC 2003-499

Two years of monitoring (1991 and 1992 growing seasons) provided data that suggest the areal coverage of the two dominant species was similar to that of control marshes located adjacent to the *Carex lyngbyei* donor site at the blind end of McDonald Slough and a *Scirpus validus* marsh on the south foreshore of 'Woods Island Slough'.

A conspicuous design feature of this marsh is the log boom that encompassed the riverward margin of the marsh. The purpose of the boom was to prevent the deposition and accumulation of wood debris upon the marsh. The constructed boom, however, has not been able to withstand the wave-energy regime of the site. The majority of waves breaking on the boom are generated by industrial boat traffic. Piles have worn and broken, with sections of the boom floating untethered. Wood debris now accumulates on the marsh.

A marsh-creation project within the Middle Arm of the river employed an alternative design to prevent the accumulation of wood debris within the marsh (Table 3, project no. 25). The project was implemented in 1991 as compensation for impacts associated with the design and construction of the No. 2 Road Bridge. A historical dredge-spoil site located several hundred metres downstream of the bridge, with substrate elevations above normal high water, was excavated down to elevations typical of *Carex lyngbyei* marshes. The total area encompassed by the compensation site is approximately 4500 m^2. The compensation area was transplanted with *C. lyngbyei* obtained from marsh donor sites in proximity to the marsh-creation site. The transplant plugs (approximately 10 cm square and 20 cm deep) were extracted with spades at 0.50 m intervals from the donor sites and transplanted to the recipient site at 0.75 m intervals. The site design incorporated a 'barrier' island and debris screens (Fig. 7) at two channel openings connecting the compensation marsh to the Middle Arm. Both features successfully minimized the amount of woody debris entering the compensation marsh. Structural degradation of the screens has not yet occurred.

Project monitoring included both the transplant and a natural (i.e. control) marsh. Areal-cover data for the third year of monitoring demonstrated that *Carex lyngbyei* coverage was greater in the control marsh than in the transplant marsh, whereas areal-cover data for the fourth year showed greater areal cover for the transplant marsh. The habits and distribution of plants differed between the two marshes. Plants within the transplant marsh were generally shorter than their control-marsh counterparts. The appearance of the stand of *C. lyngbyei* in the transplant marsh was reminiscent of an agricultural crop, a monoculture with little spatial heterogeneity. In contrast, the control marsh was characterized by small mud pannes throughout the *C. lyngbyei* stand.

The success of marsh-creation efforts at Deering Island and the Middle Arm and other locations such as 'Tugboat Landing', 'Fraser Lands', and 'Woods Island' (Table 3, project numbers 31, 32, and 36, respectively), is attributable to the adherence to sound design criteria during the construction and planting of the created marshes. Emphasis on quality assurance and control, as for any other construction project, is a necessary precursor to project success.

RESEARCH NEEDS

To date, the realm of parameters monitored for created marshes has been limited. Propagule survivorship, areal cover, stem density, and biomass according to species are only preliminary indicators of the success of establishing vegetation at a particular location. They facilitate a cursory comparison of created marshes with natural counterparts. Monitoring protocols should further seek to describe the autecology of plant species within both created and natural marshes. This would afford a better understanding of the parameters that contribute to the presence and vigour of plant species that compose observed assemblages.

Autecological studies of plant species would facilitate an understanding of the influence of the salt wedge upon species presence and structure within tidal marshes of the estuary. Botanical studies, conducted in association with investigations of the prevailing inundation regimes of surveyed marshes throughout the estuary, are required.

Standardization of monitoring protocols is required. The environmental agencies, through either their own research initiatives or as a condition of development-project approval, should implement a standard monitoring protocol for all projects. The protocol must be flexible, with the monitoring effort being a function of project size.

Furthermore, greater research is required to assess the feasibility of utilizing nursery stock as a source of plant material, rather than natural marshes within the estuary. The Department of Fisheries and Oceans has utilized limited nursery stock for its project at 'Burnaby Bend'; however, monitoring of the performance of this stock is currently not being conducted. The monitoring protocol used for transplant projects should be implemented for nursery-stock projects so as to facilitate the assessment of the relative performance of these planting strategies.

As the focus of marsh creation is to provide fish habitat and, to a lesser extent, wildlife habitat, the functional attributes provided by created marshes relative to natural marshes require detailed study. The ability of created marshes to function as natural marshes for fish and wildlife has yet to be adequately quantified.

Monitoring results obtained from standardized studies must be summarized within technical documents to facilitate ready access to up-to-date information regarding created marshes and their performance, both in their ability to represent natural assemblages of plant species and their ability to function as fish and wildlife habitat. These documents would form the technical basis of future management initiatives, such as the establishment of annual objectives for the procurement of data regarding tidal-marsh creation and performance.

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REFERENCES

Adams, D.A.
1963: Factors influencing vascular plant zonation in North Carolina salt marshes; Ecology, v. 44, p. 445–456.

Adams, M.A.
1993: Discussion Paper: Purple loosestrife (*Lythrum salicaria*) in the Fraser River estuary; Fraser River Estuary Management Program Technical Report H-93-01; Fraser River Estuary Management Program, New Westminster, British Columbia, 26 p.

Ages, A.
1979: The salinity intrusion in the Fraser River: salinity, temperature and current observations, 1976, 1977; Institute of Ocean Sciences, Department of Fisheries and Oceans (Canada), Sidney, British Columbia, Pacific Marine Science Report 79-14, 193 p.

Ages, A. and Woollard, A.
1976: The tides in the Fraser Estuary; Institute of Ocean Sciences, Department of Fisheries and Oceans, Victoria, British Columbia, Pacific Marine Science Report 76-5, 100 p.

Armstrong, W., Wright, E.J., Lythe, S., and Gaynard, T.J.
1985: Plant zonation and the effects of the spring-neap tidal cycle on soil aeration in a Humber salt marsh; Journal of Ecology, v. 73, p. 323–339.

Bertness, M.D. and Ellison, A.M.
1987: Determinants of pattern in a New England salt marsh plant community; Ecological Monographs, v. 57, no. 2, p. 129–147.

Bertness, M.D., Wise, C., and Ellison, A.M.
1986: Consumer pressure and seed set in a New England salt marsh plant community; Oecologia, v. 71, p. 190–200.

Bowden, K.F.
1967: Circulation and diffusion; *in* Estuaries, (ed.) G.F. Lauden; American Association for the Advancement of Science, Publication No. 83, p. 15–36.

Bradfield, G.E. and Porter, G.L.
1982: Vegetation structure and diversity components of a Fraser estuary tidal marsh; Canadian Journal of Botany, v. 60, p. 440–451.

Burg, M.E., Tripp, D.R., and Rosenberg, E.S.
1980: Plant associations and primary productivity of the Nisqually salt marsh on southern Puget Sound, Washington; Northwest Science, v. 54, p. 222–236.

Burgess, T.E.
1970: Foods and habitat of four anatinids wintering on the Fraser delta tidal marshes; M.Sc. thesis, University of British Columbia; Vancouver, British Columbia, 124 p.

Chapman, V.J.
1960: Salt Marshes and Salt Deserts of the World; Leonard Hill Books, London, United Kingdom, 342 p.

Dawe, N.K. and White, E.R.
1982: Some aspects of the vegetation ecology of the Little Qualicum estuary, British Columbia; Canadian Journal of Botany, v. 60, p. 1447–1460.
1986: Some aspects of the vegetation ecology of the Nanoose-Bonell estuary, Vancouver Island, British Columbia; Canadian Journal of Botany, v. 64, p. 27–34.

del Moral, R. and Watson, A.F.
1978: Vegetation on the Stikine Flats southeast Alaska; Northwest Science, v. 52, p. 465–475.

Denno, R.F.
1977: Comparison of the assemblages of sap-feeding insects inhabiting two structurally different salt marsh grasses in the genus *Spartina*; Environmental Entomology, v. 6, p. 359–372.

Disraeli, D.J. and Fonda, R.W.
1979: Gradient analysis of the vegetation in a brackish marsh in Bellingham Bay, Washington; Canadian Journal of Botany, v. 57, p. 465–475.

Ellison, A.M.
1987: Effects of competition, disturbance, and herbivory on *Salicornia europaea*; Ecology, v. 68, p. 576–586.

Ewing, K.
1983: Environmental controls in Pacific Northwest intertidal marsh plant communities; Canadian Journal of Botany, v. 61, p. 1025–1039.
1986: Plant growth and productivity along complex gradients in a Pacific Northwest brackish tidal marsh; Estuaries, v. 9, no. 1, p. 49–62.

Gray, A.J. and Scott, R.
1977: The ecology of Morecambe Bay; VII; The distribution of *Puccinellia maritima*, *Festuca rubra*, and *Agrostis stolonifera* in the salt marshes; Journal of Applied Ecology, v. 14, p. 229–241.

Hartman, J., Caswell, J., and Valiela, I.
1983: Effects of wrack accumulation on salt marsh vegetation; *in* Proceedings of the Seventh European Marine Biology Symposium; Oceanologica Acta Special Issue, p. 99–102.

Hillaby, F.B. and Barrett, D.T.
1976: Vegetation communities of a Fraser River salt marsh; Habitat Protection Directorate, Department of Environment, Fisheries and Marine Service (Canada), Vancouver, British Columbia; Technical Report Series Pac/T-76-14; 18 p. plus appendices.

Howes, B.L., Howarth, R.W., Teal, J.M., and Valiela, I.
1981: Oxidation-reduction potentials in a salt marsh: spatial patterns and interactions with primary production; Limnology and Oceanography, v. 26, p. 350–360.

Hutchinson, I.
1982: Vegetation-environment relations in a brackish marsh, Lulu Island, Richmond, B.C.; Canadian Journal of Botany, v. 60, p. 452–462.
1986: Primary Production Functions of Wetlands in the Pacific Northwest; Chapter 5 *in* Wetland Functions, Rehabilitation, and Creation in the Pacific Northwest: The State of our Understanding, (ed.) R. Strickland; Proceedings of a Conference; Washington State Department of Ecology Publication No. 86-14, p. 73–91.

Keefe, C.W.
1972: Marsh production: a summary of the literature; Contributions in Marine Science (Texas A&M University), v. 16, p. 163–181.

King, G.M., Klug, M.J., Wiegert, R.G., and Chalmers, A.G.
1982: Relation of soilwater movement and sulfide concentration to *Spartina alterniflora* production in a Georgia salt marsh; Science, v. 218, p. 61–63.

Mason, H.L.
1957: A Flora of the Marshes of California; University of California Press, Berkeley, California, 878 p.

Mendelssohn, L.A. and Seneca, E.D.
1980: The influence of soil drainage on the growth of salt marsh cordgrass, *Spartina alterniflora*, in North Carolina; Estuarine and Coastal Marine Science, v. 11, p. 27–40.

Mendelssohn, L.A., McKee, K.L., and Patrick, W.H.
1981: Oxygen deficiency in *Spartina alterniflora* roots: metabolic adaption to anoxia; Science, v. 214, p. 439–441.

Moody, A.I.
1978: Growth and distribution of the vegetation of a southern Fraser delta marsh; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 153 p.

Parsons, C.O.
1975: Vegetation patterns in a salt marsh at Boundary Bay, British Columbia; Lamda, v. 1, no. 2, p. 45–52.

Pidwirny, M.J.
1990: Plant zonation in a brackish tidal marsh: descriptive verification of resource-based competition and community structure; Canadian Journal of Botany, v. 68, p. 1689–1697.

Pielou, E. and Routledge, R.
1976: Salt marsh vegetation: latitudinal gradients in the zonation patterns; Oecologia, v. 24, p. 311–321.

Pomeroy, W.M.
1980: Deas Slough marsh transplant project; *in* An Account of a Workshop on Restoration of Estuarine Habitats, (ed.) C.D. Levings; Canadian Manuscript Report of Fisheries and Aquatic Sciences No. 1571, p. 9.

Pomeroy, W.M., Gordon, D., and Levings, C.D.
1981a: Data report of brackish marsh transplant experiments at the Fraser River estuary; Canadian Data Report of Fisheries and Aquatic Sciences No. 274, 76 p.
1981b: Experimental transplants of brackish and salt marsh species on the Fraser River estuary; Canadian Technical Report of Fisheries and Aquatic Sciences No. 1067, 35 p.

Porter, G.L.
1982: Vegetation-environment relationships in the tidal marshes of the Fraser River delta, British Columbia; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 143 p.

Ranwell, D.S.
1972: Ecology of Salt Marshes and Sand Dunes; Chapman and Hall, London, United Kingdom, 258 p.

Redfield, A.C.
1972: Development of a New England salt marsh; Ecological Monographs, v. 42, p. 201–237.

Reidenbaugh, T.G. and Banta, W.C.
1980: Origin and effects of tidal wrack in a Virginia salt marsh; Gulf Research Reports, v. 6, p. 393–401.

Shepperd, J.E.
1981: Development of a salt marsh on the Fraser delta at Boundary Bay, British Columbia, Canada; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 99p.

Silander, J.A. and Antonovics, J.
1982: Analysis of interspecific interactions in a coastal plant community — a perturbation approach; Nature, v. 298, p. 557–560.

Smalley, A.E.
1960: Energy flow of a salt marsh grasshopper population; Ecology, v. 41, p. 672–677.

Snow, A. and Vince, S.W.
1984: Plant zonation in an Alaskan salt marsh; II; an experimental study of the role of edifice conditions; Journal of Ecology, v. 71, p. 669–684.

Teal, J.M.
1962: Energy flow in the salt marsh ecosystem of Georgia; Ecology, v. 43, p. 614–624.

Valiela, I. and Teal, J.M.
1974: Nutrient limitation in salt marsh vegetation; *in* Ecology of Halophytes, (ed.) R.J. Reimold and W.H. Queen; Academic Press, New York, New York, p. 547–563.

Vince, S.W. and Snow, A.
1984: Plant zonation in an Alaskan salt marsh: I. Distribution, abundance, and environmental factors; Journal of Ecology, v. 72, p. 651–667.

Vince, S.W., Valiela, I., and Teal, J.M.
1981: An experimental study of the structure of herbivorous insect communities in a salt marsh; Ecology, v. 62, p. 1662–1678.

Williams, G.L.
1993: Mitchell Island marsh compensation project: monitoring results and implications for estuarine management; *in* Proceedings of the 1993 Canadian Coastal Conference, May 4–7, 1993, Vancouver, B.C.; The Coastal Zone Engineering Program, National Research Council of Canada, Ottawa, Ontario, p. 417–429.

Yamanaka, K.
1975: Primary productivity of the Fraser River delta foreshore: yield estimates of emergent vegetation; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 133 p.

Fraser River delta seagrass ecosystems, their distributions and importance to migratory birds

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Abstract: Seagrasses flourish in shallow-water habitats where their roots can penetrate into soft sediments and their leaves can receive adequate sunlight, but remain wet even at low tide. Only the native eelgrass and the dwarf eelgrass occur in the Fraser River delta. Seagrass beds worldwide are prone to destruction by the effects of port and marina construction, shipping, and pollution; however, the beds of the study area have expanded in recent decades, because of improved growing conditions and the introduction of dwarf eelgrass. The ecological implications of this expansion into adjacent ecosystems are complex. Bird species will be affected, because some depend on the seagrass beds for food whereas others require unvegetated tidal flats. This paper documents the ecological importance of seagrass beds in the delta, especially to birds; provides accurate maps of seagrass distributions; explains some the changes since 1950; discusses conservation issues; and predicts possible seagrass-system response to climate change.

Résumé : Les herbes marines prospèrent dans les habitats en eau peu profonde, où leurs racines peuvent pénétrer dans les sédiments mous tandis que leurs feuilles reçoivent une lumière suffisante tout en restant mouillées, même à marée basse. Seules les espèces *Zostera marina* (indigène) et *Z. japonica* sont présentes dans le delta du Fraser. Les herbiers marins de la planète sont en danger d'être détruits par les effets de la marine marchande, de la pollution, et de la construction de ports et de marinas; néanmoins, les herbiers de la zone d'étude gagnent en superficie depuis quelques décennies, en raison de l'amélioration des conditions de croissance et de l'introduction de *Z. japonica*. Les conséquences écologiques de cette expansion vers les écosystèmes adjacents sont complexes. Des espèces d'oiseaux seront touchées, car certaines trouvent leur nourriture dans les herbiers alors que d'autres ne se nourrissent que sur les bas-fonds intertidaux dépourvus de végétation. Cet article documente l'importance écologique des herbiers du delta, particulièrement pour les oiseaux; présente des cartes précises de la distribution des herbes marines; explique certains changements survenus depuis 1950; discute d'enjeux de conservation; et prévoit la réaction éventuelle des systèmes d'herbes marines aux changements climatiques.

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SEAGRASS SYSTEMS AS HABITAT

Native eelgrass and dwarf eelgrass

Native eelgrass beds provide animals with shelter, stable sediment, and food. A walk through the vegetation at low tide or a swim in the channels that extend through the dense foliage reveals many small invertebrates and some larger ones (e.g. cockles, Dungeness crab), many fish, and a variety of birds. Kellerhals and Murray (1969) noted that the eelgrass zone contains the most varied and abundant fauna in Boundary Bay and on Roberts Bank. Baldwin and Lovvorn (1994a) also concluded that the biomass and numbers of invertebrates that are food for some waterfowl were greatest in the eelgrass community of Boundary Bay. High biological diversity is a feature of eelgrass beds elsewhere as well. In the Trent River delta, Vancouver Island, for example, of the 124 species of birds identified (over 38 000 individuals), 48% were recorded using the intertidal eelgrass-algae zone of the delta (for feeding, foraging, preening, or loafing) at some time during the year, suggesting that a diversity of food sources was available there (Brooks et al., 1994).

Native eelgrass plants retain a leafy biomass year-round (Harrison, 1982a), and because the plants are rarely exposed to the air, the habitat is available to marine animals almost continuously. Animals living in eelgrass beds are protected from predators by a dense canopy of leaves that impedes the movement of larger fish and birds, and by a mat of underground stems and roots that prevents the easy movement of predators into and through the sediment (Brenchley, 1982). The buoyant leaves act as baffles in the water, reducing water velocities, and also protect animals from extremes of temperatures and from drying.

Figure 1. Dwarf eelgrass (Zostera japonica) in Boundary Bay. Flowering shoots appear lighter in colour. One sloughed leaf of native eelgrass (measuring approximately 30 cm in length) is visible running diagonally from the lower right. Photograph by M. Dunn, Canadian Wildlife Service.

Seagrasses provide food in several ways. Only a few species eat the living leaves, but among these consumers are snails and amphipods that can be important prey for fish and birds (Phillips, 1978; Webb and Parsons, 1991; Heck et al., 1995; Thom et al., 1995). On Roberts Bank, the eelgrass food chain is important for great blue heron, which appear to have increased in number in recent decades (Friends of Boundary Bay, written comm., 1995). In addition, some dabbling ducks rely directly on eelgrass leaves for food (Baldwin and Lovvorn, 1994a). Other invertebrates (snails, nudibranchs, isopods, amphipods) graze on the bacteria and microalgae that adhere to the leaves, and become especially abundant during the summer months (Phillips, 1978). Still other invertebrates depend on the detritus formed when old leaves drop off the plants and decay on and in the sediment (Fenchel and Jorgensen, 1977).

The contribution of algal communities to the overall food web of seagrass systems has not been well studied. Bulthuis (1991) noted that the biomass of all macroalgae attached to leaves or shells or loosely floating beneath the leaves in seagrass habitats in Padilla Bay, Washington was greater than the native eelgrass shoot biomass. In the Trent River delta on Vancouver Island, British Columbia (Brooks et al., 1994), 33 species of macroalgae were recorded along with the native eelgrass. Some of the common algal species were *Monostroma zostericola, Punctaria hesperia,* and *Smithora naiadum*, all found attached to eelgrass leaves. Other algae commonly growing on native eelgrass leaves on Roberts Bank and in Boundary and Semiahmoo bays are *Ceramium gardneri* and a *Platythamnion* species (M. Dunn, Canadian Wildlife Service, unpub. field notes, 1992). The density of the attached algal community increases through the summer so that by late August the leaves are almost completely covered by algae. The contribution of this biomass to the overall productivity of the seagrass system requires further study.

The habitat value of dwarf eelgrass has been less well studied than that of the native eelgrass. As dwarf eelgrass stabilizes the sediments (in much the same way as the larger native eelgrass), it attracts some types of sediment-dwelling invertebrates (Posey, 1988). Dwarf eelgrass tolerates drying and thus can grow at higher elevations than native eelgrass (Harrison, 1982b). In the Fraser River delta there are areas where the two species co-occur, with dwarf eelgrass colonizing the higher microrelief that dries at low tides and native eelgrass in microdepressions that contain standing water even at the most extreme low-water tidal conditions (M. Dunn, Canadian Wildlife Service, unpub. field notes, 1992). Seed production is much higher in dwarf eelgrass than in native eelgrass (Harrison, 1979), so the addition of dwarf eelgrass to the ecosystem may increase the overall value of the vegetation to seed-eating birds. See Figures 1 and 2 for comparison.

The expansion of seagrasses onto previously unvegetated sandflats may have benefited some animals, but harmed others. On the positive side, the feeding habitat of great blue heron and Pacific brant has increased. On the negative side, at least one invertebrate that prefers bare sediment, the ghost shrimp (*Callianassa californiensis*), declined in abundance on Roberts Bank (Harrison, 1987) as the native eelgrass expanded shoreward. The effects of colonization by dwarf eelgrass on animal communities are largely unknown (Harrison, 1987; Posey, 1988). One way in which seagrass influences surrounding communities is by the production of leaves that are sloughed in large numbers in autumn and winter and then decay on the sediment (Bach et al., 1986; Zieman et al., 1979; Thresher et al., 1992). Breakdown of the leaves adds to the organic and inorganic nutrients in the sediment (Kistritz et al., 1983), but the bacteria that decay the leaves may use up the oxygen needed by animals living there. Overall, expansion of seagrass on Roberts Bank and in Boundary Bay probably has reduced the available feeding habitat for shorebirds, such as Western sandpiper, which forage for invertebrate prey in the unvegetated intertidal zone, but the degree of threat posed by these losses to shorebird populations is currently unknown. Studies are needed to compare the chemical environment and animal communities in sediments that are influenced by seagrass (either through direct colonization or via imported leaves) and those that are bare.

Figure 2. Subtidal edge of native eelgrass (Zostera marina) zone in Boundary Bay, showing algae around shoot bases. Eelgrass is 75 cm high on average. Photograph by Stephen Hamet, Canadian Wildlife Service.

Birds in seagrass systems

Over 2.3 million birds (representing 150 species) use the intertidal part of the Fraser River delta every year. Areas used most commonly include northwestern Boundary Bay, Mud Bay (eastern Boundary Bay), and southern Roberts Bank (Butler and Cannings, 1989), particularly the area between the Westshore Terminals and British Columbia Ferry Corporation causeways (the intertidal zone in the intercauseway area, Fig. 3). A study using radio-tagged ducks (widgeon, pintail, and mallard) confirmed the high frequency of daytime use of

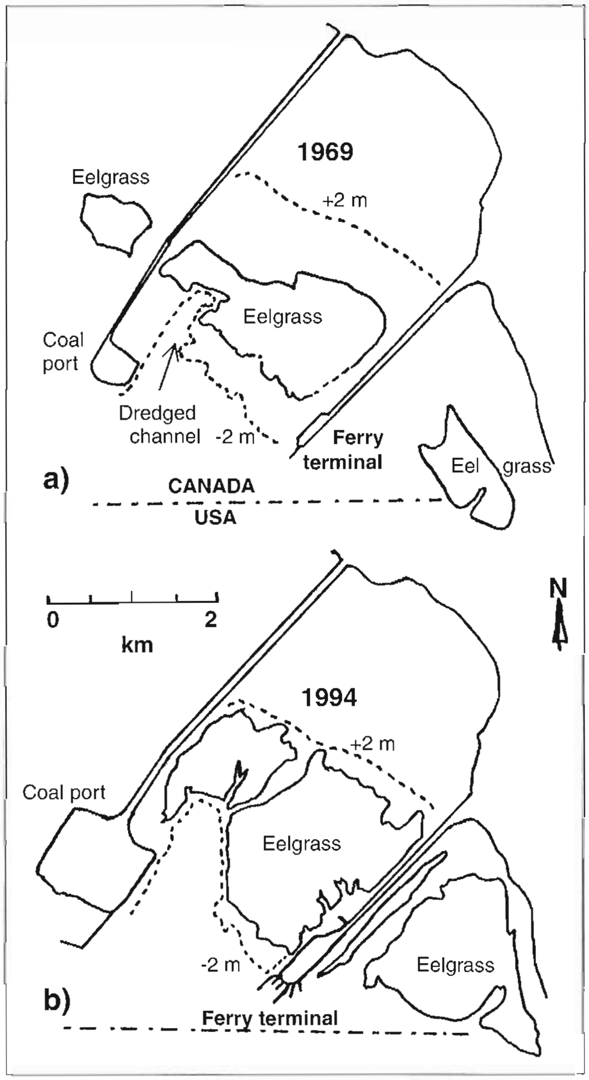

*Figure 3. Distribution of native eelgrass on Roberts Bank in **a**) 1969 and **b**) 1994. Elevation contours in the intercauseway area are relative to, in Canada, the point on the shore of the lowest low-tide reach; it is the 0.0 elevation on a hydrographic chart. For the location of Roberts Bank in the Fraser River delta, see Figure 4. Note the loss of eelgrass northwest of the coal port causeway after 1969, the expansion of eelgrass elsewhere, and the development of erosion channels in the intercauseway eelgrass bed. The coal port, British Columbia Ferry Corporation terminal, and dredged channel all were expanded after 1969. Data after M. Tarbotton and P.G. Harrison (unpub. report, 1996).*

two of these areas: northwestern Boundary Bay and the intercauseway area (Lovvorn and Baldwin, 1996). In another study (Butler and Cannings, 1989), it was found that during fall and spring migration peaks, shorebirds were the most commonly seen group, representing about 39% of all birds observed. This reflects the strong seasonal component to the use of these areas by birds. The next most abundant group, dabbling ducks, represented 27% of the numbers, whereas diving ducks made up 21%.

Each of the represented species or group of species has evolved unique foraging strategies and food preferences. Duration of exposure of intertidal habitats determines when, where, and for how long birds may feed in these habitats. Factors such as bill length and shape, or preferred water depth, can result in different food use in the same intertidal habitats (Baldwin and Lovvorn, 1994a). Furthermore, food preferences can range from opportunistic to plant- or animal-specific, and methods of foraging include grazing, probing, pecking, and grubbing (excavating pits in search of plant roots) (Baldwin and Lovvorn, 1994a; Boyd, 1995). Diet can show great variability even within the same groups of birds. For instance, in four waterfowl species using Boundary Bay, diets (as per cent of dry mass) ranged from 90% seagrass in American widgeon to 80% invertebrates and almost no seagrass in green-winged teal (Baldwin and Lovvorn, 1994b). More specifically, American widgeon seemed to prefer dwarf eelgrass leaves; mallard and pintail ducks ate mostly leaves, seeds, and rhizomes of dwarf eelgrass, as well as gastropods; and green-winged teal consumed amphipods and saltmarsh plant seeds (Baldwin and Lovvorn, 1992, 1994b).

Black brant geese (*Branta bernicla L.*) feed extensively on eelgrass beds of Boundary Bay and southern Roberts Bank. These beds support both a small wintering population of brant geese (about 600) and larger migratory populations that move through in spring. Ninety-eight percent by weight of the diet of these birds consists of the leaves of dwarf (57%) and native (41%) eelgrass (Baldwin and Lovvorn, 1994b). Dwarf eelgrass appears to be replacing native eelgrass as the preferred food. The importance of extensive and accessible eelgrass beds, particularly during spring migration, was studied in Willapa Bay and Dungeness, Washington over a ten-year period (Wilson and Atkinson, 1995). The study found a correlation between brant geese use of these areas and the availability of eelgrass; a 52% decline in brant geese use was associated with a 22% decline in eelgrass (Wilson and Atkinson, 1995). The authors hypothesized that a shortage of eelgrass during the critical spring staging period in certain years may have led to low reproductive success. The study did not identify the species of eelgrass that the brant geese consumed; however, the data did suggest that the health of the brant geese populations is correlated with the availability of eelgrass beds.

Shorebirds eat a wide range of invertebrate species; many show no preference for particular species in their food choice. This dietary flexibility is advantageous to birds that migrate long distances and exploit a variety of habitat types (Skagen and Oman, 1996). Two shorebird species are particularly abundant in the Fraser River delta: Western sandpiper and dunlin.

Three areas of the Fraser River delta are known for feeding concentrations of migrating Western sandpipers on unvegetated intertidal flats: northern Roberts Bank (off Westham Island), central Roberts Bank (Brunswick Point), and western Boundary Bay. Studies elsewhere have shown a correlation between foraging areas and areas of highest invertebrate abundance (Wilson, 1994), suggesting that the above three areas represent zones of abundance for prey items. Studies of Western sandpiper stomachs found amphipods, arthropods, polychaete annelids, bivalve molluscs, and gastropods (Wilson (1991); K. Vermeer and R. Elner, unpub. data (1993); Sewell (1996); for a general account *see* Wilson (1994)); however, Sewell (1996) found little evidence that Western sandpiper predation caused a decline in the abundance of any invertebrate species.

Western sandpiper have different preferred foraging microhabitats in their wintering, migration stopover, and breeding sites. For migration stopover sites, birds have been observed to forage at the tideline of a falling tide for a period of time and then to disperse over the exposed portions of the tidal flats; shallow intertidal pools (2–10 cm deep) were also used. On sandflats, higher densities of birds were recorded in the upper intertidal zone, followed by the lower intertidal zone and the middle intertidal zone, respectively (Wilson, 1994). In the Fraser River delta, it is the upper intertidal zones of Roberts Bank and Boundary Bay that are used by the birds (Sewell, 1996). In virtually all cases, the foraging concentrations observed in the latter study were on unvegetated, exposed surfaces.

Dunlin, a shorebird that winters in the Fraser River delta, shows a strong preference for the sand flats and mud flats of Boundary Bay. Dunlin forage by pecking small crustaceans at the surface and probing for large polychaetes in the substrate. In contrast to studies cited earlier, E.H. McEwan and D.K. Gordon (unpub. report, 1985) found that the maximum diversity for invertebrate species in Boundary Bay occurred in the area covered by blue-green algal mats seaward of the saltmarsh zone that borders the dyke (Adams and Williams, 2004). The highest densities of invertebrates were found in the algal mats, and the lowest in the sand and eelgrass zones. Dunlin use of these zones showed a seasonal distribution. During fall and spring the birds spent more time feeding in the sand and eelgrass zones, whereas in winter they were confined to the algal mat and sand zones because the daytime winter high tides prevented them from foraging in the lower zone (E.H. McEwan and A. Farr, unpub. report, 1986).

Coupling dietary flexibility with opportunism (i.e. altering prey selections to those available or concentrating where prey is abundant) (refer to Skagen and Oman (1996) for primary studies) is a very desirable characteristic when the food resource can be very unpredictable. It would appear that the Boundary Bay–Roberts Bank system provides a variety of productive habitats that together support a diverse group of shorebirds.

Distributions of other bird groups (loons, grebes, diving ducks, and cormorants) also have strong seasonal components, with Roberts Bank and Boundary Bay consistently recording the highest observed numbers in the Fraser River delta for some part of the year (Vermeer et al., 1994). The prey groups that these birds exploit include sculpin, eulachon, herring, gastropods, mud shrimp, clams, and crabs (Butler and Campbell, 1987). Various authors have studied the distribution of these prey groups and their relative abundance (Kellerhals and Murray, 1969; Swinbanks, 1979; E.H. McEwan and D.K. Gordon, unpub. report, 1985; Sewell, 1996).

One of the most visible and well-known users of the intertidal eelgrass beds of Boundary Bay and Roberts Bank is the coastal subspecies of great blue heron (*Ardea herodias fannini*). Herons reside year-round, and large breeding colonies are located at Point Roberts, Washington (350 pairs) and within Pacific Spirit Park (150 pairs) (Butler, 1995). The heron chooses woodlots with large trees for nesting habitats, preferring woodlots that are extensive enough in area to provide a buffer against disturbance. The population is contracting because small colonies are being abandoned in favour of fewer larger colonies closer to secure food sources (Butler, 1995). The shift was attributed to loss of woodlot habitats and to disturbances caused by humans and eagles. As a result, the coastal subspecies was listed as vulnerable by the Committee on the Status of Endangered Wildlife in Canada in 1997.

The heron's primary food source for much of the year in the Fraser River delta is small fish, particularly shiner perch, Pacific staghorn sculpin, and saddleback and crescent gunnels (63%, 30%, and 3%, respectively, of the total fish in the diet of adult herons) (Butler, 1995). These values apply to spring, summer, and fall feeding periods. Little is known about the diet and foraging behaviour of herons, particularly adults, during winter (Butler, 1995).

In summary, the 8000 ha of tidal flats that constitute southern Roberts Bank and Boundary and Semiahmoo bays make for a rich system of marine invertebrates, both on unvegetated flats and in extensive eelgrass beds. This is a key stopover in the Pacific Flyway migration route; birds that pass through this stopover range over three continents and 20 countries (Butler and Campbell, 1987). Nowhere else in Canada are winter populations of great blue heron, black-bellied plover, and mew gull as numerous or dense. In addition, 40 of the world's 214 species of shorebirds are found here, an extraordinary diversity. Boundary Bay alone supports most of the world's population of Western sandpiper during migration (R.W. Butler, pers. comm., 1997). This area exceeds the criteria for numbers of waterfowl and shorebirds established for internationally important wetlands by the Ramsar Convention on Wetlands of International Importance (Butler and Campbell, 1987). There are no comparable sites along the Pacific Coast between California and Alaska.

Importance of adjacent agricultural areas

Any discussion of the significance of the Boundary Bay–Roberts Bank eelgrass systems to the bird fauna must also include the role of adjacent agricultural areas in the continued productivity of this system. Upwards of 70% of the wetland areas have been replaced by agricultural, industrial, and residential development (Schaefer, 2004). Even so, the Fraser River delta continues to support large and diverse populations of migratory birds. Although there are no estimates of historical bird populations or documentation of their use of wetland habitats prior to losses of these areas, recent studies have suggested that certain species have adapted their foraging strategies to include agricultural food sources. The switch in foraging areas from the intertidal zone to nearby farmland occurs in fall and winter and has been attributed to the effect of winter tides, which reduce intertidal foraging opportunities during the day, and to the overall reduced prey availability.

Western sandpiper, dunlin, and black-bellied plover roost and forage in farmlands within 2 km of the intertidal areas over the fall-to-spring period (Butler, 1992). For dunlin, mean body weight peaks in December and subsequently decreases over the next two months (McEwan and Whitehead, 1984), coinciding with a switch from intertidal foraging to farmland foraging. Thus, farmlands may provide alternate foraging habitats for individuals that cannot find sufficient food to meet their daily energy needs.

Most great blue herons, both juvenile and adult, that use the Fraser River delta intertidal areas switch to foraging in freshwater marshes and grasslands (and old, once cultivated, fields) during late fall and winter months when intertidal food availability is below the required daily energy needs (Butler, 1995). Townsend's vole (*Microtus townsendii*), which peaks in abundance during this period, is the main prey item (Butler, 1995). Butler (1991) also observed that juvenile herons utilize the old field and grassland habitats more commonly than adults do because the young are less efficient at capturing prey items in the intertidal areas at this time of year (i.e. when low tides are at night).

The amount of food in Boundary Bay may be insufficient to provide for the energy needs of the three largest duck populations during the winter months (American widgeon, Northern pintail, and mallard) (Baldwin and Lovvorn, 1992). This possible factor among others was believed to be responsible for the shift of large numbers of these species to foraging at night on farmlands, consuming seeds, grasses, corn, potatoes, cabbage, and insects. The largest concentrations of these ducks were found along the northwestern shore of Boundary Bay, along the Serpentine and Nicomekl rivers, and south of Ladner (Breault and Butler, 1992). Other studies noted that the farmland adjacent to marsh areas had become a significant and sometimes critical alternate food source at certain times of the year, even when there was available and ample intertidal food (Boyd, 1995; Lovvorn and Baldwin, 1996). Therefore, it would appear that it is critical to the long-term productive capacity of the Fraser River delta to ensure that any conservation plans integrate viable soil-based agriculture with protection of the intertidal marsh and eelgrass ecosystems.

CHANGES IN THE ROBERTS BANK SEAGRASS SYSTEM

Response of native eelgrass to British Columbia Ferry Corporation terminal and Westshore Terminals coal port construction

The area of native eelgrass on Roberts Bank approximately doubled between 1950 and 1994, despite losses of vegetation resulting directly from the construction of the British Columbia Ferry Corporation terminal and the Westshore Terminals coal port (M. Tarbotton and P.G. Harrison, unpub. report, 1996; Fig. 3). Native eelgrass is sensitive to changes in its physical environment, especially to the availability of light and the duration of water cover. It is intolerant of drying at low tide (Harrison, 1982b), and it cannot grow more than 1 to 2 m below the lowest tide line in local waters because the turbid Fraser River water limits the penetration of light (P.G. Harrison, unpub. report, 1985; Dennison, 1987; Dennison et al., 1993). Those factors became more favourable after the construction of the British Columbia Ferry Corporation terminal in 1960 and the Westshore Terminals coal port in 1969. Here we review a mechanism for eelgrass expansion proposed by Tarbotton et al. (1993) that is based on the control of eelgrass growth by light and water cover. The effects of other physical factors that may have been changed by the construction, such as exposure to winds and tidal currents, are explored as well, but appear to have had little influence on the plants. Of prime importance, however, has been the introduction and rapid spread of dwarf eelgrass, and the effects of dwarf eelgrass are incorporated into the proposed mechanism of eelgrass expansion.

Little is known about the ecology of Roberts Bank before the mid-1970s, but studies of seagrass growth, distribution, and establishment were conducted during and following the changes in habitat associated with the coal port expansion in 1981–1983. The major sources of information on the seagrass beds of the area have been the environmental impact assessment by Beak Hinton (unpub. report, 1977) prepared before the Phase II expansion of the coal port in 1982–1983, as well as studies by Swinbanks (1982), Harrison and Bigley (1982), P.G. Harrison (unpub. report, 1985), Harrison (1987, 1990), Duggan and Luternauer (1985), Nomme and Harrison (1991a, b), Tarbotton et al. (1993), and M. Tarbotton and P.G. Harrison (unpub. report, 1996). These studies relied on a combination of field investigations and interpretation of aerial photography.

Detailed analysis of aerial photographs revealed that expansion of native eelgrass after 1960 resulted from two phenomena: the initial transformation of patchy vegetation to areas of continuous cover, and the colonization of unvegetated sediment shoreward of existing native eelgrass (M. Tarbotton and P.G. Harrison, unpub. report, 1996). Thus, a mechanism is needed that would both promote increased growth rates of existing plants as well as allow the colonization of unvegetated flats. The mechanism proposed here has three components. First, a physical change, the construction of causeways across a broad intertidal zone leading to the British Columbia Ferry Corporation terminal and the coal port, directed the turbid Fraser River water offshore, improved the light regime, and induced higher productivity in the eelgrass. Second, the denser eelgrass bed restricted the flow of water ebbing off the tidal flats and impounded water, allowing plants to colonize shoreward. Third, the impounded water collected in drainage channels that eroded through the eelgrass vegetation, leading to an eventual end to the landward expansion. The mechanism was detailed by Tarbotton et al. (1993) and by M. Tarbotton and P.G. Harrison (unpub. report, 1996); therefore, only a basic outline and supporting evidence follow.

It is hypothesized that the two causeways on Roberts Bank have been diverting turbid water, both the water that drains off the tidal flats and Fraser River water that floats over the area at high tide. If that change had resulted in increased light reaching the plants, then plant productivity would have increased and the vegetation would have accumulated a larger biomass of leaves. It is also possible that the native eelgrass would have been more successful in flowering and setting of seeds, but the environmental controls on sexual reproduction are not well known (de Cock, 1981). If light were the only limiting factor, then the native eelgrass would have started to grow into the gaps that existed in the vegetation cover in the late 1950s (M. Tarbotton and P.G. Harrison, unpub. report, 1996).

Once the native eelgrass began to grow more vigorously, the plants themselves became the driving force for further expansion. A major characteristic of the vegetation is its resistance to the flow of water — in this case, water draining off the upper intertidal flats. The increased friction due to the increased biomass of leaves in the water (Fonseca et al., 1982; Fonseca and Fisher, 1986) would have resulted in impoundment of a thin layer of water landward of the original vegetation limit. Without the danger of drying, new shoots branching from underground stems could have colonized landward year by year. Aerial photographs revealed features that resembled 'annual rings' at the landward edge of the seagrass bed, where eelgrass was colonizing and expanding in shoot density, in the 1970s and early 1980s (Harrison, 1987). This scheme of shoreward expansion of eelgrass beds has a maximum upper limit, where the friction of the leaves is insufficient to pond enough water over the eelgrass bed to prevent drying of the intertidal area.

According to the hypothesized mechanism, the British Columbia Ferry Corporation terminal and the coal port should each have initiated shoreward expansion of the adjacent native eelgrass. Although only recently documented, expansion has occurred since 1960 southeast of the British Columbia Ferry Corporation terminal, towards the Canada–U.S.A. border. Vegetation expanded 100 to 150 m landward and became more dense; overall, the vegetated area has increased by about 200% (M. Tarbotton and P.G. Harrison, unpub. report, 1996). In the intercauseway area, landward expansion since 1969 has progressed by up to 1000 m (Fig. 3). The more gradual slope in the intercauseway area compared with the area southeast of the British Columbia Ferry Corporation terminal provides a more extensive intertidal zone from which water drains at low tide. Hence, there has been more opportunity for the eelgrass to expand in the intercauseway area.

The expansion of the native eelgrass beds and the resulting increase in frictional resistance to water flow contributed to the development of erosion channels (Duggan and Luternauer, 1985; Tarbotton et al., 1993). Small irregularities in topography and in plant density provided points of focus for increased rates of water flow. Once erosion began, it was a self-feeding process that led to the removal of sediment, and ultimately of the plants, in local areas. As channels grew, less water was impounded shoreward of the eelgrass bed, and the eelgrass stopped expanding. The erosion channels are thus the result of interactive biological and physical factors ultimately stemming from the initial British Columbia Ferry Corporation terminal and coal port developments.

Other contributing factors

Changes in the wind patterns, tidal currents, and mean water levels do not appear to have had a major effect on the distribution and abundance of native eelgrass. First, because the prevailing winds in the Strait of Georgia are predominantly from the southeast and the northwest, if moderation of the wave climate by the causeways had been a major factor in the changes observed in the seagrass vegetation, then the effect should have been seen only in the intercauseway area (M. Tarbotton and P.G. Harrison, unpub. report, 1996). The area southeast of the British Columbia Ferry Corporation terminal has remained open to the predominant wind waves, and yet the seagrass bed there has expanded too. Second, the patterns of flood and ebb tides on the flats are likely determined by local topography and water depth rather than by the main tidal currents in the strait. Thus, it is likely that the causeways have had only a minimal effect on tidal currents (Thomson, 1981; M. Tarbotton and P.G. Harrison, unpub. report, 1996). Third, the local rate of sea-level rise is on the order of 2 mm per year, and there appears to be no significant increase in natural deposition of sediment in recent decades to counter the small rate of seafloor subsidence (M. Tarbotton and P.G. Harrison, unpub. report, 1996). If we consider the seagrass bed to have a uniform slope of 1:1000 and the relative sea-level rise to be 4 mm per year (2 mm sea level plus 2 mm settlement), then the water line would have moved shoreward 40 m in the period 1950–1994, or 0.9 m per year. The observed average rate of migration of the landward edge of the seagrass bed is 33 m per year in the period from 1959 to 1992 (M. Tarbotton and P.G. Harrison, unpub. report, 1996), so the effect of sea-level change is minimal. Future changes resulting from global warming may, however, be more marked (*see* discussion below in 'Effects of climate change on eelgrass habitat').

The introduction of dwarf eelgrass on Roberts Bank in the late 1970s led to a rapid increase in the rate of landward expansion of the native eelgrass. Dwarf eelgrass colonized in two areas: on the intertidal flats far above the limits of the native eelgrass, forming a discrete seagrass bed, and farther seaward at the upper edge of the bed of native eelgrass (Swinbanks, 1979; Harrison, 1987). Dwarf eelgrass is largely dependent on seed production and is thus capable of more rapid dispersal and establishment than is the native eelgrass (Harrison, 1979; Harrison and Bigley, 1982; Orth et al., 1994). Field studies in the 1980s confirmed that dwarf eelgrass initiated the process of vegetating the sand flats, but that native eelgrass replaced the smaller invader after about two years (Harrison, 1987; Nomme and Harrison, 1991b). Shoots of dwarf eelgrass grow in dense swards and most probably contributed to the retention of the water ebbing off the intertidal flats. Thus, the presence of dwarf eelgrass landward of the eelgrass bed rapidly turned the otherwise unsuitable sand flats into available habitat for the native species. Without the accelerating effect of the introduced seagrass, the rates of landward extension of the seagrass bed, which averaged 33 m per year in the 1970s (M. Tarbotton and P.G. Harrison, unpub. report, 1996), would not have been achieved.

The upper limit reached by the native eelgrass in the early 1980s has remained unchanged, with only minor fluctuations both landward and seaward, in the intervening years (Harrison, 1987; M. Tarbotton and P.G. Harrison, unpub. report, 1996). Neither seagrass species has established lush vegetation at this limit; native eelgrass remains patchy, whereas dwarf eelgrass grows from almost no shoots in spring to a moderately dense cover in late summer and dies away each fall.

VEGETATION MAPPING IN BOUNDARY BAY AND ON ROBERTS BANK

Development of vegetation maps

In the summers of 1992 and 1993, an extensive mapping program for the eelgrass areas of Boundary Bay, Semiahmoo Bay, and Roberts Bank was undertaken. The decision to undertake this program was based on the knowledge that these bays represented perhaps the most extensive eelgrass habitats of western Canada, that conservation of this system included the need for detailed vegetative maps, and that no comprehensive maps of these areas had been made. Earlier studies had only identified the extent of the vegetation zones, or made estimates of coverage based on a few samples (Swinbanks, 1979; Ward et al., 1992; Baldwin and Lovvorn, 1994a). The objectives of the 1992–1993 mapping program were to determine the extent of intertidal vegetation cover, by species, through an extensive ground survey; to develop a digital map base and relational database of the survey results; and to generate a digital map of vegetation zones using a Geographic Information System mapping model (M. Dunn, Canadian Wildlife Service, unpub. field notes, 1992). Figures 4 to 7 show the locations of the survey transects and the distributions of the vegetation types.

Mapping results

Native eelgrass dominates 32% of the vegetated area; in comparison, dwarf eelgrass dominates about 9% (based on Table 1). For Boundary Bay (excluding Semiahmoo Bay), native eelgrass dominates 28% of the 6344 ha surveyed, whereas dwarf eelgrass dominates about 8% of the intertidal area. Of interest is the area of overlap between the two species, which occupies 29% of the Boundary Bay survey area.

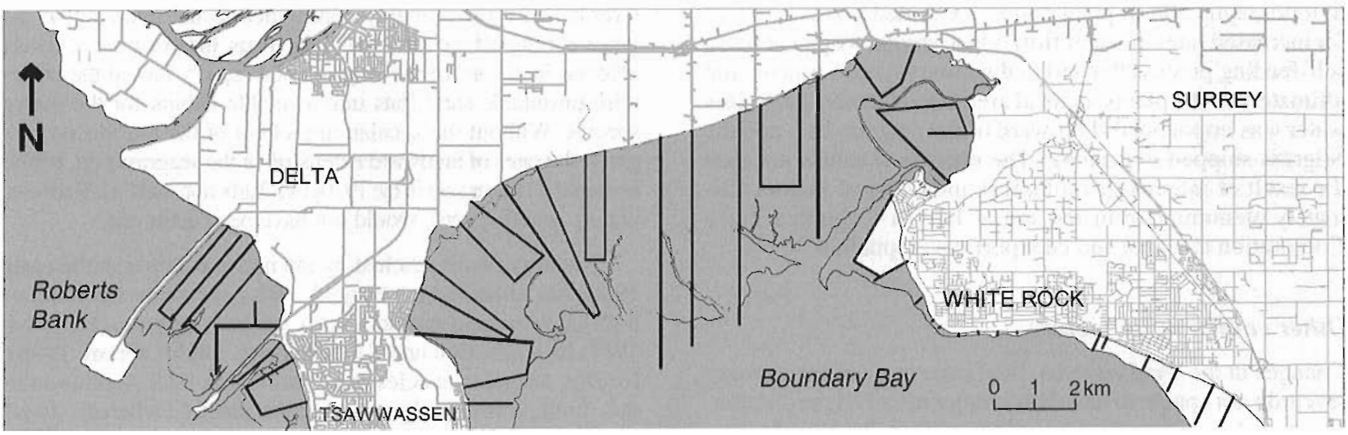

Figure 4. Intertidal vegetation survey transects (1992–1993).

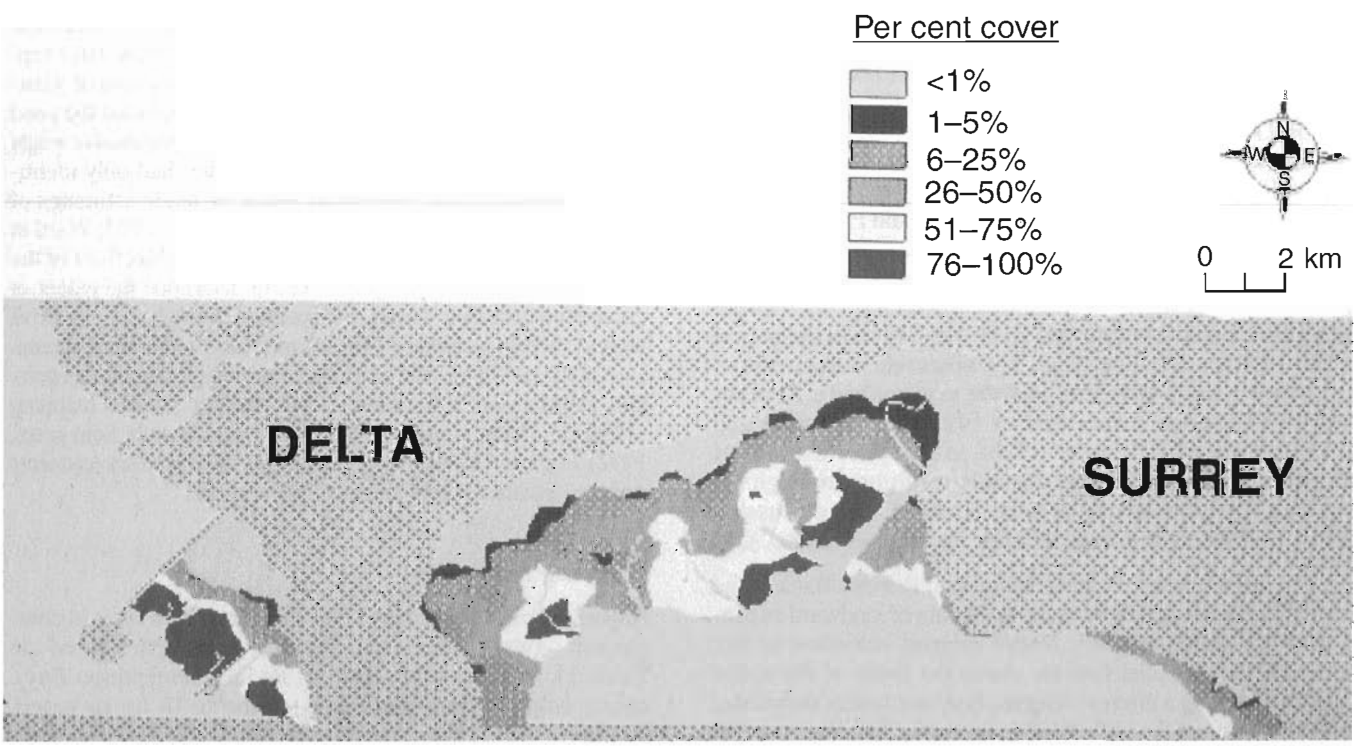

Figure 5. Distribution of native eelgrass (Zostera marina) by per cent cover.

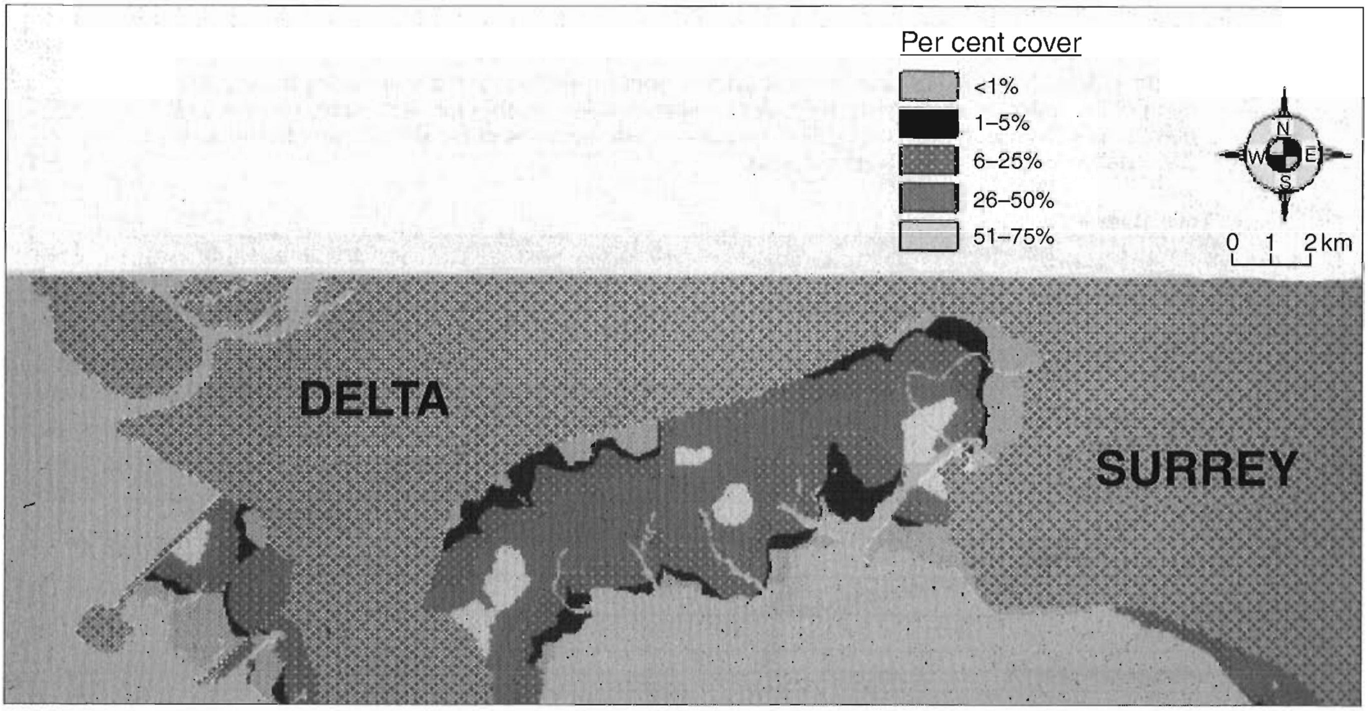

Figure 6. Distribution of dwarf eelgrass (Zostera japonica) by per cent cover.

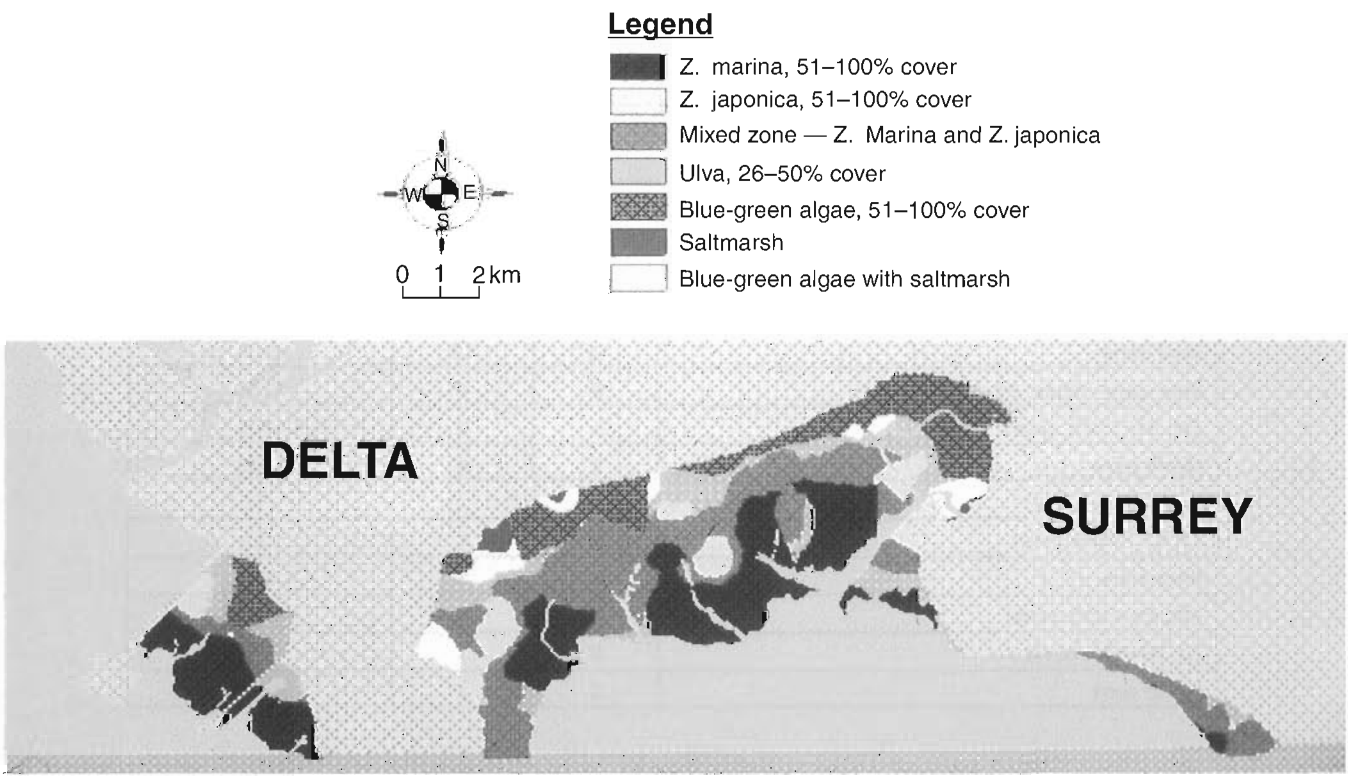

Figure 7. Distribution of selected vegetation types by per cent cover.

Table 1. Area (hectares) of each of the vegetation zones identified for the whole study area and for each of the separate study units. Key: class = identification number for each zone; count = total number of polygons in each class; Sum hectares = total hectares of the specific vegetation zone; ZM = native eelgrass; ZJ = dwarf eelgrass.

Description	Class	Count	Sum hectares
Total study area			
ZJ, 26–50% cover	9	1	36
Ulva, 26–50% cover	4	1	65
Saltmarsh	6	4	133
ZM, 26–50% cover	8	3	176
Blue-green algae with saltmarsh	7	8	319
ZJ, 51–100% cover	2	12	588
Bare zone	10	18	780
Blue-green algae, 51–100% cover	5	5	1317
Mixed zone	3	14	2252
ZM, 51–100% cover	1	13	2272
Intercauseway area			
ZJ, 51–100% cover	2	1	59
Mixed zone	3	1	136
Bare zone	10	3	163
Blue-green algae, 51–100% cover	5	1	164
ZM, 51–100% cover	1	2	408
Southern Roberts Bank			
ZJ, 51–100% cover	2	1	2
Mixed zone	3	3	10
Ulva, 26–50% cover	4	1	65
ZM, 51–100% cover	1	2	233
Boundary Bay			
Saltmarsh	6	4	133
ZM, 26–50% cover	8	3	176
Blue-green algae with saltmarsh	7	8	319
ZJ, 51–100% cover	2	9	525
Bare zone	10	13	597
Blue-green algae, 51–100% cover	5	4	1153
ZM, 51–100% cover	1	7	1605
Mixed zone	3	8	1836
Semiahmoo Bay			
ZJ, 51–100% cover	2	1	2
Bare zone	10	2	20
ZM, 51–100% cover	1	2	26
ZJ, 26–50% cover	9	1	36
Mixed zone	3	1	270

In contrast, in the 930 ha intercauseway area of Roberts Bank, native eelgrass dominates 44% of the area, dwarf eelgrass 6%, and the mixed zone 15% (Table 1). Table 1 also provides cover values for the other two units of the study area — southern Roberts Bank and Semiahmoo Bay. Comparison of cover estimates from this and previous studies confirms that large increases occurred between 1969 and 1989, but that changes since then have been slower (Table 2).

The analysis also revealed that native eelgrass coverage averaged about 44% over all plots in which it was observed. Dwarf eelgrass, on the other hand, averaged only 19% coverage for all plots in which it was detected. This suggests that the native species is much more concentrated within its range than the introduced species. Because shoot densities were not recorded in the present study, it is difficult to draw specific conclusions from this finding. In Padilla Bay, Washington, where density and biomass of the two eelgrass species were measured, density values did not correspond well with per cent cover or standing crop values (Bulthuis, 1991).

Table 2. Selected previous calculations (hectares) of extent of eelgrass in each study area unit. Key: zm = native eelgrass; zj = dwarf eelgrass; Z. spp = species not identified; nd = no data available.

Year	Intercauseway area	Southern Roberts Bank	Boundary Bay	Semiahmoo Bay
1969	250 (*Z.* spp)	nd	nd	nd
1970	nd	nd	211 zj 1560 zm	nd
1987	430 (*Z.* spp)	nd	nd	nd
1989	516 (*Z.* spp)	288 (*Z.* spp)	3274 (*Z.* spp)	nd
1991	nd	nd	3845 zj 3444 zm 1684 overlap	nd
1992–1993	59 zj 408 zm 136 zm/zj	2 zj 233 zm 10 zm/zj	525 zj 1605 zm 1836 zm/zj	2 zj 26 zm 270 zm/zj

Table 3. Elevation limits for native eelgrass and dwarf eelgrass and the mixed-vegetation zone in Boundary Bay, showing comparisons between this study and previous reports. Data are elevations in metres above or below geodetic datum. Key: nd = no data available.

Data source	Native eelgrass		Mixed	Dwarf eelgrass	
	upper	lower	range	upper	lower
Swinbanks (1979)	-1.49	-3	nd	~ 0.0	nd
Harrison (1982a)	-0.95	nd	nd	~ 0.0	nd
Baldwin and Lovvorn (1994b)	-0.8	nd	-0.8 to -1.8	0	-1.8
This study	-0.42	-3.21	-0.42 to -1.65	0.98	-1.65

While it has been possible to produce accurate comparative studies of eelgrass expansion on Roberts Bank, similar comparisons for Boundary Bay are unlikely. This is mainly due to the different methodologies employed by past studies for calculation of eelgrass distribution. For instance, Ward et al. (1992) used aerial photographs to calculate eelgrass cover for the Boundary Bay areas (refer to Table 2). Their study found that in 1989, 2995 ha were covered with continuous eelgrass. Areas of patchy eelgrass distribution were not part of the total calculated area of eelgrass cover. In contrast, the present study identifies a total of 4142 ha of Boundary Bay as dominated by one or both species of eelgrass. Even if only the coverage classes where eelgrass would be described as continuous (i.e. greater than 50% cover) are used, 3966 ha of the intertidal area are identified as covered. This is a difference of just under 1000 ha between the two findings, but the validity of the difference is in doubt.

Nonetheless, the digital map of intertidal vegetation communities for Boundary Bay, Semiahmoo Bay, and Roberts Bank is an accurate portrayal of the distribution of vegetation for that period in time. With this map and the associated database, it will now be possible to monitor the Roberts Bank and Boundary Bay systems and their response to a range of environmental pressures.

Comparison of the survey data and earlier reports reveals some possible changes in the elevation ranges for the seagrasses, but differences in the time of year when sampling occurred may contribute to some of the differences. In this study, the range for native eelgrass was 2.8 m and the range for dwarf eelgrass was 2.6 m, with an overlap of about 1.2 m (from – 0.42 m to –1.65 m geodetic datum; Table 3). Although Swinbanks (1979) found a similar lower limit for native eelgrass (–3.0 m) as that found in the present study (–3.21 m), he reported lower values for the upper elevation limits for both species (Table 3). That comparison suggests that both seagrasses have expanded shoreward since 1979, which is in agreement with the earlier discussion of changes in seagrass distribution in the intercauseway area of Roberts Bank; however, the hypothesis that dwarf eelgrass has colonized shoreward was not supported by Baldwin and Lovvorn (1994b), who defined three habitat zones in Boundary Bay based on two transects (Table 3). Their upper limit for dwarf eelgrass in Boundary Bay was at or near 0.0 m, the same upper limit identified by Swinbanks (1979). Harrison's (1982a) study (Table 3) was also based on limited transect sampling, but it did reveal a marked seasonal variation in the upper limit of dwarf eelgrass, which advances by about 400 m during the summer and then retreats during the winter. One reason for the regression may be the actions of birds grazing and grubbing in the eelgrass beds in the fall. Since Baldwin and Lovvorn (1994b) sampled in fall and winter, it is not surprising that they found a lower value for the upper limit of dwarf eelgrass than the summer samples of the 1992–1993 survey revealed. Thus, birds could have a significant effect on the interannual distribution of dwarf eelgrass, and possibly on that of native eelgrass as well.

Figure 8. Physical constraint to landward saltmarsh migration under rising sea levels: the sea dykes of Boundary Bay. Photograph by M. Dunn, Canadian Wildlife Service.

EFFECTS OF CLIMATE CHANGE ON EELGRASS HABITAT

A model of sea-level rise predicts that native eelgrass will expand, but dwarf eelgrass will become less extensive (J.A. Stronach and D.S. Dunbar, unpub. report, 1992). It is difficult to make accurate predictions about the effects of global warming on the Fraser River delta system, due to complexities of tectonic, oceanographic, meteorological, and man-induced effects (Intergovernmental Panel on Climate Change, 1995; Taylor, 2004). However, it has been recently estimated that the Fraser River delta region is experiencing a sea level rise of 0 to 6 mm/a (Beckmann et al., 1997; Thomson and Crawford, 1997; Taylor, 2004). The seagrass beds can be expected to migrate landward in response to more frequent and extensive inundation of present high-tide areas (Dunn, 1988). Landward migration of dwarf eelgrass will be limited by the dykes ringing much of the shoreline (Fig. 8), but local topography will also play a role, according to the mean exposure-duration model of J.A. Stronach and D.S. Dunbar (unpub. report, 1992). In Boundary Bay, for example, the model predicts a decrease of almost 50% in the coverage by dwarf eelgrass and an expansion of the native eelgrass by almost the same amount. The authors caution that there are many other factors which would affect these predictions, including wave climate, storm frequency, and sedimentary regime. As well, they note that the original distribution map for the native eelgrass (from Swinbanks, 1979) was not well documented, and that its extent may well have been overestimated (J.A. Stronach and D.S. Dunbar, unpub. report, 1992). Nonetheless, the predicted decrease of dwarf eelgrass from its present extent would significantly reduce its ability to support even the present numbers of waterfowl that use it as a primary food source.

Other effects of sea-level rise might include the colonization of formerly unvegetated tidal flats and very productive algal mat zones by dwarf eelgrass, light-limited losses of native eelgrass in deep water, and a landward shift of the zone of overlap between the two species. What this means to the associated plant and animal communities cannot be predicted at this time. As well, the impact of this shift on the diversity of habitats and organisms available to meet the food-energy needs of migratory birds is largely unknown. Even so, some general observations are possible.

Changes in mean water levels and shifts of the eelgrass communities could have significant effects on the foraging strategies of some birds. As discussed earlier, some intertidal forage areas become seasonally inaccessible due to changes in water levels, thus limiting feeding opportunities for some waterfowl species (Baldwin and Lovvorn, 1994a). Adjacent agricultural areas have been alternate feeding sites for these species. If sea level rises, it is possible that there will be an increased need for waterfowl to find alternate foraging areas because of reduced frequency and extent of intertidal exposure. For instance, Baldwin and Lovvorn (1994a) hypothesized that 20 cm is the maximum water depth in which dabbling ducks can feed to reach sediments in the dwarf eelgrass zone. Grazers are expected to reach floating leaves at water depths of up to 0.5 m. Two species, mallard and pintail, are also known for their habit of excavating pits in search of eelgrass rhizomes and invertebrates. Additionally, the apparent dependence of many shorebird species, especially Western sandpiper and dunlin, on the algal mat and unvegetated zones for critical food supplies will likely be severely compromised by these potential shifts.

In 'Birds in seagrass systems', it was noted that certain waterfowl and shorebird species had already evolved flexible and opportunistic foraging strategies. For instance, before the availability of dwarf eelgrass, certain waterfowl utilized the roots, leaves, and seeds of native marsh plants such as *Carex* species, *Triglochin maritimum,* and *Potentilla* species (Lovvorn and Baldwin, 1996). Skagen and Oman (1996) identified this same opportunistic characteristic in their review of dietary flexibility of western-hemisphere shorebird species. The key risk to the ability of these species to adapt is the extent and distribution of accessible food sources, in terms of both water depth and exposed surfaces that will be available under higher sea levels.

POTENTIAL FOR INTRODUCTION OF FOREIGN SPECIES

The implications of the introduced dwarf eelgrass for the seagrass system have been discussed. There is a long history of introductions to the marine ecosystem that have had measurable effects on native populations, including virtual displacement. For instance, the invasion of coastal areas of Washington by the introduced saltmeadow cordgrass (*Spartina alterniflora*) is changing the function of coastal habitats (British Columbia/ Washington Marine Science Panel, 1994). The Marine Science Panel assigned a high priority to preventing introductions of exotic organisms, both intentional and unintentional, because resulting changes could be persistent or irreversible and the effects very significant.

Table 4. Principal habitats used by waterfowl, shorebirds, birds of prey, and songbirds near Boundary Bay.

Habitats	Dabbling ducks	Shorebirds and herons	Birds of prey	Songbirds
Farmlands				
Old field		•	•	•
Overgrown pasture			•	•
Cultivated field	•	•		•
Pasture	•	•	•	•
Hedgerows and trees		•	•	•
Beach				
Mudflat	•	•	•	
Saltmarsh	•	•	•	
Eelgrass	•	•		

Major vectors for new introductions are ballast water of international shipping, importation of exotic marine species for aquaria, and imported commercial fisheries products. Another, less studied, pathway is the result of climate-change effects on ocean temperature, e.g. a poleward shift of warmer subtropical waters and their associated biota. The result could mean a displacement of our native temperate species assemblages by these new assemblages. The 1982–1983 El Niño–Southern Oscillation (ENSO) event caused the temporary extension of the northern limit and/or an increase in abundance of 18 species of invertebrates and 38 species of vertebrates (Beckmann et al., 1997).

In British Columbia, the importation of juvenile Pacific oyster (*Crassostrea gigas*) has led to the introduction of six bivalve species, seven snail (gastropod) species, and four polychaete worm species (Waldichuk et al., 1994), and may even have been the source of dwarf eelgrass (Harrison and Bigley, 1982). Of these, the gastropod predators Japanese drill (*Ocenebra japonica*), Eastern oyster drill (*Urosalpinx cinerea*), and Eastern mud snail (*Nassarius obsoletus*) are known to occur in Boundary Bay. Other introduced species have spread much more extensively; these include the soft shell clam (*Mya arenaria*), the Manila little neck clam (*Tapes philippinarum*), and the parasitic copepod *Mytilicola orientalis* (Waldichuk et al., 1994). No detailed study has been undertaken on introductions due to ballast-water discharges from ships entering the Strait of Georgia. Carl and Guiguet (1958) did note that the woodborer Atlantic shipworm (*Teredo navalis*) and the crustacean *Limmora tripunctata* were brought into British Columbia waters by ships. A study of San Francisco Bay, a similarly busy shipping area, documented almost 100 introduced marine invertebrates surviving within the native marine communities (Carlton, 1985).

Within the Strait of Georgia generally, and specifically within the southern Roberts Bank–Boundary Bay seagrass systems, not much is known about the full ramifications of these past introductions other than displacement and some structural changes. A potential new introduction that could have further implications for the structure and dynamics of these systems may result from the spread of saltmeadow cordgrass (*S. alterniflora*), which is able to colonize previously unvegetated mud flats in very high densities. Its s presence has been documented in Padilla Bay, Washington, just south of Boundary Bay (Bulthuis, 1991). Another potential threat is the introduced European green crab (*Carcinus maenus L.*), an aggressive predator which is presently well established in northern California and appears to be expanding its range northward (Jamieson et al., 1998).

THE FUTURE OF EELGRASS HABITAT

In 1994, only 12.8% of the wetlands of the whole Fraser Lowland, which includes Roberts Bank and Boundary Bay, had a high level of protection. The majority of the Fraser Lowland had only a medium level of protection, which is defined as being legally designated or under a conservation policy, but not owned and managed for protection (McPhee and Ward, 1994). This is not impressive, given that the wetlands have been reduced to about one-quarter of their original extent, thus reducing their capacity to sustain fish and wildlife populations (McPhee and Ward, 1994; Schaefer, 2004). In 1995, Boundary Bay and Semiahmoo Bay were designated as a Provincial Wildlife Management Area to manage and conserve the extensive biological diversity of this important area. At the same time, under the Lower Mainland Nature Legacy Program, a complex of old fields and wetlands was purchased adjacent to the northwestern corner of Boundary Bay. As noted elsewhere in this paper (*see* 'Birds in seagrass systems'), that area is important because it is one of the concentration areas for migratory birds.

The Roberts Bank area is covered by the Fraser River Estuary Management Program's (Dorcey, 2004) highest habitat classification designation: 'conservation'. This designation carries with it strict development guidelines which do not allow development that would impair the area's biological productivity. The present coal port and British Columbia Ferry Corporation terminal were in place prior to the Fraser River Estuary Management Program, and as such must abide by the federal and provincial environmental-assessment processes and the federal *Fisheries Act* (Paisley, 2004). The latter includes a 'no net loss' policy to protect fish habitat (McPhee and Ward, 1994). The Roberts Bank area is also being considered for designation as a Provincial Wildlife Management Area and as a site in the Western Hemisphere Shorebird Reserve Network (R. Elner, pers. comm., 1998).

Butler and Campbell (1987) observed that once an area has been rezoned from old field or woodlot to suburban or industrial uses, it is highly unlikely that it will ever become available for restoration. They went on to emphasize that certain habitats cannot be recreated and that the highest priority must be given to the protection of all their locations. Furthermore, as described elsewhere in this paper (*see* 'Importance of adjacent farmland'), the existing adjacent farmland is inextricably linked to the continued biological productivity of the Fraser River delta. Large tracts of mixed farming, old fields, and wooded areas are necessary to maintain the current levels of avian fauna (Butler and McKelvey, 1992). Table 4 illustrates the range of habitats that are critical for birds. It is therefore imperative that conservation strategies recognize the need to integrate compatible farming and land-development practices with migratory bird conservation. The pressure to intensify agricultural production has initiated a trend away from soil-based agriculture (i.e. towards the use of greenhouses), and this represents an emerging conservation issue.

In summary, the seagrass beds of Roberts Bank and Boundary Bay support a diverse and abundant fauna. The habitat is resilient to many, but not all, environmental changes. To ensure that this habitat continues to play a significant ecological role in the larger Fraser River delta ecosystem, key studies coupled with adaptive conservation strategies are needed in order to identify key ecological interactions, both within the seagrass system and between it and adjacent systems.

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REFERENCES

Adams, M.A. and Williams, G.L.
2004: Tidal marshes of the Fraser River estuary: composition, structure, and a history of marsh creation efforts to 1997; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Bach, S.D., Thayer, G.W., and Lacroix, M.W.
1986: Export of detritus from eelgrass (*Zostera marina*) beds near Beaufort, North Carolina, USA; Marine Ecology Progress Series, v. 28, p. 265–278.

Baldwin, J.R. and Lovvorn, J.W.
1992: Populations, diet, food availability and food requirements of dabbling ducks in Boundary Bay; *in* Abundance, Distribution and Conservation of Birds in the Vicinity of Boundary Bay, British Columbia, (ed.) R. W. Butler; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 155, p. 42–69.
1994a: Habitats and tidal accessibility of the marine foods of dabbling ducks and brant in Boundary Bay, British Columbia; Marine Biology, v. 120, p. 627–638.
1994b: Expansion of seagrass habitat by the exotic *Zostera japonica*, and its use by dabbling ducks and brant in Boundary Bay, British Columbia; Marine Ecology Progress Series, v. 103, p.119–127.

Beckmann, L., Dunn, M.W., and Moore, K.
1997: Effects of climate change on coastal systems in British Columbia and Yukon; *in* Responding to Global Climate Change in British Columbia and Yukon: Volume 1 of the Canada Country Study: Climate Impacts and Adaptation, (ed.) E. Taylor and B. Taylor; Environment Canada and British Columbia Ministry of Environment, Lands and Parks, Vancouver, British Columbia, p. 8-1–8-26.

Boyd, W.S.
1995: Lesser snow geese (*Anser c. caerulescens*) and American three-square bulrush (*Scirpus americanus*) on the Fraser and Skagit river deltas; Ph.D. thesis, Simon Fraser University, Burnaby, British Columbia, 154 p.

Breault, A.M. and Butler, R.W.
1992: Abundance, distribution and habitat requirements of American widgeons, northern pintails and mallards in farmlands; *in* Abundance, Distribution and Conservation of Birds in the Vicinity of Boundary Bay, British Columbia, (ed.) R. W. Butler; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 155, p. 19–41.

Brenchley, G.A.
1982: Mechanisms of spatial competition in marine soft-bottom communities; Journal of Experimental Marine Biology and Ecology, v. 60, p. 17–33.

British Columbia/Washington Marine Science Panel
1994: The shared marine waters of British Columbia and Washington: a scientific assessment of current status and future trends in resource abundance and environmental quality in the Srait of Juan De Fuca, Strait of Georgia, and Puget Sound; Washington Dept. of Ecology, Olympia, Washington and British Columbia Ministry of the Environment, Victoria, British Columbia, 119 p.

Brooks, B., Bush, G., and Morton, N. (ed.)
1994: A study of the vegetation, marine fauna and birds of the Trent River delta and estuary — 1987; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 205, 156 p.

Bulthuis, D.A.
1991: Distribution of habitats and summer standing crop of seagrasses and macroalgae in Padilla Bay, Washington, 1989; Padilla Bay National Estuarine Research Reserve Technical Report 2; Washington State Department of Ecology, Olympia, Washington, 35 p.

Butler, R.W.
1991: A review of the biology and conservation of the Great Blue Heron (*Ardea herodias*) in British Columbia; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 154, 17 p.
1992: Populations, distribution and habitat requirements of Western Sandpipers, Dunlins, Black-bellied Plovers and Great Blue Herons; *in* Abundance, Distribution and Conservation of Birds in the Vicinity of Boundary Bay, British Columbia, (ed.) R.W. Butler; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 155, p. 70–85.
1995: The patient predator: foraging and population ecology of the Great Blue Heron *Ardea herodias* in British Columbia; Canadian Wildlife Service, Ottawa, Ontario, Occasional Paper No. 86, 44 p.

Butler, R.W. and Campbell, R.W.
1987: The birds of the Fraser River delta: populations, ecology and international significance; Canadian Wildlife Service, Ottawa, Ontario, Occasional Paper No. 65, 73 p.

Butler, R.W. and Cannings, R.J.
1989: Distribution of birds in the intertidal portion of the Fraser River delta, British Columbia; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 93, 60 p.

Butler, R.W. and McKelvey, R.
1992: Conclusions and recommendations for the conservation of the birds of Boundary Bay; *in* Abundance, Distribution and Conservation of Birds in the Vicinity of Boundary Bay, British Columbia; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 155, p. 124–132.

Canadian Hydrographic Service
1984: Strait of Georgia, Southern Portion; Chart 3463, scale 1:80 000.

Carl, G.C. and Guiguet, C.J.
1958: Alien animals in British Columbia; B.C. Provincial Museum Handbook No. 14, Victoria, British Columbia, 94 p. plus illustrations.

Carlton, J.T.
1985: Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water; Oceanography and Marine Biology: an Annual Review, v. 23, p. 313–371.

de Cock, A.W.A.M.
1981: Influence of light and dark on flowering in *Zostera marina* L. under laboratory conditions; Aquatic Botany, v. 10, p. 115–123.

Dennison, W.C.
1987: Effects of light on seagrass photosynthesis, growth and depth distribution; Aquatic Botany, v. 27, p.15–26.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., and Batiuk, R.A.
1993: Assessing water quality with submersed aquatic vegetation; BioScience, v. 43, p. 86–94.

Dorcey, A.H.J.
2004: Evolution of estuarine governance in a metropolitan region: collaborating for sustainability in the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Duggan, D.M. and Luternauer, J.L.
1985: Development-induced tidal flat erosion, Fraser River delta, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 85-1A, p. 317–326.

Dunn, M.W.
1988: Sea-level rise and implications to coastal British Columbia: an overview; *in* Impacts of Climate Variability on British Columbia; Environment Canada, Pacific and Yukon Region, British Columbia, p. 59–76.

Fenchel, T.M. and Jorgensen, B.B.
1977: Detritus food chains of aquatic ecosystems: the role of bacteria; *in* Advances in Microbial Ecology, (ed.) M. Alexander, v. 1, p. 1–58.

Fonseca, M.S. and Fisher, J.S.
1986: A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration; Marine Ecology Progress Series, v. 29, p. 15–22.

Fonseca, M.S., Fisher, J.S., Zieman, J.C., and Thayer, G.W.
1982: Influence of the seagrass, *Zostera marina* L., on current flow; Estuarine, Coastal and Shelf Science, v. 15, p. 351–364.

Harrison, P.G.
1979: Reproductive strategies in intertidal populations of two co-occurring seagrasses (*Zostera* spp.); Canadian Journal of Botany, v. 57, p. 2635–2638.
1982a: Spatial and temporal patterns in abundance of two intertidal seagrasses, *Zostera americana* den Hartog and *Zostera marina* L.; Aquatic Botany, v. 12, p. 305–320.
1982b: Comparative growth of *Zostera japonica* Aschers. & Graebn. and *Z. marina* L. under simulated intertidal and subtidal conditions; Aquatic Botany, v. 14, p. 373–379.
1987: Natural expansion and experimental manipulation of seagrass (*Zostera* spp.) abundance and the response of infaunal invertebrates; Estuarine, Coastal and Shelf Science, v. 24, p. 799–812.
1990: Variations in success of seagrass transplants over a five-years' period; Environmental Conservation, v. 17, p. 157–163.

Harrison, P.G. and Bigley, R.E.
1982: The recent introduction of the seagrass *Zostera japonica* Aschers. and Graebn. to the Pacific coast of North America; Canadian Journal of Fisheries and Aquatic Sciences, v. 39, p. 1642–1648.

Heck, K.L., Jr., Able, K.W., Roman, C.T., and Fahay, M.P.
1995: Composition, abundance, biomass, and production of macrofauna in a New England estuary: Comparisons among eelgrass meadows and other nursery habitats; Estuaries, v. 18, p. 379–389.

Intergovernmental Panel on Climate Change.
1995: Climate change 1995, the science of climate change; World Meteorological Organization, United Nations Environment Program, Geneva, Switzerland, Second Assessment Report, 572 p.

Jamieson, G.S., Grosholz, E.D., Armstrong, D.A., and Elner, R.W.
1998: Potential ecological implications from the introduction of the European green crab, *Carcinus maenas*, to British Columbia, Canada, and Washington, USA; Journal of Natural History, v. 32, p. 1587–1598.

Kellerhals, P. and Murray, J.W.
1969: Tidal flats at Boundary Bay, Fraser River delta, British Columbia; Bulletin of the Canadian Petroleum Geologists, v. 17, p. 67–91.

Kistritz, R.U., Hall, K.J., and Yesaki, I.
1983: Productivity, detritus flux, and nutrient cycling in a *Carex lyngbyei* tidal marsh; Estuaries, v. 6, p. 227–236.

Lovvorn, J.R. and Baldwin, J.R.
1996: Intertidal and farmland habitats of ducks in the Puget Sound Region: a landscape perspective; Biological Conservation, v. 77, p. 97–114.

McEwan, E.H. and Whitehead, P.M.
1984: Seasonal changes in body weight and composition of dunlin (*Calidris alpina*); Canadian Journal of Zoology, v. 62, p. 154–156.

McPhee, M. and Ward, P.
1994: Wetlands of the Fraser Lowland: ownership, management, and protection status, 1992; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 200, 71 p.

Nomme, K.M. and Harrison, P.G.
1991a: A multivariate comparison of the seagrasses *Zostera marina* and *Zostera japonica* in monospecific versus mixed populations; Canadian Journal of Botany, v. 69, p. 1984–1990.
1991b: Evidence for interaction between the seagrasses *Zostera marina* and *Zostera japonica* on the Pacific Coast of Canada; Canadian Journal of Botany, v. 69, p. 2004–2010.

Orth, R.J., Luckenbach, M., and Moore, K.A.
1994: Seed dispersal in a marine macrophyte: implications for colonization and restoration; Ecology, v. 73, p. 1927–1939.

Paisley, R.K.
2004: Laws, the legal system, and the conservation and protection of the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Phillips, R.C.
1978: Seagrasses and the coastal marine environment; Oceanus, v. 21, p. 30–40.

Posey, M.H.
1988: Community changes associated with the spread of an introduced seagrass, *Zostera japonica;* Ecology, v. 69, p. 974–983.

Schaefer, V.
2004: Ecological setting of the Fraser River delta and its urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Sewell, M.A.
1996: Detection of the impact of predation by migratory shorebirds: an experimental test in the Fraser River estuary, British Columbia (Canada); Marine Ecology Progress Series, v. 144, p. 23–40.

Skagen, S.K. and Oman, H.D.
1996: Dietary flexibility of shorebirds in the western hemisphere; Canadian Field Naturalist, v. 110, p. 419–444.

Swinbanks, D.D.
1979: Environmental factors controlling floral zonation and the distribution of burrowing and tube-dwelling organisms on Fraser River Delta tidal flats, British Columbia; Ph.D. thesis, Department of Geological Sciences, University of British Columbia, Vancouver, British Columbia, 273 p.
1982: Intertidal exposure zones: a way to subdivide the shore; Journal of Experimental Marine Biology and Ecology, v. 62, p. 69–86.

Tarbotton, M.R., Luternauer, J.L., and Mattila, M.
1993: Tidal flat response to development and mitigation work at Roberts Bank, Fraser River delta, British Columbia; *in* Proceedings of the 1993 Canadian Coastal Conference, May 4–7, 1993, Vancouver, British Columbia, p. 445–457.

Taylor, E.
2004: Impacts of future climate change on the Fraser River delta and its urban estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Thom, R., Miller, B., and Kennedy, M.
1995: Temporal patterns of grazers and vegetation in a temperate seagrass system; Aquatic Botany, v. 50, p. 201–205.

Thomson, R.E.
1981: Oceanography of the British Columbia Coast; Canadian Special Publication of Fisheries and Aquatic Sciences Number 56; Department of Fisheries and Oceans, Ottawa, Ontario, 291 p.

Thomson, R.E. and Crawford, W.R.
1997: Processes affecting sea level change along the coasts of British Columbia and Yukon; *in* Responding to Global Climate Change in British Columbia and Yukon; Canada Country Study: Climate Impacts and Adaptation; Environment Canada and British Columbia Ministry of Environment, Lands and Parks, v. 1, p. 4-1–4-19.

Thresher, R.E., Nichols, P.O., Gunn, J.S., Bruce, B.D., and Furlani, D.M.
1992: Seagrass detritus as the basis of a coastal planktonic food chain; Limnology and Oceanography, v. 37, p. 1754–1758.

Vermeer, K., Butler, R.W., and Morgan, K.H.
1994: Comparison of seasonal shorebird and waterbird densities within Fraser River delta intertidal regions; *in* The Abundance and Distribution of Estuarine Birds in the Strait of Georgia, British Columbia, (ed.) R.W. Butler and K. Vermeer; Canadian Wildlife Service, Ottawa, Ontario, Occasional Paper No. 83, p. 6–17.

Waldichuk, M., Lambert, P., and Smiley, B.
1994: Exotic introductions into B.C. marine waters; *in* Biodiversity in British Columbia: Our Changing Environment, (ed.) L.E. Harding and E. McCullum; Environment Canada, Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, p. 220–223.

Ward, P., Moore, K., and Kistritz, R.
1992: Wetlands of the Fraser Lowland, 1989: an inventory; Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series 146, 216 p.

Webb, D.G. and Parsons, T.R.
1991: Impact of predation-disturbance by large epifauna on sediment-dwelling harpacticoid copepods: field experiments in a subtidal seagrass bed; Marine Biology, v. 109, p. 485–491.

Wilson, W.H.
1991: The foraging ecology of migratory shorebirds in marine soft-sediment communities: the effects of episodic predation on prey populations; American Zoologist, v. 31, p. 840–848.
1994: Western Sandpiper (*Calidris mauri*); *in* The Birds of North America, No. 90, (ed.) A. Poole and F. Gill; The Academy of Natural Sciences, The American Ornithologists' Union, Washington, D.C., p. 19.

Wilson, W.H. and Atkinson, J.B.
1995: Black brant winter and spring-staging use at two Washington coastal areas in relation to eelgrass abundance; The Condor, v. 97, p. 91–98.

Zieman, J.C., Thayer, G.W., Robblee, M.B., and Zieman, R.T.
1979: Production and export of seagrasses from a tropical bay; *in* Ecological Processes in Coastal and Marine Systems, (ed.) R. J. Livingston; Plenum Press, New York, New York, p. 21–33.

Biogeochemistry of the intertidal area of the Fraser River estuary

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Abstract: The Fraser River estuary provides vital habitat for a wide range of wildlife as well as serving as an important agricultural, industrial, and urban area. The input of contaminants (i.e. inorganics, organics, nutrients) at any point along the river is of concern, as they can eventually be transported downriver and deposited in the estuarine sediments. Sturgeon Bank was the site of a direct sewage outfall from the Iona Island sewage treatment plant from 1963 to 1988. In 1988, sewage was redirected to discharge directly into the Strait of Georgia. This study integrates previous studies directed at assessing the recovery of the Fraser River estuary intertidal region, and presents baseline information on the state of this intertidal region. Four biogeochemical processes that occur within the Fraser River estuary intertidal region were assessed: 1) deposition and erodibility of sediments within the Sturgeon Bank intertidal region; 2) intertidal pore-water and sediment geochemistry; 3) nutrient cycling and benthic microalgal biomass; and 4) secondary productivity.

Résumé : En plus d'être un important secteur agricole, industriel et urbain, la région de l'estuaire du Fraser fournit un habitat vital à une grande diversité d'espèces fauniques. La présence de contaminants (composés inorganiques, composés organiques, nutriments) dans le fleuve est inquiétante, quel que soit leur point d'entrée, car ces substances peuvent finir par se déplacer vers l'aval et se déposer dans les sédiments estuariens. De 1963 à 1988, le banc Sturgeon a été le site de déversement d'un émissaire d'évacuation directe de l'usine de traitement des eaux usées de l'île Iona. En 1988, on a redirigé les eaux d'égout de manière à les déverser directement dans le détroit de Georgia. Cette étude intègre des études antérieures visant à évaluer le rétablissement de la zone intertidale de l'estuaire du Fraser, et présente des renseignements de base sur l'état de cette zone. Les auteurs ont évalué quatre aspects biogéochimiques de la zone intertidale de l'estuaire du Fraser : 1) le dépôt et l'érodabilité des sédiments à la hauteur du banc Sturgeon, 2) la géochimie des eaux de porosité et des sédiments intertidaux, 3) le cycle nutritif et la biomasse des microalgues benthiques, et 4) la productivité secondaire.

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INTRODUCTION

The Fraser River estuary and its intertidal region

Of the various ecosystems that together describe the Fraser River estuary, the most understudied but ecologically important is its intertidal region, which consists of mud flats. The intertidal region of the Fraser River estuary provides vital habitat for a diverse macrofauna and meiofauna (less than 500 μm in diameter), which, in turn, supports the highest densities of waterfowl, shorebirds, and raptors in Canada during winter months. Furthermore, the Fraser River intertidal area provides habitat for numerous fish species and serves as the point of entry and exit for five species of salmon. Despite its vast ecological importance, however, little is known about the fundamental processes that influence the biogeochemistry and ecology of the Fraser River estuary intertidal region.

Specific areas within the intertidal region have been subjected to point sources of pollution, such as the Iona Island sewage treatment plant, which have contaminated parts of the mud flat area with associated pollutants such as metals and organic material. Given the biological importance of this region and the ever-increasing anthropogenic pressures upon it, it is imperative to obtain a good understanding of the biogeochemical processes that occur within the intertidal region.

With the creation of the Fraser River Action Plan, a federal government initiative to study the state of the Fraser River and provide recommendations to ensure the maintenance of its health, several studies were undertaken to evaluate various aspects of the biogeochemistry of the intertidal region. This paper provides an overview of these studies. Following a brief description of the regional setting, the first section details physical processes influencing the deposition and erosion of sediments within the intertidal region, and how this in turn both spatially and temporally influences the geochemistry of the region. The second section addresses processes that determine sediment geochemistry in the intertidal region, and discusses the role of trace-metal geochemistry in influencing the movement of metal contaminants through the intertidal food web. The third and fourth sections discuss factors influencing nutrient dynamics, algal biomass, and primary and secondary productivity in the intertidal region, with a special emphasis on the recovery of primary and secondary productivity after the cessation of sewage discharge onto the intertidal area by the Iona Island sewage treatment plant. The Iona Island sewage treatment plant discharged directly into an intertidal channel that frequently spilled onto the intertidal region from 1963 to 1988. After 1988 the effluent was redirected into the Strait of Georgia via a deep-sea ocean outfall.

REGIONAL SETTING

The Fraser River, which measures more than 1400 km in length and drains an area of approximately 230 000 km^2, enters the sea in the Strait of Georgia in southern British Columbia. Approximately 25 km upstream from the mouth, the river bifurcates into the North Arm and the main arm. The North Arm, which carries about 16% of the total river discharge, bifurcates again at Richmond where about 30% of the flow (approximately 5% of the total Fraser River flow) exits via the Middle Arm, and the remaining 70% (9% of the total Fraser River flow) exits via the North Arm (Feeney, 1995).

The seasonality of the Fraser River discharge is strong, with peak discharge occurring in late June, coincident with snowmelt from its watershed in the interior of British Columbia. The low-discharge period extends from February to April. Maximum and minimum discharges for the Fraser River are 10 000 m^3/s and 800 m^3/s, respectively (Waldichuk, 1984). During the spring freshet the Fraser River may undergo a rapid increase in discharge, up to 850 m^3/s within one day. The decline is usually less abrupt. Tidal cycles are also major factors influencing the biogeochemical processes within the Fraser River estuary. Seasonal variation in tidal ranges, the differences between highest high water and lowest low water within one day for the Fraser River intertidal zone, is due to the change in the water level at low tides; the greatest ranges (about 5 m) occur in June and December, and the smallest (less than 3 m) in March and September. This change in tidal range determines the period and the range of inundation (or exposure) of the intertidal zone.

The Fraser River delta consists of the alluvial lowlands lying west of New Westminster and between the North Arm of the Fraser River and Boundary Bay (Kistritz, 1978). This area covers approximately 337 km^2 and either has been dyked or is above the influence of the tide (Kistritz, 1978). The Fraser River estuary consists primarily of the river estuary and the intertidal flats of Sturgeon and Roberts banks as well as Boundary Bay. Sturgeon and Roberts banks lie off the delta's western edge, whereas Boundary Bay lies to the south of the Fraser River delta. The total area of mud flats is approximately 115 km^2 (Kistritz, 1978). The intertidal zone on Sturgeon and Roberts banks consists of a 1 km wide fringe of foreshore marshes and a 6 km wide expanse of mud flat. The mud flat ends abruptly where the topographical gradient breaks into a steep slope. This break in slope occurs at about 10 m below the lowest normal tide level. The Fraser River distributary channels flow through these areas.

Of the three discrete intertidal regions — Sturgeon Bank, Roberts Bank, and Boundary Bay — the Sturgeon Bank mud flat has been severely altered by the construction of jetties, the disposal of spoil on the inner mud flats, and the disposal of primary treated sewage effluent. The Iona Island sewage treatment plant, located on the northeastern tip of Sturgeon Bank, contributed contaminants to the mud flat from the time of its construction in 1963 until 1988, when a submerged outfall consisting of two large pipes was constructed to transport primary treated effluent across the mud flat and directly into the Strait of Georgia at 150 m depth. Contaminants from the sewage treatment plant included organic contaminants, nutrients, and trace metals. An overview of the effects of these sewage contaminants is presented in Figure 1.

The studies on the biogeochemistry of the Fraser River intertidal region that are discussed below are primarily focused on Sturgeon Bank, specifically in order to 1) study

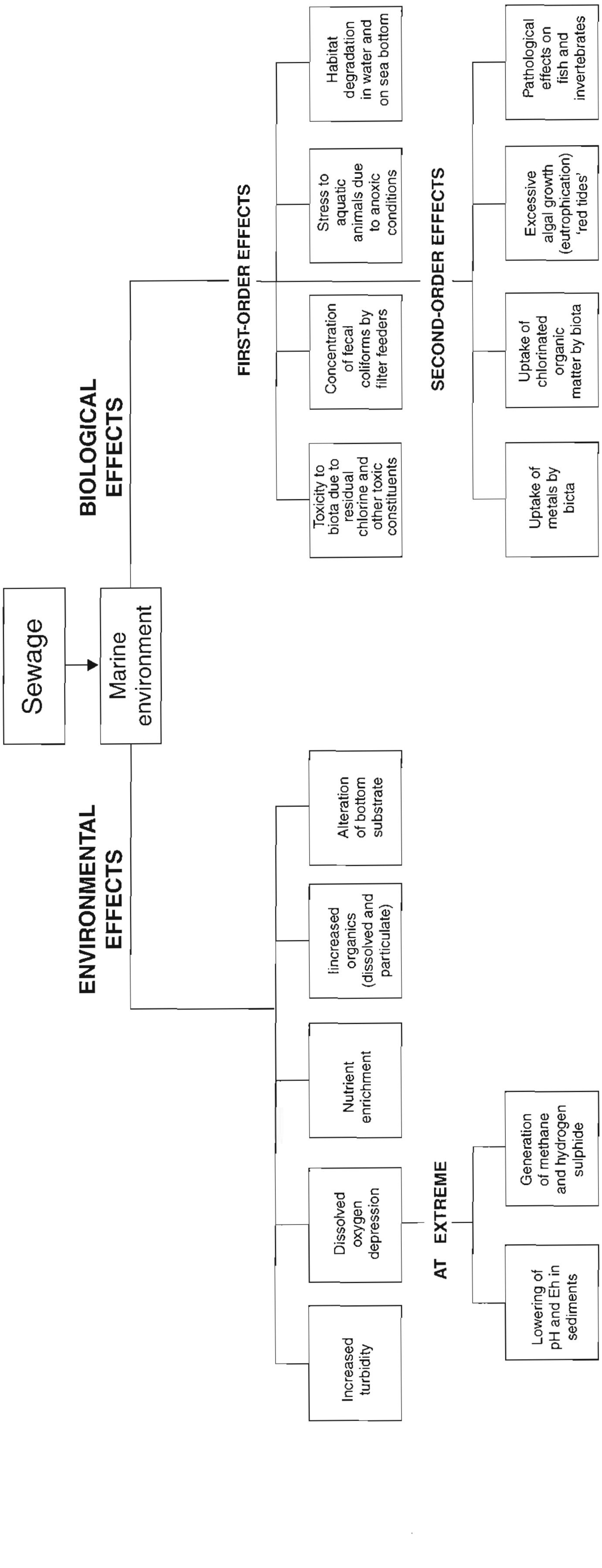

Figure 1. *Schematic diagram illustrating the effects of sewage in the marine environment* (after *Waldichuk, 1984*).

sediment-transport processes within the impacted region and 2) assess recovery of the mud flat with respect to primary and secondary productivity since the cessation of sewage discharge onto the mud flat. The study on intertidal sediment geochemistry includes Sturgeon Bank, Roberts Bank, and Boundary Bay. Sample sites for the studies on geochemistry and physical processes influencing sediment deposition are presented in Figure 2. Sample sites for the remaining three studies (sediment geochemistry; nutrients and chlorophyll; primary and secondary productivity) are presented in Figure 3.

PROCESSES INFLUENCING SEDIMENT DEPOSITION AND TRANSPORT

After the installation of the deep outfall pipe to redirect sewage from the Sturgeon Bank mud flat to the Strait of Georgia, the Department of Fisheries and Oceans began monitoring the recovery of the intertidal area; however, concerns remained with regard to the final depositional sites of the contaminated sediments. Specifically, it was recognized that although the fate of the contaminants could be followed (concentrations measured), processes that led to either their removal (erosion) or deposition (burial) remained poorly understood. To address this lack of information, a study was initiated to elucidate the major processes controlling sediment transport on Sturgeon Bank and to relate these processes to the fate of the contaminants deposited within the region.

Major findings of the sediment-transport study indicated that sediments on the inner bank (closest to shore) are not easily eroded because currents on the bank rarely reach velocities high enough to initiate sediment movement. Current velocity values ranging from 3.1 cm/s to 4.7 cm/s and 1.3 cm/s to 3.5 cm/s would be required to erode the cohesive and noncohesive sediments, respectively. High suspended-sediment concentrations on the inner bank imply a diffuse supply of sediments from the outer bank (furthest from shore) resulting in sediment accumulation on the inner bank. Accumulation of elements such as Fe, V, Ti, Cr, and Zr suggests that their distribution on Sturgeon Bank is controlled not only by sediment texture (grain size), but by the physical controls on sediment transport.

Tides and wave action

Studying the physical processes responsible for sediment movement involves identifying areas of erosion and deposition as well as pathways of migration of sediments and associated contaminants. This is complex at best; but within intertidal zones such as Sturgeon Bank, further complexity is added by physical processes such as tides, waves, and river runoff, all of which contribute to the ever-changing morphology of the sediments.

Tides in the Strait of Georgia are mixed semidiurnal, with mean tidal ranges of 2.7 m over the delta slope and 2.6 m over the tidal flats (Canadian Hydrographic Service, 1972; R.E. Thomson, unpub. report, 1977). The average range for spring tides over the seaward edge of the delta is 4.7 m; however, extreme tides can reach 5.4 m (Canadian Hydrographic Service, 1972). During periods of low river discharge and spring tides, mixing of fresh and salt waters is enhanced and the Fraser River estuary is classified as moderately stratified (Hodgins et al., 1977). At times of high river discharge, mixing is restricted and the estuary is classified as a salt-wedge system (Kostaschuk et al., 1989). Maximum significant wave

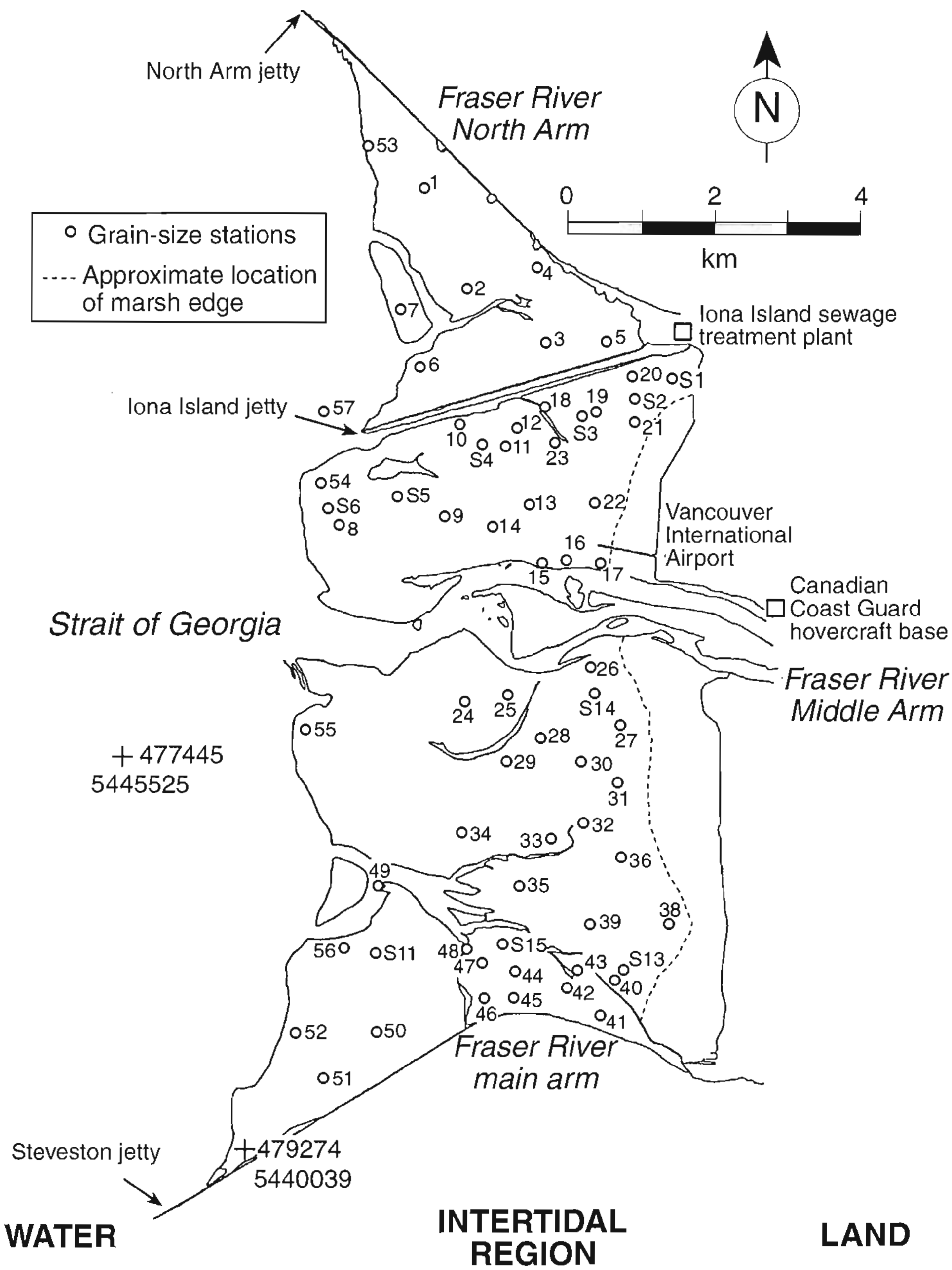

Figure 2. Sturgeon Bank study site showing station locations for sediment-transport and erosional studies.

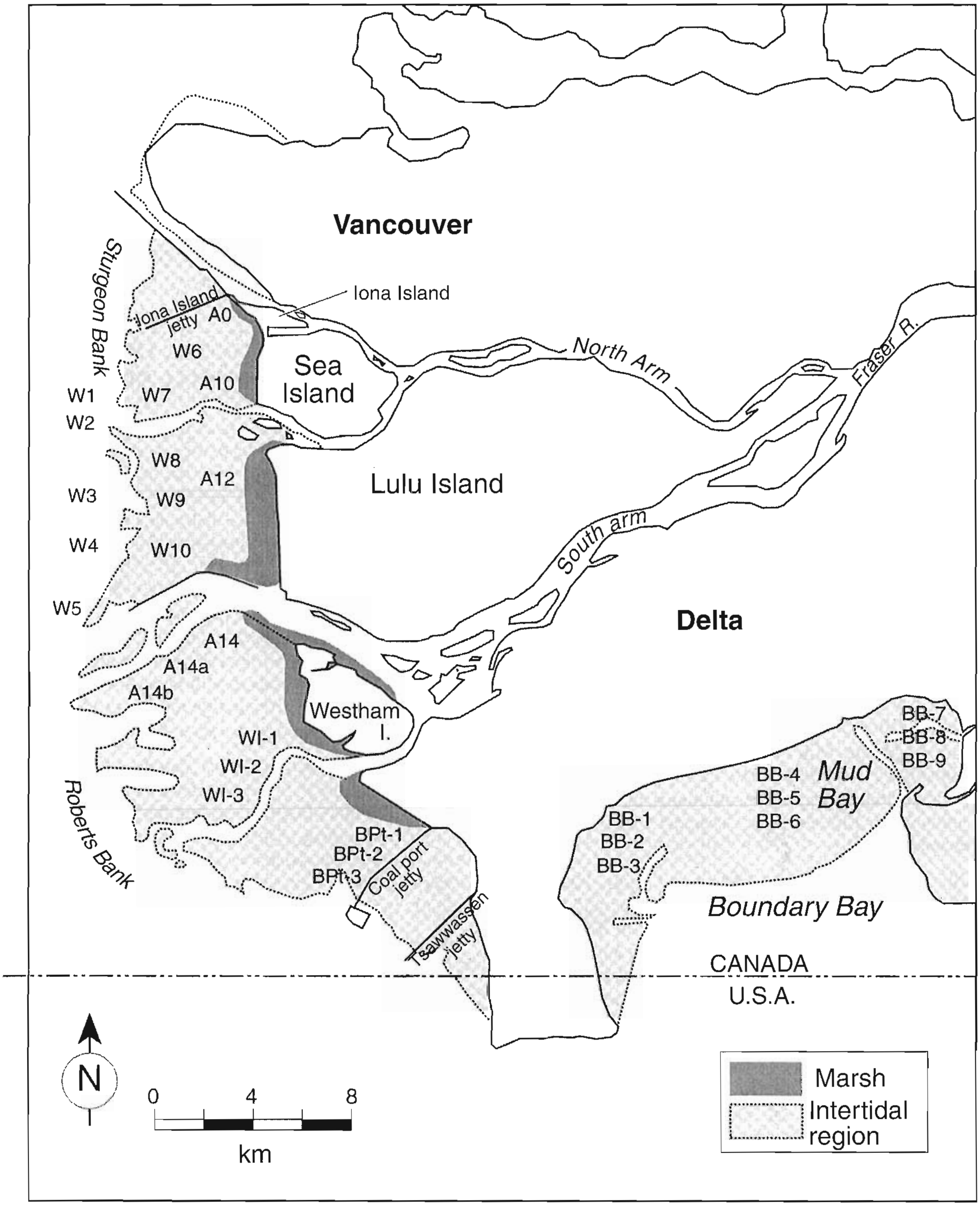

__Figure 3.__ Intertidal geochemistry sampling locations; all sites are sediment sampling sites except for W1, W2, W3, W4, and W5. W1, W2,...W10 are the stations for water samples and A0, A10, A12, and A14 are the sites for sediment cores.

heights in the Strait of Georgia are about 1.5 m, and average heights are about 0.6 m (Hoos and Packman, 1974). Based on these values, the waves having the highest probability of reaching the delta foreshore are 2.9 m in height (R.E. Thomson, unpub. report, 1977). Waves generated by winds from the northwest have the longest fetch (>100 km), and therefore presumably contribute the most to wave-related processes on the delta front. Wind waves breaking tangentially to the slope and breaking internal gravity waves may contribute to onshore drift of sediments and suspended material along the delta front, with flows reaching 50 cm/s (Thomson, 1975). Surface currents over the foreslope flow northward at 0.3 to 0.5 cm/s (Tabata et al., 1971), and a general northward flow of fresh turbid water from the main arm of the Fraser River across Sturgeon Bank has been observed (Tabata, 1972).

Sediment transport and erodibility

To assess processes influencing the transport of sediment within Sturgeon Bank, various geochemical and physical parameters were determined. These included 1) sediment erodibility: sediment response to induced current was determined at 10 sites on Sturgeon Bank (Fig. 2), using an instrument called Sea Carousel (Feeney, 1995). Erodibility was interpreted from the rate of change in suspended-sediment concentrations detected within the flume with time throughout each deployment; 2) current speed and direction: at 50 cm above bed sediments, current speed and direction were measured every 1.5 seconds for one minute per hour; and 3) suspended sediment, sediment grain size, and geochemistry: water samples were collected using depth-integrated sampling at high-water slack tide (minimizing flooding and ebb-tide current effects). Suspended sediment was removed via filtration (0.45 µm Millipore® filter). Bulk-sediment samples (upper 0–2 cm) were collected from Sturgeon Bank (Fig. 2) and analyzed for grain size and major and/or minor elements using X-ray fluorescence. Complete details can be found in Feeney (1995).

Noncohesive sediments are suspended more easily because of their lack of cohesive strength, especially the fine-grained sands on the outer southern Sturgeon Bank. A considerable amount of sediment is transported in a flooding direction from the outer southern Sturgeon Bank, implying advective movement of sediment in a shoreward direction. Sediment transported shoreward from the outer southern bank suggests erosion in this area, and no evidence of sediment replacement from the Fraser River has been observed. The grain-size sorting and geochemical data also support transport of sediment shoreward. The majority of the sediments on the bank fell into the fine sand category (44%), whereas only 9, 7, 13, 10, and 17% were fine silt, medium silt, coarse silt, very fine sand, and medium sand, respectively, with the coarser grained, better sorted, heavy-mineral–rich sediments occurring on the inner southern bank. The concentrations of metals such as Fe, V, Ti, Cr, and Zr in areas of heavy-mineral accumulation on the inner southern Sturgeon Bank and adjacent to the North Arm channel at station S14 (*see* Fig. 2) indicate movement of sediment shoreward.

In summary, the generally high erosion thresholds, low erosion rates, and low current velocities measured on the bank imply that a considerable amount of the sediment in suspension on the bank is derived from the Fraser River, with a smaller amount derived from erosion of the bank itself. Waves can strongly influence the concentration of suspended sediment, especially on the southern bank. The observed erosion of the outer southern bank could be a consequence of a diminishing supply of sediment discharged through the Fraser River system due to dredging, and/or to the construction of jetties altering natural sediment-transport patterns. This finding requires further study to determine whether erosion on the outer bank represents a potential hazard to the intertidal region of Sturgeon Bank.

SEDIMENT GEOCHEMISTRY OF THE FRASER RIVER INTERTIDAL REGION

The Fraser River intertidal region is subject to a number of anthropogenic stresses leading to the release of contaminants, such as trace metals, directly onto the mud flats. Given that the intertidal region serves as an efficient depositional zone for sediment and that estuarine sediments are efficient scavengers of metals of both anthropogenic and natural origins, this could lead to higher concentrations of metals in the sediments (Turekian, 1977; Langston, 1982). The fate of sediment-bound metals in estuarine ecosystems is especially important because consumption of detrital particles from bottom sediments is of major importance in estuarine food webs. The accumulation of metals in sediments above background levels can pose a threat to the indigenous biota and potentially lead to the transfer of these metals to higher trophic levels.

Findings of higher levels of metals at Roberts Bank (where riverine input is the greatest) relative to Sturgeon Bank and Boundary Bay suggest that the Fraser River serves as a significant source of metals to this region. The foreshore surrounding the Iona Island sewage treatment plant provides another example of how anthropogenic inputs have increased levels of metals beyond natural background levels.

As noted above, elevated levels of metals in sediments can lead to higher levels in the associated benthic organisms, potentially creating problems for organisms higher up in the food chain. To predict the impact that these contaminants are having on the receiving environment, it is important to develop an understanding of the factors that control the bioavailability of metals to aquatic organisms. The sediment geochemical matrix, and the partitioning of metals among key geochemical components that make up this matrix (*see* next paragraph), are important factors to consider when measuring the bioavailability and uptake of metals. In addition to the physical processes influencing sediment transport and hence composition, as outlined above in 'Processes influencing sediment deposition and transport', chemical and geological processes that occur in the overlying water column as well as within the sediment pore waters — specifically, sediment diagenesis — can contribute to the geochemistry at the sediment-water interface.

Aerobic sediments are composed of a number of geochemical components that can act as potential sinks for metals entering an estuarine system. These components include clay; silt; sand; organic material; oxides of iron, manganese, aluminum, and silica; carbonates; and sulphide complexes (Shea, 1988). In this case, the sediment geochemical matrix is defined as the combination of the amount of iron oxides recovered by a strong reducing agent, the amount of manganese oxides recovered by a mild reducing agent, and the amount of organic matter determined by loss-on-ignition. Metal partitioning is defined as the relative amounts of trace metals, such as Zn and Cd, recovered from the three major sediment components that together define the sediment geochemical matrix. Oxides of iron, oxides of manganese, and organic matter are considered to be the most important geochemical components controlling metal binding in the oxidized portion of the sediments (Jenne, 1968; Luoma and Bryan, 1981; Lion et al., 1982). The carbonate fraction of the sediments is not considered a key substrate for metal binding, because in estuarine sediments this fraction is mostly biogenic in origin and occurs as relatively large shell fragments that have low surface-area-to-volume ratios and are mostly coated with organic matter (Davies-Colley et al., 1984; Samant et al., 1990).

Thus far, intensive concurrent studies of trace-metal geochemistry in sediments and biota have not been carried out in the Fraser River estuary. The current state of knowledge with regard to trace-metal geochemistry within the Fraser River intertidal area consists of a study by Grieve and Fletcher (1976), who noted the following total abundances of metals in sediments (values in parentheses are maximum observed total levels of metal observed in this study): Zn = 56 µg/g (95 µg/g), Cu = 17 µg/g (45 µg/g), Ni = 43 µg/g (47 µg/g), and Pb = 7 µg/g (14 µg/g). These values are based on the average of 69 sites. It is generally agreed, however, that total abundances of metals in sediments are rarely a good indication of their potential bioavailability to biota (Luoma and Davis, 1983; Tessier et al., 1984). Partial extraction techniques, i.e. the partition of trace metals between operationally defined geochemical phases, such as oxides of manganese (easily reducible), oxides of iron (reducible), and organic matter, constitute one approach used to improve the correlation between metals bound to the various sedimentary phases and tissue levels in organisms (Luoma and Bryan, 1981; Tessier et al., 1984; Samant et al., 1990; Bendell-Young et al., 1994).

In order to assess, first, the important processes that establish the sediment geochemistry within specific sites in the Fraser River intertidal region, and second, the role of the resulting sediment geochemistry in influencing metal availability to benthic invertebrates, our objectives were to determine the following at three locations along the intertidal zone of the Fraser River estuary (i.e. Boundary Bay, Roberts Bank, and Sturgeon Bank (Fig. 3)): 1) the role of sediment diagenesis in contributing to the geochemical matrix of the sediment-water interface (as defined by oxides of manganese and iron and by organic matter); 2) the distribution of manganese, iron, organic matter, and trace metals at the three sites; 3) the implications of surface-sediment composition for metal partitioning; and 4) the implications of trace-metal geochemistry to metal availability in the bivalve *Macoma balthica*.

Sediment diagenetic controls on the composition of intertidal sediments

The supply of Fe and Mn to the sediment-water interface can come from two sources: the overlying water column, and subsurface sediments and pore waters. In estuarine water, concentrations of dissolved Mn and Fe in the overlying water column are extremely low, Mn^{+2} concentration being approximately 0.2 to 5.0 nmol/kg, and Fe^{+2} being basically undetectable in aerobic estuarine waters (Kennish, 1986). The concentration profiles obtained through the use of in situ dialysis membranes (i.e. pore-water peepers) can provide useful information concerning the diagenetic processes that take place in the sediments. Diagenesis refers to the chemical, physical, and mineralogical changes that occur in the sediments during and after their deposition. Some examples of diagenetic reactions are the formation of Fe and Mn oxides as a result of changes in redox potential. Understanding how diagenesis affects these two elements, as inferred from pore-water chemistry, is important in understanding the cycling of trace elements. Metals deposited in the sediments undergo partitioning among the various geochemical components present; the resulting metal-particulate associations have important implications with regard to bioavailability to organisms.

Interstitial water samples were obtained using methods of Hesslein (1976) and Carignan et al. (1985). In general, pore-water profiles of Fe and Mn at all of the sites were of two generalized types (Fig. 4): 1) profiles typical of redox-sensitive species, with subsurface maxima, and 2) linear profiles with uniformly low concentrations. Profiles taken from Sturgeon and Roberts banks were all classic profiles of redox-sensitive species; reduced Fe and Mn diffuse to the surface and precipitate at the oxic interface. Both Fe and Mn are redox-sensitive elements which should respond similarly to a changed redox potential in the sediments (Davison, 1982). The subsurface maxima of Fe and Mn that appear in most of these profiles provide evidence that the sediments are a source of these elements to the overlying sediments. In contrast, profiles from Boundary Bay exhibit uniformly low concentrations, which result from reduced Fe and Mn diffusing to the surface and possibly being leached into the overlying water column.

Metal partitioning among sediment components

To determine the geochemical matrix of the intertidal sediments, as defined by oxides of Mn and Fe and by organic matter, a simultaneous extraction scheme was applied (Bendell-Young et al., 1992). In addition, the residual fractions of metals were also measured. 'Residual fraction' refers to the fraction of a metal that is bound tightly within the lattice framework of the sediments and is considered unavailable for uptake by an organism. Concentrations of the various metals were measured in each of the extracts to determine the

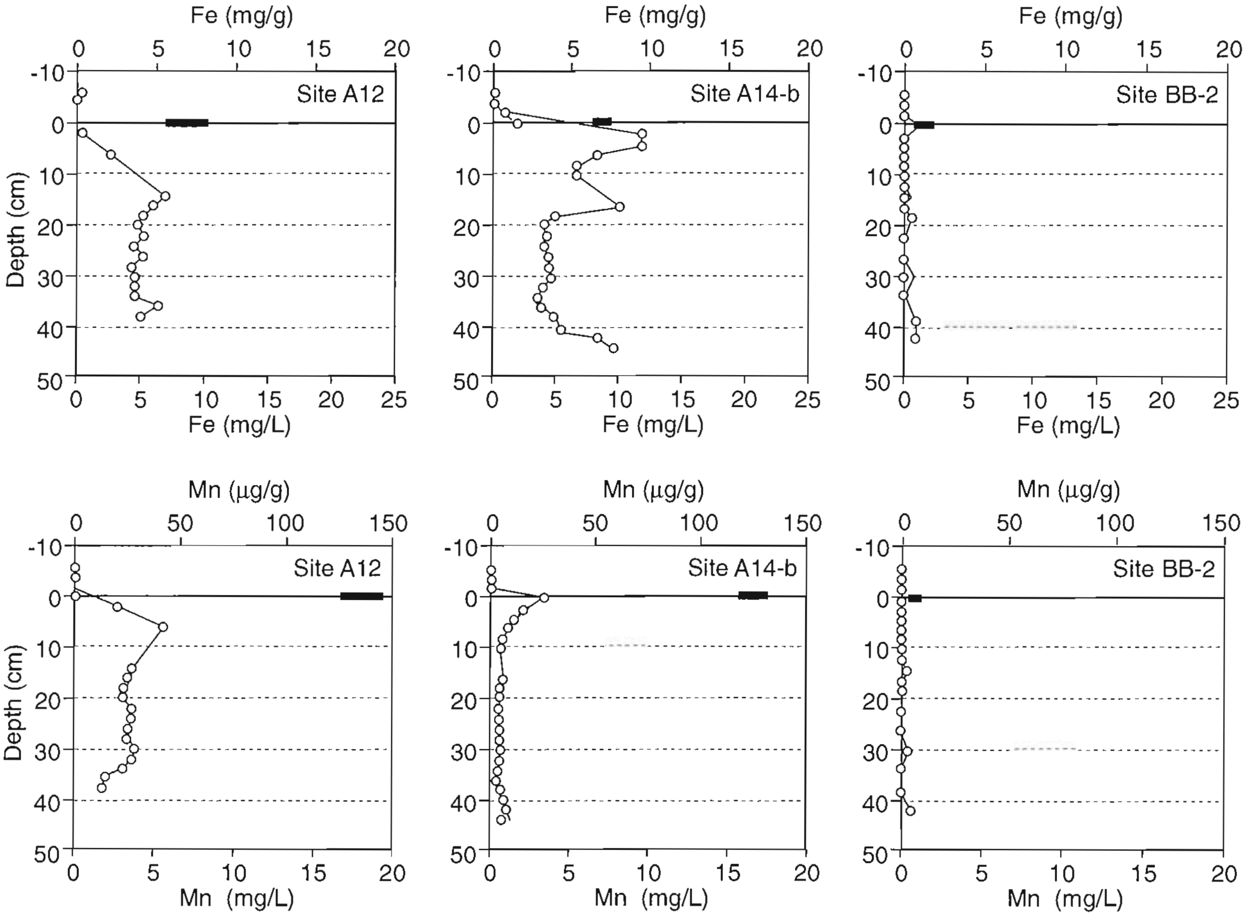

Figure 4. Examples of classic and linear pore-water profiles for total dissolved Fe and Mn (mg/L). Solid bar at depth = 0 (i.e. sediment-water interface) is the concentration of reducible Fe (mg/g) and easily reducible Mn (µg/g) recovered from the sediments. Profiles consist of means of replicate measures at each sampling location.

partitioning of each metal among the different geochemical fractions. Iron was primarily (17.0–37.0%) recovered in the reducible fraction of the sediments, with the easily reducible fraction accounting for 0.3 to 3.4% of Fe, and the organic fraction accounting for 0.0 to 1.7% (Fig. 5). Sediments from Boundary Bay were on average two to four times lower in reducible-fraction Fe concentrations than either Sturgeon or Roberts banks sediments. The highest concentration of reducible-fraction Fe was observed at Brunswick Point (15 291 µg/g), and the lowest at Boundary Bay (1636 µg/g). Manganese was primarily (14.0–41.5%) recovered in the reducible fraction of the sediments, with the easily reducible fraction accounting for only slightly less (10.0–34.0% of Mn) (Fig. 5). Very little Mn partitioned into the organic fraction, which is consistent with this metal's weak affinity for organic material. Concentrations of easily reducible Mn were on average an order of magnitude lower than concentrations of reducible-fraction Fe. In a trend similar to that observed for reducible-fraction Fe, the concentration of easily reducible Mn in the sediments was two to four times lower at Boundary Bay than at the other two sites. The maximum and minimum concentrations of easily reducible Mn were 144 µg/g and 1.4 µg/g, found at Westham Island and Boundary Bay, respectively.

The percentages of organic matter did not show as wide a range among all sites as the percentages of easily reducible Mn and reducible-fraction Fe. Sites varied in their organic matter content from 1.5 to 7.0% (Fig. 5). The highest concentration of organic matter was found at Brunswick Point, which is located just west of the coal port jetty. Organic matter tended to be higher in concentration at sites closer to the shore than at other sites located within the same transect, but farther from shore (Fig. 5). The only exceptions to this were the sites located at Sturgeon Bank, which tended to show fairly consistent levels of organic matter regardless of the distance from shore. Elevated levels of organic matter at sites A0 and W6 were most likely a result of primary treated effluent being discharged directly onto the mud flats in the vicinity of these sites in previous years.

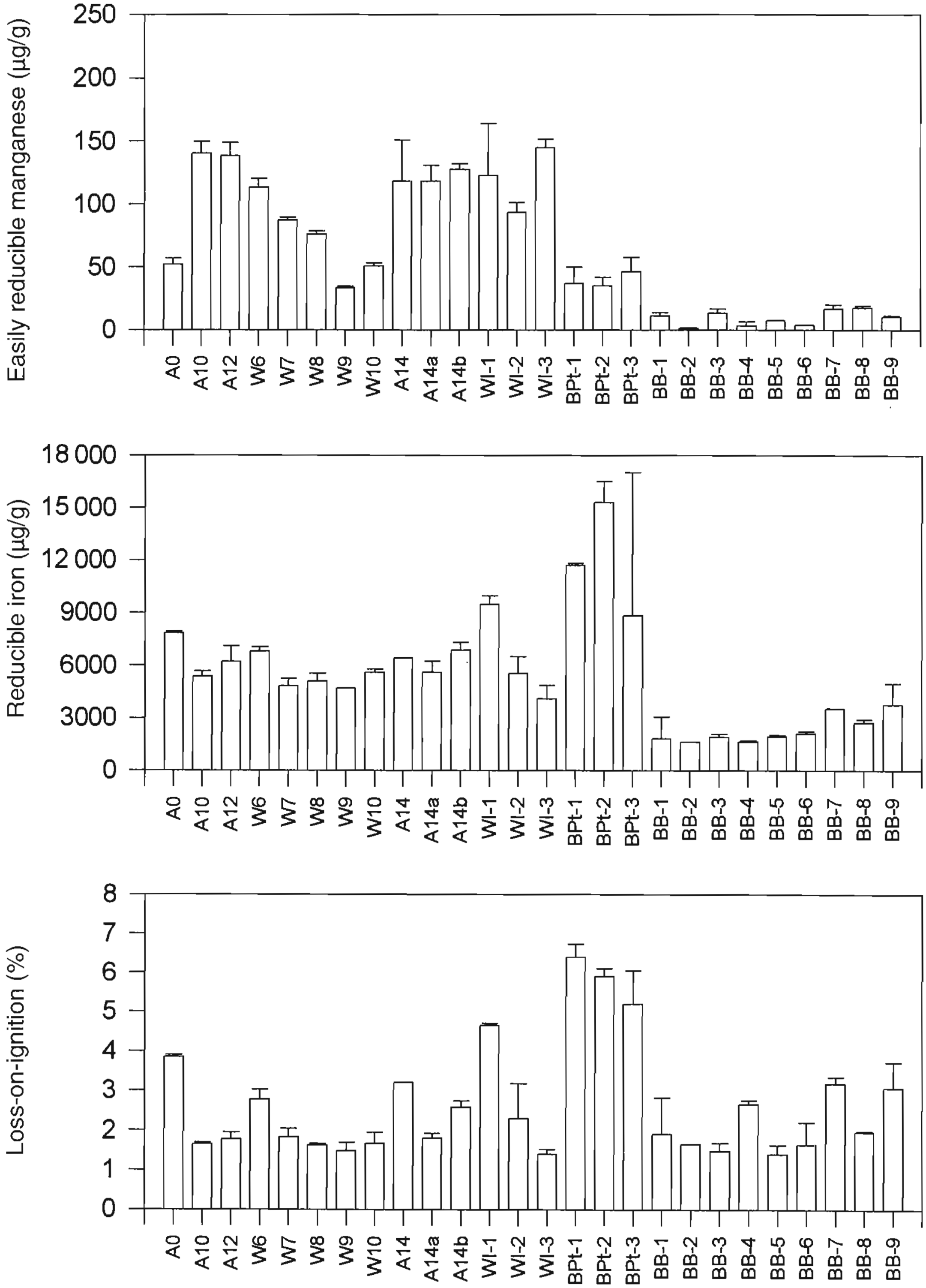

Figure 5. Concentrations of the three sediment components: easily reducible Mn, reducible Fe, and per cent loss-on-ignition (organic matter) in the surficial sediments from all stations at each of the three sites. Values are means of three replicates, ±1 standard deviation.

Overall sediment geochemistry, as defined by concentrations of easily reducible Mn, reducible-fraction Fe, and organic matter as per cent loss-on-ignition, exhibited extreme variation both within and among sites (Fig. 5). This variability, however, is not an uncommon phenomenon in estuaries (Luoma and Bryan, 1981; Langston, 1985). It is not unusual to find metal concentrations, as well as concentrations of the various geochemical components, varying by one to three orders of magnitude.

Concentrations of the metals Zn, Cu, Ni, Cd, and Pb were measured in each of the operationally defined sediment fractions: easily reducible Mn, reducible fraction Fe, organic, and residual (Fig. 6). Most sediment-quality criteria guidelines are based on residual or total levels of metals and consequently are not indicative of the potential bioavailable fraction. A summary of the key sediment components with which each of the trace metals was associated is presented in Table 1.

Implications of surface-sediment composition for metal partitioning

The ranges in the concentrations of reducible-fraction Fe and easily reducible Mn observed at the sediment-water interface suggest that pore waters contribute significantly to the geochemistry of the sediment-water interface. In the oxic surficial sediments, most of the reducible Fe occurs as ferric (Fe^{+3}) oxyhydroxides (Tessier et al., 1994). The reduction of Fe^{+3} oxyhydroxides by organic matter or through seasonal fluctuations of the redox transition level is responsible for the release of most Fe (as dissolved ferrous iron, Fe^{+2}) into the pore waters. This creates a pool of dissolved Fe^{+2}, which can diffuse either upward or downward because of the presence of iron sinks that are capable of lowering the dissolved-iron concentrations. At the surface, Fe^{+2} can be oxidized by downward-diffusing oxygen to form Fe^{+3} oxyhydroxides, or it can escape into the overlying surface water where Fe^{+2} concentrations

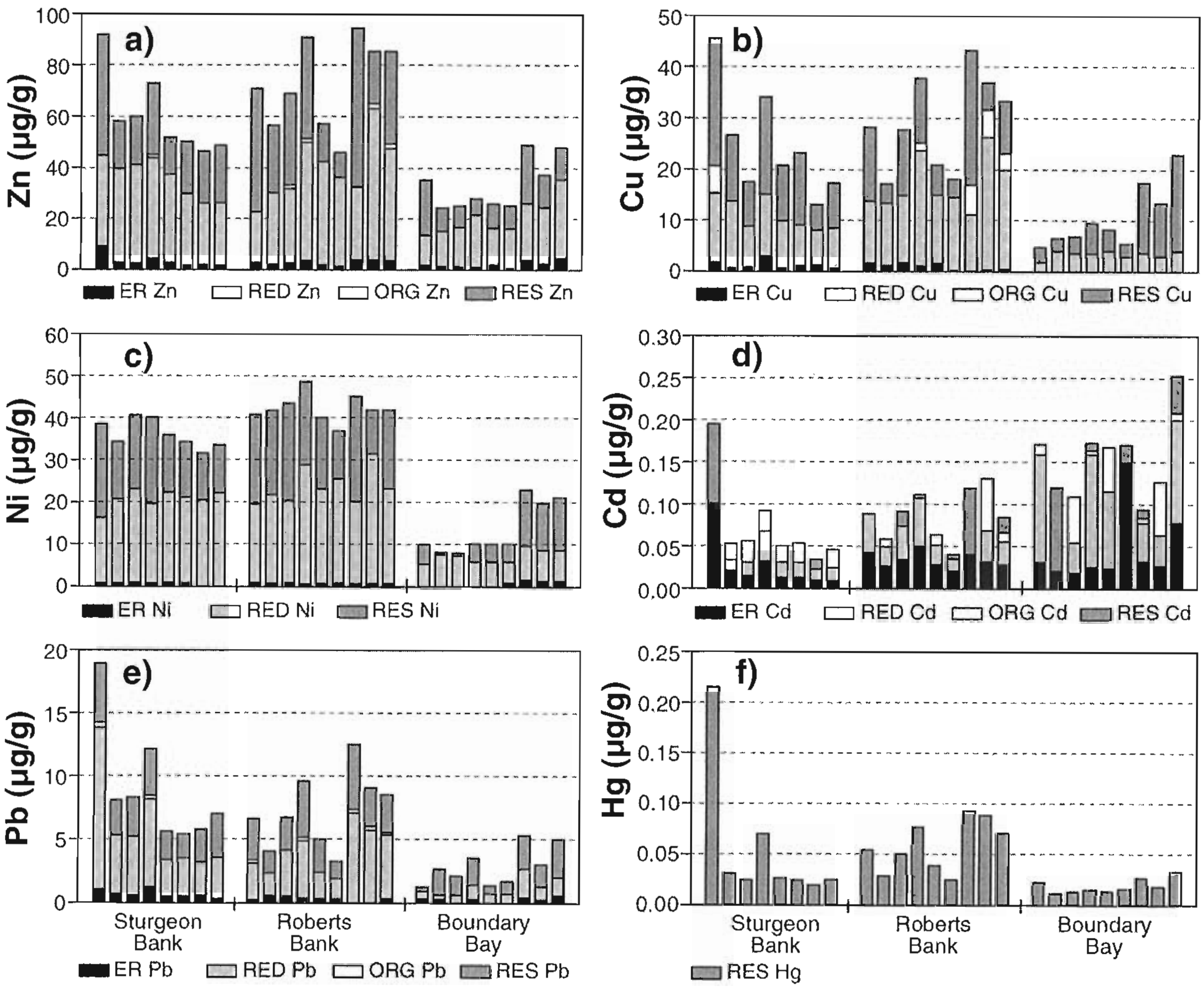

__Figure 6.__ Metal partitioning of Zn, Cu, Ni, Cd, and Pb in the surficial sediments from all sampling sites in each of three areas. Values are means of three measurements. ER = easily reducible; RED = reducible; ORG = organic; RES = residual.

Table 1. Summary of trace-metal partitioning among the various sediment components. Mercury values have not been included, as they were only measured in the residual phase. Mercury concentrations were greatest at site A0, at 0.22 μg/g, which exceeded the 'lowest observable effects level' of 0.15 μg/g.

Metal	Easily reducible fraction	Reducible fraction	Organic fraction	Maximum metal level (μg/g) and location	Region with highest metal level (in μg/g)	LOEL[1] (μg/g)
Zn	2–9%	28–74%	1.3%	95 Brunswick Point	Roberts Bank	120
Cu	<8%	37–70%	Negligible	45 A0[2]	Roberts Bank	70
Ni	5%	34–96%	Negligible	47 Westham Island	Roberts Bank	30
Cd	33%	45%	18%	0.25 Boundary Bay	Boundary Bay	5.0
Pb	Negligible	46%	8%	18.0 A0 and W6[2]	Roberts Bank	35

[1]LOEL = Lowest Observable Effects Level (Nagpal, 1995).
[2]A0 and W6 are the sites closest to the Iona Island sewage outfall.

are much lower (Tessier et al., 1994). The downward diffusion of dissolved Fe^{+2} depends on the presence at depth of a sulphide pool that will combine with the Fe^{+2} to form the insoluble precipitate FeS.

In the oxic portion of the sediments, Mn primarily occurs as Mn oxyhydroxide. The oxidation of Mn in estuarine systems occurs primarily through the activity of oxidizing bacteria (Santschi et al., 1990). As a result of the physical and biological mixing of the surficial sediments, Mn oxyhydroxides can be deposited below the sediment-water interface, where reducing conditions exist. Under these conditions, the reduction of Mn by organic matter, H_2S, and microbes can occur (Santschi et al., 1990). Reduced Mn then diffuses towards the sediment surface where it is oxidized, or it can form insoluble precipitates such as MnS and $MnCO_3$ and remain at depth in the sediments.

Other processes that can cause subsurface peaks (positive or negative) in Fe and Mn concentrations include bioturbation (the random agitation of sediment fluids and solids by macroinvertebrates usually present in the upper 30 cm of marine sediments), biological irrigation (nonrandom transport of solutes resulting from the ventilation of burrows or tube-like structures by benthic organisms), currents, and tides (Tessier et al., 1994). Considering that all of these sites are near-shore environments where the biological and physical activity is high, these processes could contribute significantly to the distribution and movement of Fe and Mn (Emerson et al., 1984).

The overall influence of each geochemical component on trace-metal partitioning is related to its abundance relative to the other components present. For example, Luoma and Bryan (1981) observed a strong correlation of Pb with the Fe-oxide fraction when both the Mn-oxide and organic fractions were low in concentration; however, when Fe- and Mn-oxide levels were both low, most of the Pb was associated with Mn oxides, suggesting strong competition between these two components for sorption. Davies-Colley et al. (1984) found that Fe oxides should dominate the binding capacity for Cd in oxidized estuarine sediments; however, at very high concentrations of Mn oxides with concomitant low Fe content, Mn oxides became the dominant phase to bind with Cd.

The reducible fraction in the surficial sediments accounted for the majority of the binding for Zn, Cu, Ni, and Pb (Table 1). In most cases, relatively higher levels of metals were recorded at sites A0 and W6 (Fig. 6). These levels can be explained by the proximity of the sites to the Iona Island sewage treatment plant, which in previous years discharged primary treated sewage into an intertidal channel whose contents frequently spilled onto the foreshore. It is interesting to note, however, that if sites A0 and W6 are excluded, the highest overall level of each metal is found at Roberts Bank. This implies that the Fraser River is an important source of trace metals to the estuary, as Roberts Bank receives input from two major arms of the Fraser River, the south arm and the main arm.

Cadmium partitioning and distribution was fairly atypical in relation to the behaviour of the other metals. Even though the reducible fraction accounted for the majority of Cd binding (44.6%), the easily reducible fraction accounted for a significant percentage (32.5%), which was not seen with any other metal. It is worth noting that the highest overall levels of Cd were found at Boundary Bay, suggesting a potential source of Cd contamination in this area (Fig. 6). This was unusual, because this was the site with the overall lowest concentrations of all the other metals.

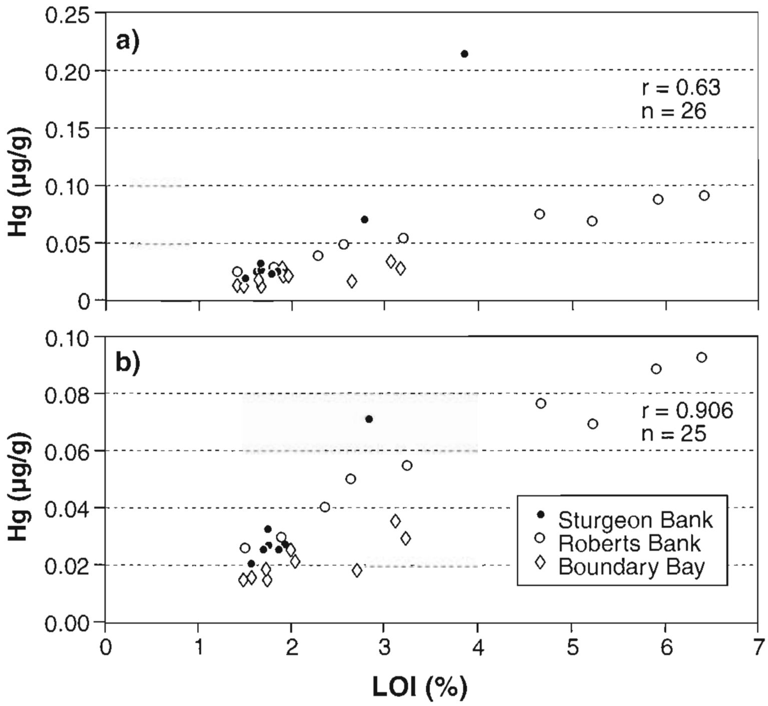

Figure 7.

***a)** Total concentration of Hg in the surficial sediments from all sampling sites in each of three areas. **b)** Correlation of Hg and per cent loss-on-ignition (organic matter), with site A0 removed (n = 25, r = 0.906).*

Results for mercury (Hg) are consistent with several other studies that have shown that Hg has a high affinity for organic matter in the oxic surficial sediments (Lingberg and Harriss, 1974; Langston, 1982) (Fig. 7). The correlation between Hg and per cent LOI improved from r = 0.63 to r = 0.96 when site A0 was removed, because this site had an external source of Hg (i.e. the Iona Island sewage treatment plant) that contributed to the high levels observed. Furthermore, removing site A0 from the correlation shows that the highest overall levels of Hg are found at Roberts Bank. Levels of Hg at Sturgeon Bank (0.2 µg/g) have decreased significantly (by a factor of about four) since 1981, when levels right near the Iona Island sewage treatment plant were up to 0.89 µg/g Hg (McGreer, 1981). Most of the Hg measured in this study is assumed to be in the inorganic phase (i.e. <1% as methylmercury), as methylation rates are much lower in marine and estuarine systems than in freshwater systems (Compeau and Bartha, 1984).

Implications for metal bioavailability

The distribution of a metal among the geochemical components present will affect the passage of this metal from sediments to organisms. Some studies suggest that the metals associated with the Mn oxides in the sediments are those most available to deposit-feeding organisms. Luoma et al. (1995) found that the concentration of Ag associated with the Fe and Mn oxides was a reasonably good predictor of Ag bioavailability to *Macoma balthica* in estuarine sediments. Bendell-Young et al. (1994) also showed that chironomid Zn and Cu concentrations correlated with Zn and Cu concentrations associated with the Mn-oxide portion and were modified by amounts of organic matter. Langston (1982) also found that as the percentage of organic matter in the sediments increased, the bioavailability and hence the uptake of Hg decreased.

Macoma balthica, a deposit-feeding bivalve which is found throughout the Fraser River estuary, has commonly been used to monitor the levels of bioavailable metals in the sediments (Bryan et al., 1980; Langston, 1982). Because these bivalves are in intimate contact with the sediments and feed mainly on the surficial sediments (they will occasionally filter feed; Harvey and Luoma (1985)), their tissue concentrations tend to reflect levels of bioavailable metals in the sediments. By correlating levels of metals found in the different sediment fractions to tissue levels in *M. balthica*, one can get a good indication of the primary source of metal contamination as well as of any interactions between geochemical components that inhibit or promote the uptake of metals.

In summary, the Fraser River estuary provides a vital habitat for a wide range of wildlife, as well as serving as an important agricultural, industrial, and urban area. The input of metals at any point along the length of the river creates reason for concern, as they can eventually be transported downriver and deposited in the estuarine sediments. To be able to assess the impact that these contaminants can have on biota, it is important to understand the processes that result in the metals becoming bioavailable to benthic organisms.

Pore-water profiles and partial extraction techniques are useful tools to employ when trying to understand the influence of sediment geochemistry on metal availability. Pore-water profiles were helpful in revealing any contribution of the subsurface sediments to the geochemical matrix at the sediment-water interface. For example, sites with linear profiles and low abundances of dissolved Fe and Mn tended to have low concentrations of Fe and Mn oxides at the sediment-water interface. Partial extraction techniques were useful in defining the geochemistry at the sediment-water interface. In all cases, more than 50% of each metal was recovered in the 'biologically relevant' or labile fractions (excluding Hg). By separating metals into 'biologically relevant' fractions, a much better indication of the proportions of metals that are actually available to an organism is obtained. In the long term, an understanding of the biogeochemical cycling, partitioning, and uptake of metals in the particulate phase can be useful in predicting which sites pose a greater risk of metal bioaccumulation to organisms.

NUTRIENT CYCLING AND DYNAMICS

Nutrient cycling and dynamics in the water column and sediments are an essential component of the ecosystem of Sturgeon and Roberts banks. In spite of frequent environmental monitoring in the region, nutrient cycling and dynamics have not been studied before. Therefore, the nutrient concentrations presented in this section are the first data set for the region.

Factors influencing nutrients in the water column

Many physical and biological factors and processes affect the concentration of nutrients in the Fraser River estuary. They include river discharge, tidal cycles, winds, water-sediment interface exchange, foreshore marshes, sewage effluent, activity of benthic animals, and utilization of nutrients by phytoplankton and benthic algae.

The interaction between the river flow and tidal cycles has been mostly studied in the main arm of the Fraser River. During a flood tide, the river flow is dammed at the river mouth and a salt wedge intrudes into the river channel at the bottom. During an ebb tide, the salt wedge retreats and the river flow is released into the Strait of Georgia (Fig. 8). The outflow of fresh water forms the riverine plume which moves clockwise due to the Coriolis effect and hence can flow onto Sturgeon Bank with the tidal current; however, the movement of the riverine plume can vary depending on winds (LeBlond, 1983). Extensive study has been conducted on the physical processes of the salt wedge (Ages and Woollard, 1988; Geyer and Farmer, 1989; Kostaschuk and Atwood, 1989) and on the dynamics of nutrients associated with these physical processes (Yin et al., 1995a, b, c).

Nutrients in the Fraser River estuary are low in abundance relative to other estuaries such as Chesapeake Bay, the Hudson River estuary, and San Francisco Bay in the United States. Nitrate is maximal in winter (not exceeding 20 µmol/L) and minimal in summer (2–5 µmol/L) (R.W. Drinnan and M.J.R. Clark, unpub. report, 1980). Concentrations of nutrients in the river are even lower than in the deep seawater in the strait, except for silicate. Nitrate levels in the strait are high in winter (26 µmol/L) (Stephens et al., 1969) and can be undetectable in late spring and summer in the surface layer (Clifford et al., 1989, 1990, 1991a, b, 1992).

The intertidal zone is exposed to air during ebb tides and is inundated with water during flood tides. There is an exchange between sediments and water in the intertidal zone during the tidal cycle, as illustrated in Figure 9. Organic particles in water could be carried to the intertidal zone and deposited on

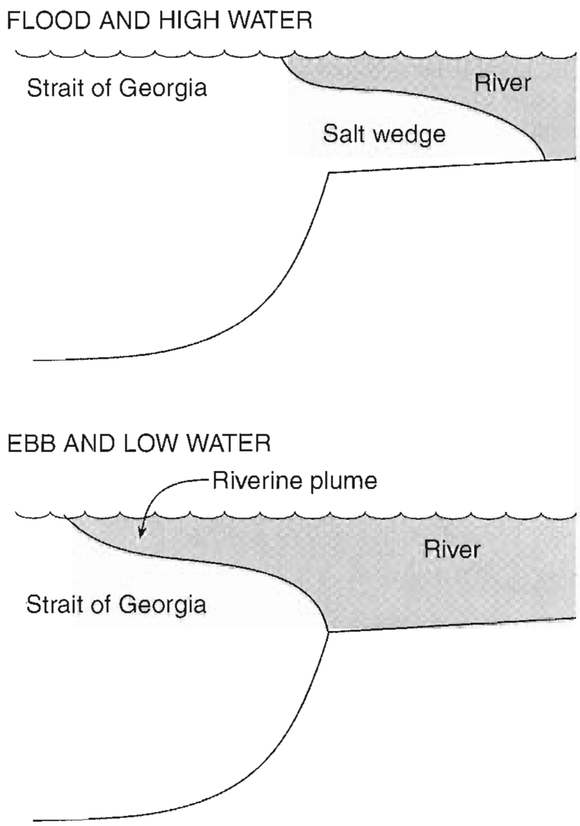

Figure 8. Damming effect of a tidal cycle on the Fraser River outflow. The river outflow is dammed at the river mouth and a salt wedge invades the river during a flood tide and higher high water, and the riverine plume is formed as the salt wedge retreats during an ebb tide.

the sediments (the nearby salt marsh also could be a possible source of organic particles to the area). Because of active mineralization and the activity of benthic animals, inorganic nutrients are generated in the sediments. The exchange of nutrients between sediments and the overlying water depends on the concentration gradient of each nutrient. Usually the nutrient concentration is much higher in sediments than in water, and therefore nutrients are released into the overlying water. When the water retreats into the strait during an ebb tide, nutrients in the water may enhance phytoplankton productivity. In an estuary, this process of nutrient release from the sediments is referred to as the 'nutrient pump'. The foreshore vegetation, especially the salt marsh in this area, forms detritus which decomposes into organic and inorganic nutrients in the fall. The dynamics of nutrients associated with these natural factors have not been studied for this intertidal zone. In addition to natural nitrogen sources, primary treated sewage effluent from the Iona Island sewage treatment plant, which contained high amounts of organic matter, was frequently spilled onto the mud flat before its diversion in 1989 by two large pipes which now carry the effluent to a depth of

150 m in the strait. The average daily nitrogen load in the effluent for 1980 to 1982 was 5169 kg/d for ammonia, 207 kg/d for nitrate, and 8881 kg/d for Kjeldahl nitrogen (total organic nitrogen + nitrate) (Swain and Holms, 1985). No study has ever assessed the effect of nitrogen in the effluent on primary productivity of the water column in the Strait of Georgia and on vegetation in the foreshore of Sturgeon Bank.

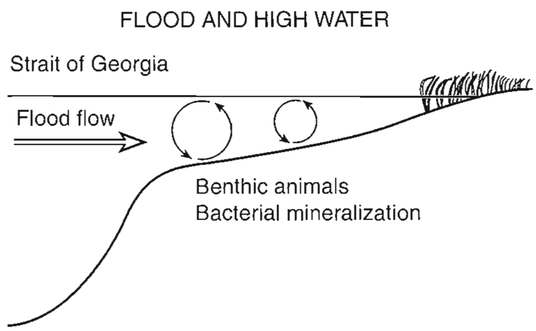

Figure 9. Effect of a tidal cycle on the mud flat of Sturgeon Bank. The water is vertically mixed as the flood tide shoals on the mud flat, and nutrients are exchanged at the water-sediment interface.

In 1994, a Fraser River Action Plan project was launched to study the dynamics of nutrients on the mud flat in order to assess the recovery of Sturgeon Bank from the contamination of the Iona Island sewage treatment plant effluent. The ten stations for water samples were designed to enclose the entire intertidal zone (Fig. 3). The incoming water was sampled during a flood tide and the outgoing water was sampled during the next ebb tide. The time interval between the two samplings was usually 13 h. Any change in nutrient concentration that was detected between the flood and ebb tides indicated the exchange between water and sediments in the intertidal zone. Preliminary results show that ammonium concentrations in the surface water were higher during ebb tides than during flood tides from June 1994 to November 1995, in spite of seasonal variation (Fig. 10). This clearly indicates that ammonium was released from the sediments into the water column throughout the year. There are several processes that might be responsible for the increased ammonium, including the feeding activity of benthic animals, remineralization of organic matter by bacteria, and leaching and decomposition of salt-marsh grasses and seagrasses. Bacterial decomposition and the activity of benthic animals could account for a portion of the increase in ammonium. This is supported by the decrease in chlorophyll at the same time (Fig. 11). Chlorophyll concentrations were lower during the ebb tide than during the flood tide, indicating a loss of chlorophyll in the water column to the animals in the

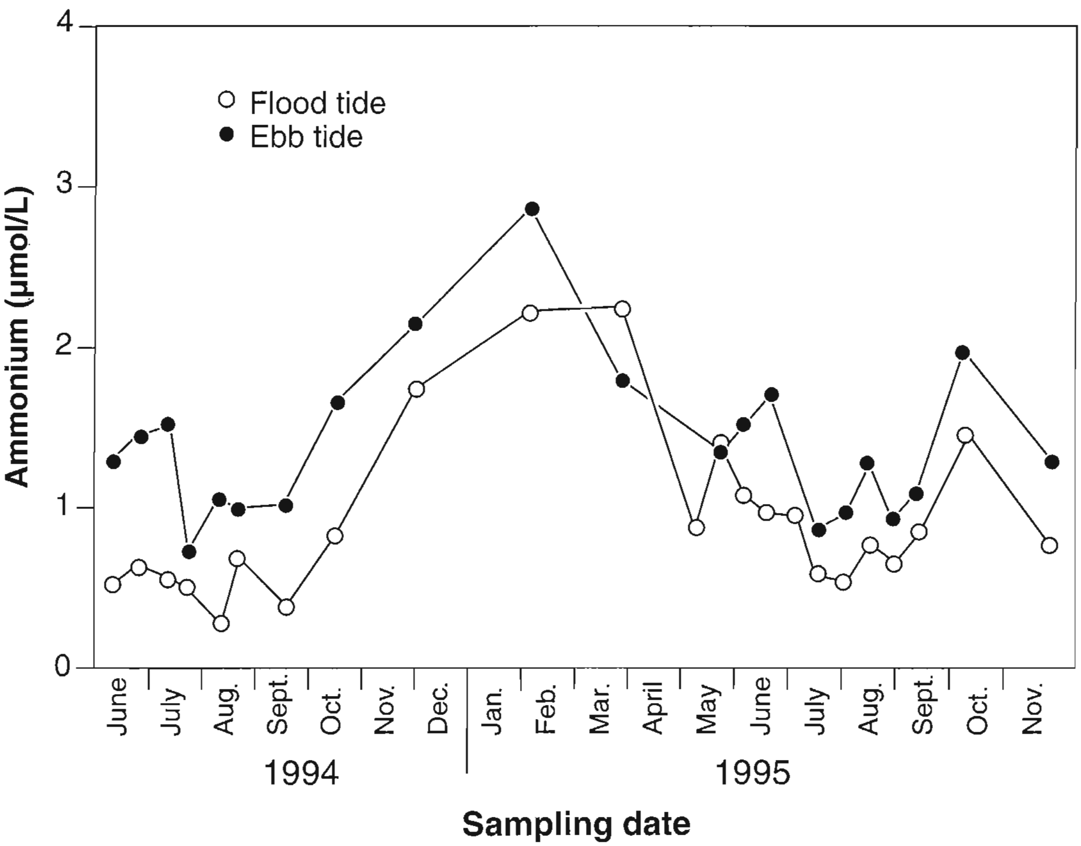

Figure 10. Effect of a tidal cycle on ammonium concentration in the water column.

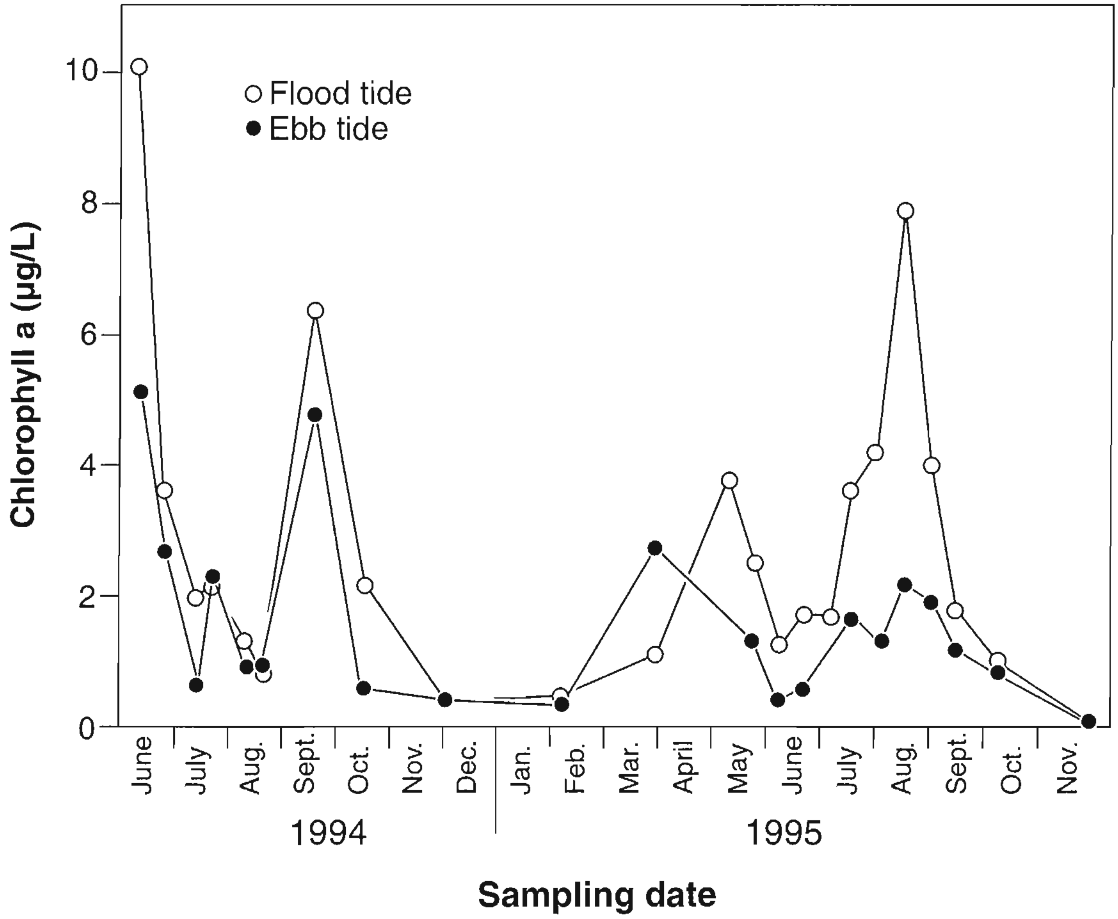

Figure 11. *Effect of a tidal cycle on chlorophyll-a concentration in the water column.*

sediments. It appears that benthic animals fed on chlorophyll as the water flowed over the sediments, while at the same time they excreted ammonium into the water. Alternatively, microalgae that were suspended by the incoming tide may have settled out during high tide, causing chlorophyll levels to be lower during the ebb tide. A similar tide-regulated phenomenon has been reported for the Bay of Somme in France, where the excretion by dense cockle beds increased ammonium in the flood-tide water (Rybarczyk et al., 1993). More examples can be found in the review by Nixon and Pilson (1984).

Factors influencing nutrients in the sediments

Nutrients in sediments play an essential role in determining trophic production of an estuarine ecosystem. The levels of nutrients in sediments are affected by factors including groundwater, sediment transport, sediment texture, organic detritus, utilization by benthic algae and vegetative plants, decomposition and mineralization of organic matter, and water-sediment exchange. In spite of extensive environmental monitoring on Sturgeon and Roberts banks, there are no data on nutrients in the sediments of the bank, let alone on the quantitative effect of sewage effluent on nutrients in the sediments.

Four sites were sampled (Fig. 3). Site A0 is near the outfall of the Iona Island sewage treatment plant, and site A14 is to the south side of the main arm of the Fraser River mouth. Both sites are muddy. Sites A10 and A12 are so sandy that no pore water could be obtained by centrifuging (note that in this case, the use of pore-water peepers, described above in 'Sediment diagenetic controls on the composition of intertidal sediments', may have been an appropriate method for obtaining pore-water ammonium concentrations). A 25 cm long sediment core was taken by inserting a plastic cylinder (8.2 cm in diameter) into the sediments. It was sliced in situ into 1 cm sections for the top 5 cm and then into 2 cm sections for the next 4 cm (only the top 9 cm were sliced). The slices of sediment were frozen immediately using dry ice. Within a few days, the sediments were thawed and centrifuged at 4000 rotations per minute for 10 min. The supernatant (the pore water) was taken by syringe, filtered through a type GF/F filter, and analyzed for nutrients (ammonium, nitrate, urea, and phosphate) on a Technicon Instruments AutoAnalyzer® (model AAII). Nutrient concentrations obtained by this method are rough estimates of actual values in pore water, because of the complicated chemistry involving adsorption and desorption when anoxic sediments were exposed to the air. For ammonium, Rosenfeld (1979) noted that adsorbed ammonium was about 10% of dissolved ammonium.

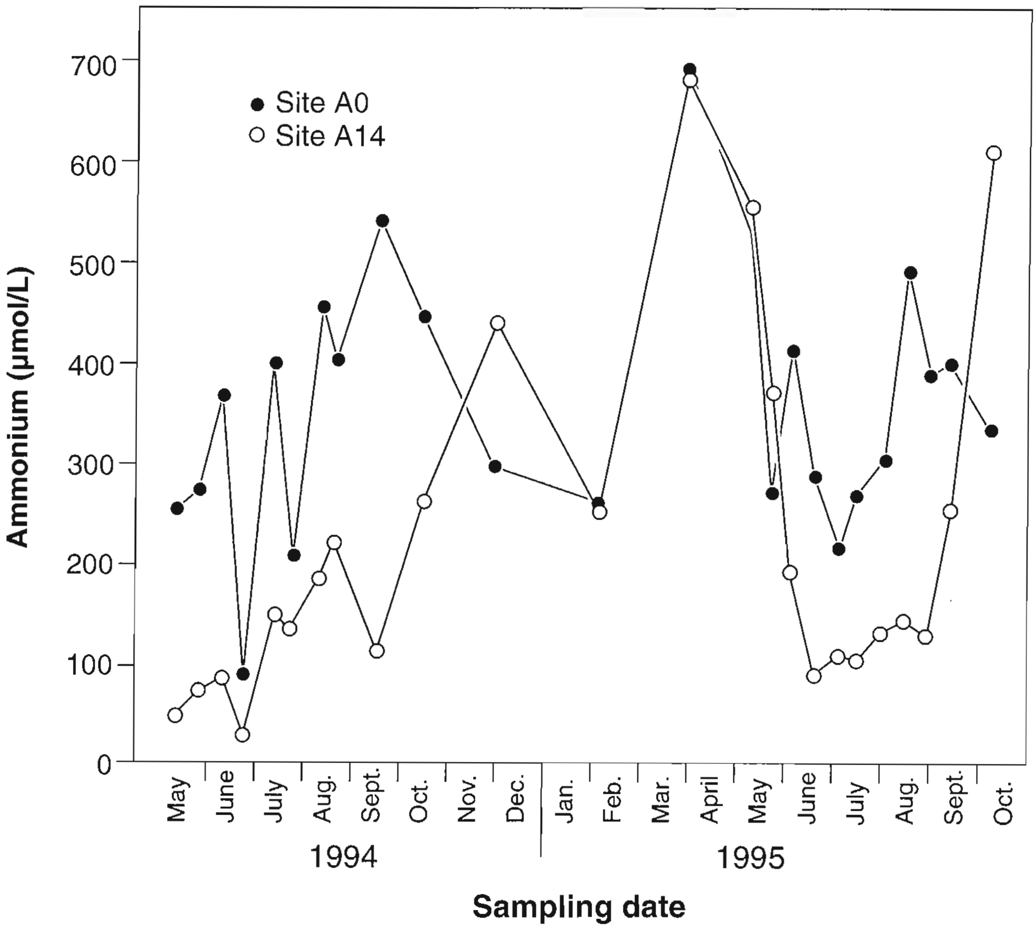

***Figure 12.** Concentrations of ammonium in pore water, averaged in the top 9 cm of sediments.*

The average concentration of ammonium in the pore water of the top 9 cm at site A0 ranged between 200 μmol/L and 500 μmol/L in the time period from May 1994 to November 1995 (Fig. 12). There was no apparent seasonality at site A0. The average ammonium concentration for the top 9 cm at site A14 was generally lower than at site A0, especially during the summer months, and ranged from 25 μmol/L to 700 μmol/L. There was a seasonal change at site A14 which showed an increase in concentration in the fall (September–November) of both years; however, maximal concentrations in May 1995 and a subsequent decline until mid-June were in contrast to the pattern of nutrient concentrations for the same period in 1994.

Concentrations of ammonium in the sediments of Sturgeon Bank are higher than in some estuaries and lower than in others. For example, ammonium concentrations in the sediments of the Tamar Estuary, in southwestern England, were less than 50 μmol/L in the top 10 cm (Watson et al., 1993), whereas in the middle of Narragansett Bay, Maine, during spring, they were 760 μmol/L in the top 10 cm (Nixon and Pilson, 1984). Very high concentrations occurred at Cape Lookout Bight, North Carolina, where organic-rich sediments accumulated at a rate of approximately 8.4 to 11.6 cm/a, and ammonium concentrations in the top 10 cm averaged 2000 μmol/L (Klump and Martens, 1981).

Ammonium is usually a major form of nitrogen mineralized from particulate organic nitrogen (Nixon and Pilson, 1984; Garber, 1984). Apparently, the higher ammonium concentrations at site A0 compared with site A14 reflect higher organic content in sediments at site A0, indicating the effect of sewage effluent. The lack of seasonality at site A0 also suggests that the site was contaminated with organic matter. Without historical data on nutrients in the sediments at site A0, it is difficult to assess to what degree the site has recovered, although other evidence such as an increase in benthic microalgae (*see* 'Benthic microalgal chlorophyll and productivity' below) and animals (*see* 'Secondary productivity' below) as well as fish (Nishimura et al., 1996) indicates that some recovery has occurred. As shown by an increase in ammonium concentration in the water column, there was a net flux of ammonium out of the sediments. At the same time, however, the ammonium concentration in the sediments did not decrease, perhaps due to constant decomposition rates of organic matter. Further studies are required to understand the nutrient fluxes between the components of the ecosystem in this mud flat.

Implications for primary productivity

Nutrients in the water column and sediments determine primary productivity of salt-marsh plants, seagrasses, benthic algae, and phytoplankton in the water column, which is transformed to secondary production. Secondary production ultimately supports wildlife such as shorebirds, waterfowl, raptors and gulls, and juvenile fish including salmon and herring, which form complex ecological communities on Sturgeon and Roberts banks.

The release of nutrients into the water column during a flood tide on Sturgeon Bank may enhance primary productivity in the water column after the water retreats to the strait. In particular, when primary productivity in the strait is limited by nitrogen during the late spring and summer (Harrison et al., 1983), the retreating water mixes with less turbid Strait of Georgia water, leading to ammonium uptake by phytoplankton. When the water returns to Sturgeon Bank during the next flood tide, it loses chlorophyll due to grazing by benthic animals or settling of suspended microalgae during high tide, and receives ammonium from the sediments. This exchange process occurs daily with each tidal cycle, and can be a significant source of nutrients for primary productivity in the strait. The tidal cycle has other effects on the recycling of nutrients. Because inorganic nutrients are low in the Fraser River, this water contributes little to primary productivity directly; however, the Fraser River contains organic detritus. The damming effect of the flood tide forces the fresh water onto the marshes along the foreshore and the mud flat. The overflow moves more slowly due to the wider area, and particles in the water, including organics, settle out onto the marshes, seagrasses, and sediments. Those organic particles are actively decomposed by bacteria into inorganic nutrients, which are either used by vegetative plants and benthic algae or exported to the water column. Unfortunately, this aspect has not been studied. In particular, during the period of sewage discharge of the Iona Island sewage treatment plant, it is assumed that inorganic nutrients in the sewage effluent would have been used for primary production and organic matter would have been recycled.

Benthic microalgal chlorophyll and productivity

Chlorophyll is an index of primary producers and its standing stock is affected by many factors including light intensity, temperature, nutrients, sediment texture, tidal height, burial rate of sediments, and grazing. Benthic algal chlorophyll has not been measured for Sturgeon and Roberts banks before, and hence we present the first measurements of benthic chlorophyll on the mud flat.

Figure 13 shows the biomass of benthic microalgae at the four sites. Spatial variation among the sites was large, and biomass increased from site A0 (muddy, near the outfall, with the lowest level of chlorophyll a: <200 mg/m^2) through sites A14 (muddy) and A12 (sandy) to site A10 (sandy, with the highest level of chlorophyll a: up to 4000 mg/m^2) (Fig. 13a, b). This spatial variation might be due to the difference in sediment texture and in grazing; however, this pattern is in contrast to that observed in Netarts Bay, Oregon, where the highest chlorophyll concentrations generally occurred in the silty sediments (94 mg/m^2 chlorophyll a), and the lowest in sand (46 mg/m^2 chlorophyll a) (Knox, 1986). There was temporal (seasonal) variation at all the sites. Benthic chlorophyll at site A10 dramatically increased from June 1994 to August 1995, and then decreased (Fig. 13b). There was a similar increase at site A12, but to a lesser degree. The temporal variation at sites A10 and A12 showed a lack of seasonality, which might have been overshadowed by the interannual variability resulting from changes in runoff, in the Fraser River discharge, in solar radiation, or in grazing.

The chlorophyll values at sites A10 and A12 were very high compared with other estuaries. Knox (1986) compiled a number of estimates of benthic microalgal chlorophyll levels, which included 0.6 to 6.7 mg/m^2 in Upper Waitemata Harbour, New Zealand; 9.3 to 109.8 mg/m^2 in Avon-Heathcote estuary, Christchurch, New Zealand; 12.5 to 30.5 mg/m^2 in Delaware Inlet, Nelson, New Zealand; and 2.6 to 10.6 mg/m^2 in Nanaimo, British Columbia. In North Inlet estuary, Georgetown, South Carolina, chlorophyll in the mud flat ranged from 20 to 100 mg/m^2 throughout the year (Pinckney and Zingmark, 1991). Chlorophyll values ranged from about 20 to 103 mg/m^2 in an intertidal sand flat of Ria de Arosa of northwest Spain (Varela and Penas, 1985). Note that there is a major difference in the depth of sampled sediments between our sampling and others in the literature, which could partially explain our higher chlorophyll values. Generally, the top 1 cm of sediments is sampled for chlorophyll. We sampled the top 4 cm at sites A0 and A14, and the top 10 cm at sites A10 and A12, since sections of the core revealed chlorophyll in the deeper sediments, particularly at sites A10 and A12. Chlorophyll at depth could be due to bioturbation and vertical movement of microalgae in the interstitial water of the sandy sediments at sites A10 and A12. Temporal variation at sites A14 and A0 showed remarkably parallel fluctuations between the two sites (Fig. 13a), suggesting that both sites were subject to the same external forcing (i.e. the Fraser River outflow). Lower chlorophyll values at site A0 than at any of the other three sites suggest that contaminants at site A0 may still have been inhibiting chlorophyll production, since this site had the highest heavy-metal concentrations of all four sites (*see* 'Sediment geochemistry of the Fraser River intertidal region' above). Alternatively, the higher abundance of animals at site A0 could be due to high grazing activity.

To date, there are no benthic algal productivity measurements for Sturgeon Bank; however, this productivity is currently being assessed by measuring changes in oxygen concentrations in light and dark chambers. Due to the intertidal nature of the mud flat, benthic chambers are used to trap water and mimic the flood portion of the tidal cycle, during which time the chambers become covered with water. Therefore, benthic primary productivity is estimated when the mud flat is flooded, and any productivity when the mud flat is exposed to air during low tide is not included. Bottle incubations also are employed to estimate water-column productivity, which serves as a comparison to benthic productivity, and this value is subtracted from the benthic-chamber productivity in order to separate water-column and benthic productivities.

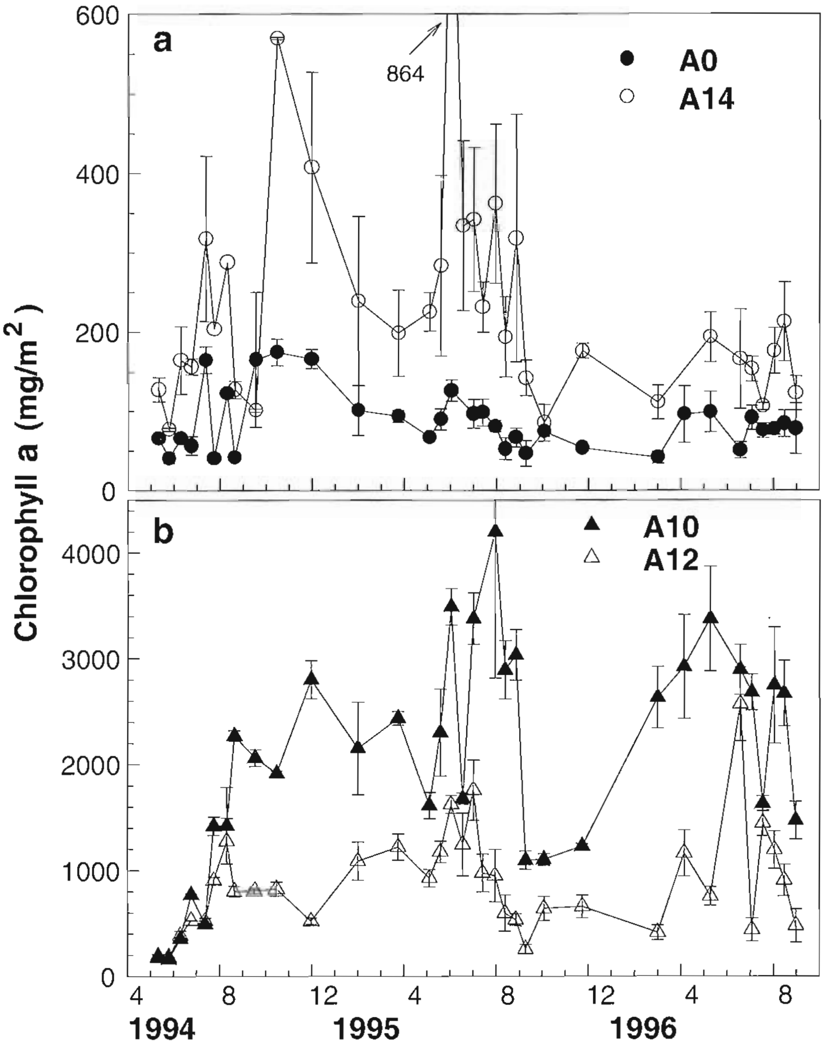

Figure 13.

*Concentrations of chlorophyll a, integrated over (**a**) the top 4 cm of sediments at sites A0 and A14 and (**b**) the top 10 cm at sites A10 and A12.*

SECONDARY PRODUCTIVITY

General conditions on Sturgeon Bank and their effects on secondary productivity

Contaminant inputs (including nutrients, organic matter, and metals) to Sturgeon Bank from the Iona Island sewage treatment plant have severely modified the composition of the mud flat's invertebrate fauna (including dominant groups such as bivalves, amphipods, nematodes, polychaetes, etc.). Improvements in the discharge practices at the sewage treatment plant, such as the construction of the submerged outfall pipe in 1988, have reduced the flow of contaminants over the mud flat; however, through the gradual decontamination of Sturgeon Bank, late successional trends have disturbed the 'postcontamination' faunal community, as can be seen in long-term data collected on the amphipod *Corophium salmonis* and the bivalve *Macoma balthica.*

In general, the discharge of sewage effluent into an estuary can have several potentially degrading effects on the biota. To begin with, most of the organic material is only partially decomposed, thereby forming a suitable substrate for bacteria. The decomposition of this organic material in natural waters leads to the uptake of dissolved oxygen by bacteria, which can result in prolonged periods of low oxygen concentrations in the sediments and overlying water in areas where oxygen replenishment is slow. The end result of this bacterial activity, therefore, is potential anoxia and stress to aquatic animals, which may lead to a reduction or elimination of secondary productivity in areas within immediate proximity of the discharge. Primary treatment of the sewage influent at the Iona Island sewage treatment plant was a significant step to reduce the oxygen demand of the effluent before it reaches Sturgeon Bank (Waldichuk, 1984).

On inner Sturgeon Bank, extensive dissolved-oxygen depletion occurred during the flood tide, due to the high oxygen demand of the organic-laden sediments when effluent was pushed out of the channel and onto Sturgeon Bank by the heavier incoming seawater. Dissolved-oxygen concentrations measured at 1 cm depth in the severely polluted zone showed that dissolved oxygen could drop to nearly zero (Otte and Levings, 1975; Birtwell et al., 1983). The lowest dissolved-oxygen values were observed on Sturgeon Bank on the south side of the effluent channel. Here, as the rising tide would push more effluent towards areas on the bank with already low dissolved oxygen, oxygen concentrations near the bottom could decline to 1.5 mg/L. Then, when shoreward currents resulting from a rising tide would decrease, dissolved oxygen levels would be able to rise (Otte and Levings, 1975).

With regard to nutrient enrichment associated with effluent dumping, sewage contains a high concentration of nitrogen (as urea, ammonium, nitrate, and other nitrogenous compounds) and phosphorus. These extra nutrients may result in an increase in algal bloom activity which, in turn, provides a bacterial substrate. Metals (Ag, Pb, Zn, Hg, Cd, etc.) are also a constituent of industrial and commercial wastes; they enter the sewage treatment plant in either dissolved or particulate form (*see* 'Implications of surface sediment composition for metal partitioning', above). When dissolved, they may be sequestered by organisms in sublethal amounts, and thus may contribute to a decrease in the secondary productivity of those organisms which lack effective means to defend against metal toxicity (e.g. through metal-binding proteins).

Specific responses of the invertebrate fauna on Sturgeon Bank to Iona Island effluent discharges

During the period when the Iona Island sewage treatment plant disposed of effluent directly onto Sturgeon bank, much of the invertebrate community on the bank was severely disrupted or excluded as a result of the effluent discharges and other factors such as jetty and causeway construction and the dumping of dredge spoils. Throughout the 1970s and until 1988, the Greater Vancouver Sewage and Drainage District continued to release primary treated effluent onto Sturgeon Bank via the dredged channel adjacent to the southern edge of the Iona Island breakwater. As expected, in the area close to the effluent channel (with the exception of the area immediately adjacent to the sewage discharge point, where an azoic condition existed), there was a reduction in the number of bottom-dwelling animals coupled with an increase in the number of individuals of those species (animal and plant) particularly tolerant to sewage. This was due in part to complex interactions of properties such as changes in sediment particle size, in the levels of organic carbon, and in the concentration of heavy metals in the area of the discharge. This resulted in lower biomass levels in the area near the dredged channel and an azoic condition immediately adjacent to the effluent discharge point. Hence, the general effect on the biota was to reduce the relative diversity near the effluent channel and to allow those species tolerant of sewage to thrive and be present in very high numbers where conditions were not lethal (B.C. Research, unpub. report, 1975; Otte and Levings, 1975).

Specifically, the benthic biomass between the Iona Island and North Arm jetties was found to be significantly lower relative to areas south of the Iona Island jetty such as Roberts Bank (Levings and Coustalin, 1975; Levings et al., 1978). This finding was likely the result of effluent dumping in the area, and was compounded by other oceanographic factors, such as the reduced flow of silt-laden fresh water over northern Sturgeon Bank (as a result of the construction of the Iona Island breakwater), which led to modifications of sediment structure. Sewage from the Iona Island sewage treatment plant also led to an increase in toxicity associated with heavy-metal contamination (McGreer, 1979) as well as a greater incidence of anoxia at high tide (Otte and Levings, 1975). This resulted in the severe disruption of the benthic environment in the vicinity of the Iona Island sewage treatment plant.

A common species in the margin between the severely polluted zone and the contaminated zone was the polychaete worm *Manayunkia aestuarina* (Levings and Coustalin, 1975; B.C. Research, unpub. report, 1975). Even though this species was common in this contaminated area, it also showed a positive correlation with respect to distance away from the outfall, as it numbered over 2 000 000 individuals/m^2 approximately 1200 m southwest of the effluent channel (B.C. Research, unpub. report, 1975). Other organisms which were found in the contaminated area included the polychaete *Eteone longa*, the bivalve *Macoma balthica* (biomass up to 10.72 g/m^2 (Levings and Coustalin, 1975)), the amphipods *Corophium salmonis* and *Corophium insidiosum* (biomass up to 2.88 g/m^2 (Levings and Coustalin, 1975)), and large numbers of harpaticoid copepods. The polychaete worm *Capitella capitata*, normally an indicator of organic pollution, occurred relatively uncommonly when compared to other invertebrates in the area (approx. 2200 individuals/m^2 at 1500 m southwest of the effluent channel mouth (B.C. Research, unpub. report, 1975)). The barnacle community was also reduced in the area. It was hypothesized that toxicity from heavy metals or chlorination, in combination with seasonal patterns of circulation, temperature, pH, dissolved oxygen, and salinity, may have been the cause of this reduction (B.C. Research, unpub. report, 1975; Otte and Levings, 1975).

Finally, suspended particles in sewage have the potential to influence the physical and chemical nature of the sediments. For example, on Sturgeon Bank, the pre-effluent sediment substrate was blanketed with fine silt associated with sewage treatment, which was high in organic matter and other contaminants associated with sewage. The result of this alteration was the exclusion of certain organisms that were once able to exist in that area and the creation of a habitat for tolerant species. The resulting impacts on secondary productivity are twofold. Firstly, a drop in secondary productivity is associated with those species that are excluded or outcompeted by tolerant species, and secondly, a rise in secondary productivity is associated with an influx of tolerant species.

The construction of the submerged ocean outfall in 1988 decreased the deleterious effects of compositional changes in sediment structure on the biota; however, the concept of ecological succession still applies to all situations where a disturbance, particularly a long-term and large-scale one, occurs and then ceases. Therefore, the return of the Sturgeon Bank area to a more natural state following years of contamination due to effluent discharges also constitutes a disturbance — albeit one that results in a 'healthier' environment by ecological standards.

During the ecological succession that has been taking place on Sturgeon Bank since the original disturbance, there must have existed (or there will exist) a point in time at which biotic abundance, diversity, and production are greatest according to the intermediate disturbance hypothesis (Connell, 1978). Continued efforts by industry (and the Iona Island sewage treatment plant) to reduce pollutants will result in continued changes in the biotic characteristics of the area, and perhaps drops in the overall secondary productivity. An example of this is the subtle, yet long-term change in sediment characteristics (larger grain sizes due to reduced fine particulate matter and reduced organic content) which serves to exclude many of the organisms that could previously thrive in the 'mildly contaminated' environment. This change in sediment composition as a result of effluent diversion may be the mechanism behind the present decline in the abundance of indicator species, such as the amphipod *Corophium salmonis*, to levels indicative of an uncontaminated environment (Fig. 14). This trend seems to be mirrored by the bivalve indicator *Macoma balthica*, which also exhibits a decline in abundance relative to the station closest to the sewage treatment plant (site A0) which is still receiving some contaminants from periodic sewage bypass dumping during heavy rainfall (Fig. 15). Similar observations can be made for these two species by comparing their secondary productivity and productivity:biomass ratios in currently contaminated areas on Sturgeon Bank and relatively uncontaminated areas nearby (Table 2).

FUTURE STUDIES

Studies to date have provided important baseline information on the state of the Fraser River intertidal region, with a special emphasis on documenting the response of Sturgeon Bank to the recovery from the effects of primary treated effluent discharged by the Iona Island sewage treatment plant; however, key information gaps need to be addressed by 1) determining, through the use of sediment cores, pre-exposure levels of contaminants such as trace metals and organic matter, and

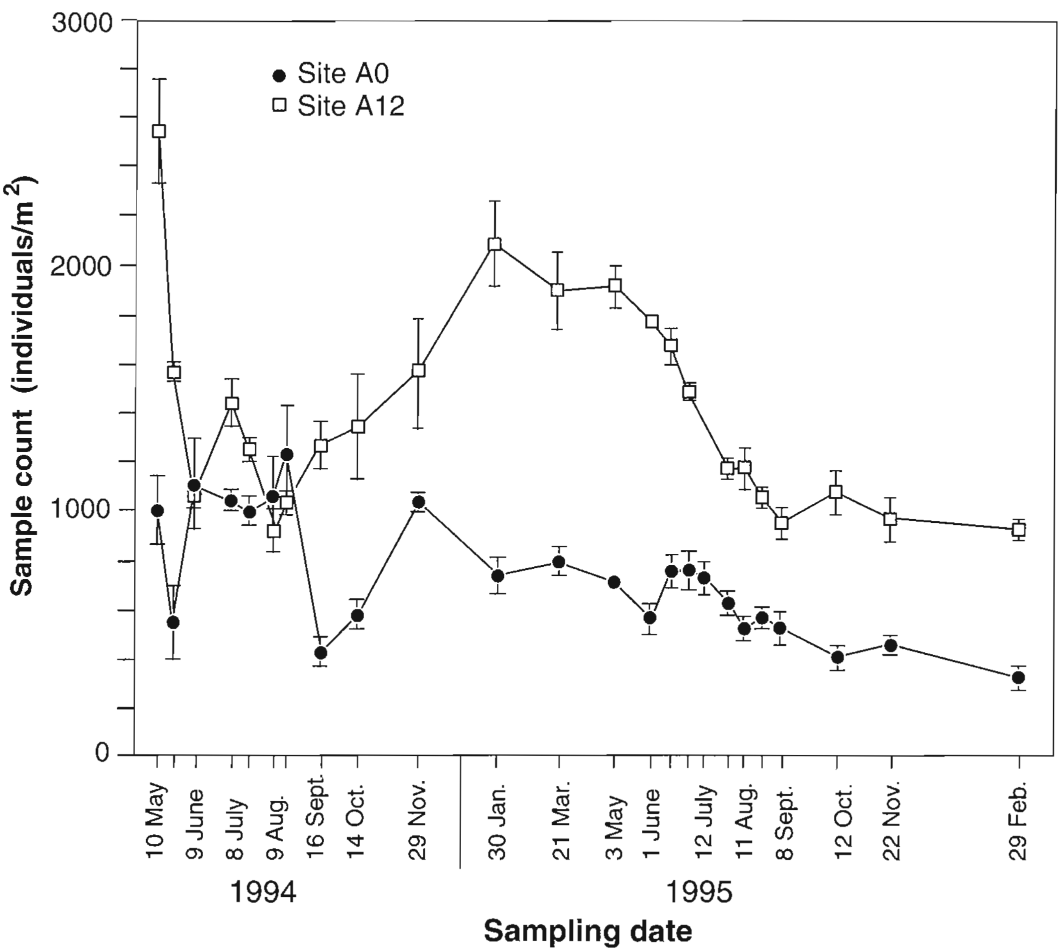

Figure 14. *Abundances of the tolerant indicator species* Macoma balthica *(Bivalvia) at two study sites (A0, located immediately adjacent to the Iona Island sewage treatment plant; A12, located approximately 1 km south) on Sturgeon Bank.*

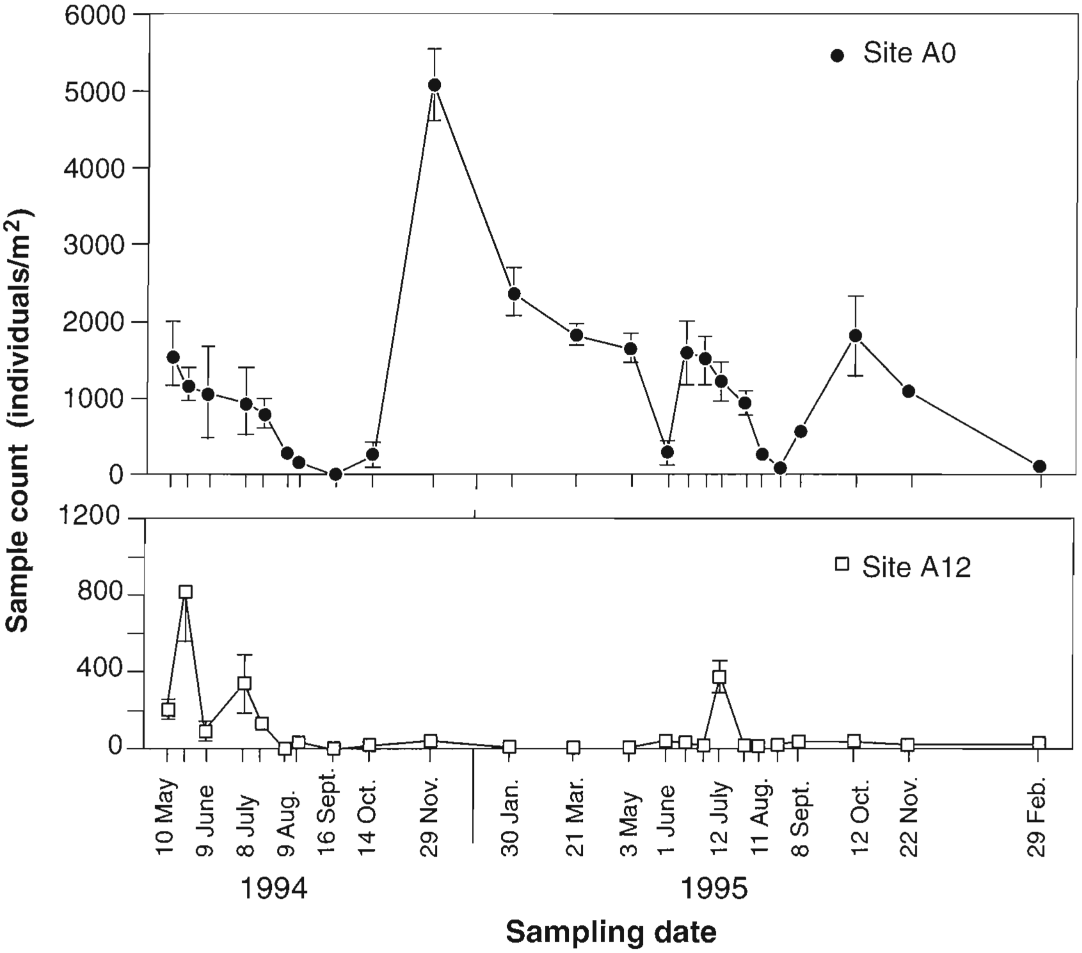

Figure 15. Abundances of the tolerant indicator species Corophium salmonis *(Amphipoda) on Sturgeon Bank at two sites (A0, located immediately adjacent to the Iona Island sewage treatment plant; A12, located approximately 1 km south). Note the absence of measurable winter abundances at site A12, likely the result of a lack of organic enrichment capable of supporting additional cohorts throughout the year. Error bars represent ±1 standard error.*

Table 2. A comparison of productivity and productivity:biomass (P:B) ratios at contaminated and uncontaminated sites for the amphipod *Corophium salmonis* and the bivalve *Macoma balthica* on Sturgeon Bank, Fraser River delta, British Columbia.

	Corophium salmonis (1996 data)		**Macoma balthica (1995 data)**	
	Secondary productivity	P:B	Secondary productivity	P:B
	$g \cdot m^{-2} \cdot a^{-1}$		$g \cdot m^{-2} \cdot a^{-1}$	
Contaminated	0.58	1.50	0.35	0.71
Uncontaminated	0.09	1.07	0.21	0.81

2) determining the response of meiofauna (less than 500 μm in diameter) to changing conditions in the intertidal region. Further study on the role of sediment interstitial waters in providing a source of metals (i.e. Fe and Mn), plus nutrients, to the overlying water column is also required in order to place findings to date within a larger framework. Furthermore, continued monitoring of metals, nutrients, chlorophyll, and primary and secondary productivity in the Sturgeon Bank intertidal region (particularly at site A0, the site closest to the previous intertidal channel) is necessary as recovery continues.

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REFERENCES

Ages, A. and Woollard, A.
1988: Tracking a pollutant in the lower Fraser River: a computer simulation; Water Pollution Research Journal of Canada, v. 23, p. 122–140.

Bendell-Young, L., Chouinard, J., and Pick, F.R.
1994: Metal concentrations in chironomids in relation to peatland geochemistry; Archives of Environmental Contamination and Toxicology, v. 27, p. 186–194.

Bendell-Young, L., Dutton, M., and Pick, F.R.
1992: Contrasting two methods for determining trace metal partitioning in oxidized lake sediments; Biogeochemistry, v. 17, p. 205–219.

Birtwell, I.K., Greer, G.L., Nassichuk, M.D., and Rogers, I.H.
1983: Studies on the impact of municipal sewage discharged onto an intertidal area within the Fraser River estuary, British Columbia; Canadian Technical Report of Fisheries and Aquatic Sciences, no. 1170, 55 p.

Bryan, G.W., Langston, W.J., and Hummerstone, L.G.
1980: The use of biological indicators of heavy metal contamination in estuaries, with special reference to an assessment of the biological availability of metals in estuarine sediments from south-west Britain; Marine Biological Association of the United Kingdom, Occasional Publication, no. 1, 73 p.

Canadian Hydrographic Service
1972: Tide and current tables; Volume 5 (Juan de Fuca and Georgia Strait), Government of Canada, Vancouver, British Columbia, 14 p.

Carignan, R., Rapin, F., and Tessier, A.
1985: Sediment porewater sampling for metal analysis: a comparison of techniques; Geochimica et Cosmochimica Acta, v. 49, p. 2493–2497.

Clifford, P.J., Cochlan, W.P., Harrison, P.J., Yin, K., Sibbald, M.J., Albright, L.J., St. John, M.A., and Thompson, P.A.
1989: Plankton production and nutrient dynamics in the Fraser River plume, 1987; Department of Oceanography, University of British Columbia, Vancouver, British Columbia, Manuscript Report No. 51, 118 p.

Clifford, P.J., Harrison, P.J., St. John, M.A., Yin, K., and Albright, L.J.
1991a: Plankton production and nutrient dynamics in the Fraser River plume, 1989; Department of Oceanography, University of British Columbia, Vancouver, British Columbia, Manuscript Report No. 54, 255 p.

Clifford, P.J., Harrison, P.J., Yin, K., St. John, M.A., and Goldblatt, R.H.
1991b: Plankton production and nutrient dynamics in the Fraser River plume, 1990; Department of Oceanography, University of British Columbia, Vancouver, British Columbia, Manuscript Report No. 58, 265 p.

Clifford, P.J., Harrison, P.J., Yin, K., St. John, M.A., Waite, A.M., and Albright, L.J.
1990: Plankton production and nutrient dynamics in the Fraser River plume, 1988; Department of Oceanography, the University of British Columbia, Vancouver, British Columbia, Manuscript Report No. 53, 142 p.

Clifford, P.J., Yin, K., Harrison, P.J., St. John, M.A., Goldblatt, R.H., and Varela, D.E.
1992: Plankton production and nutrient dynamics in the Fraser River plume, 1991; Department of Oceanography, University of British Columbia, Vancouver, British Columbia, Manuscript Report No. 59, 415 p.

Compeau, G. and Bartha, R.
1984: Methylation and demethylation of mercury under controlled redox, pH, and salinity conditions; Applied Environmental Microbiology, v. 48, p. 1203–1207.

Connell, J.H.
1978: Diversity in tropical rainforests and coral reefs; Science, v. 199, p. 1302–1310.

Davies-Colley, R.J., Nelson, P.O., and Williamson, K.H.
1984: Copper and cadmium uptake by estuarine sedimentary phases; Environmental Science and Technology, v. 18, p. 491–499.

Davison, W.
1982: Transport of iron and manganese in relation to the shapes of their concentration-depth profiles; Hydrobiologia, v. 92, p. 463–471.

Emerson, S., Jahnke, R., and Heggie, D.
1984: Sediment-water exchange in shallow water estuarine sediments; Journal of Marine Research, v. 42, p. 709–730.

Feeney, T.
1995: Physical controls on the distribution of contaminants on Sturgeon Bank, Fraser River delta, British Columbia; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 292 p.

Garber, J.H.
1984: ^{15}N tracer study of the short-term fate of particulate organic nitrogen at the surface marine sediments; Marine Ecology Progress Series, v. 17, p. 89–104.

Geyer, W.R. and Farmer, D.M.
1989: Tide-induced variation of the dynamics of a salt wedge estuary; Journal of Physical Oceanography, v. 19, p. 1060–1072.

Grieve, D.A. and Fletcher, W.K.
1976: Heavy metals in deltaic sediments of the Fraser River, British Columbia; Canadian Journal of Earth Sciences, v. 13, p. 1683–1693.

Harrison, P.J., Fulton, J.D., Taylor, F.J.R., and Parsons, T.R.
1983: Review of the biological oceanography of the Strait of Georgia: pelagic environment; Canadian Journal of Fisheries and Aquatic Sciences, v. 40, p. 1064–1094.

Harvey, R.W. and Luoma, S.N.
1985: Effect of adherent bacteria and bacterial extracellular polymers upon assimilation by *Macoma balthica* of sediment-bound Cd, Zn and Ag; Marine Ecology Progress Series, v. 22, p. 281–289.

Hesslein, R.H.
1976: An *in situ* sampler for close interval porewater studies; Limnology and Oceanography, v. 21, p. 912–914.

Hodgins, D.O., Osborn, T.R., and Quick, M.C.
1977: Numerical model of stratified estuary flows; American Society of Civil Engineers; Journal of Waterways, Ports, Coastal and Ocean Division, p. 25–42.

Hoos, L.M. and Packman, G.A.
1974: The Fraser River estuary: status of environmental knowledge to 1974; Canadian Department of the Environment Regional Board, Pacific Region, Special Estuary Series, No. 1, 518 p.

Jenne, E.A.
1968: Controls on Mn, Fe, Co, Ni, Cu, and Zn concentrations in soils and water: the significant role of hydrous Mn and Fe oxides; *in* Trace Inorganics in Water, (ed.) R.F. Gould; American Chemists Society, Washington, D.C., p. 337–387.

Kennish, M.J.
1986: Ecology of Estuaries; Volume 1, Physical and Chemical Aspects; Chemical Factors, CRC Press, Inc., Boca Raton, Florida, p. 89–137.
Kistritz, R.U.
1978: An ecological evaluation of the Fraser estuary tidal marshes: the role of detritus and the cycling of elements; WestWater Research Centre, Technical Report No. 15, 59 p.
Klump, J.V. and Martens, C.S.
1981: Biogeochemical cycling in an organic rich coastal marine basin - II: nutrient sediment-water exchange processes; Geochimica et Cosmochimica Acta, v. 45, p. 101–121.
Knox, G.A.
1986: Estuarine Ecosystems: A Systems Approach; CRC Press Inc., Boca Raton, Florida, v. I, 289 p.
Kostaschuk, R.A. and Atwood, L.A.
1989: River discharge and tidal controls on salt-wedge position and implications for channel shoaling: Fraser River, British Columbia; Canadian Journal of Civil Engineering, v. 17, p. 452–459.
Kostaschuk, R.A., Church, M.A., and Luternauer, J.L.
1989: Bedforms, bed-material and bed load transport in a salt-wedge estuary: Fraser River, British Columbia; Canadian Journal of Earth Sciences, v. 27, p. 1440–1452.
Langston, W.J.
1982: The distribution of mercury in British estuarine sediments and its availability to deposit-feeding bivalves; Journal of the Marine Biological Association of the United Kingdom, v. 62, p. 667–684.
1985: Assessment of the distribution and availability of arsenic and mercury in estuaries; *in* Estuarine Management and Quality Assessment, (ed.) J.G. Wilson and W. Halcrow; Plenum Press, New York, New York, p. 131–146.
LeBlond, P.H.
1983: The Strait of Georgia: functional anatomy of a coastal sea; Canadian Journal of Fisheries and Aquatic Sciences, v. 40, p. 1033–1063.
Levings, C.D. and Coustalin, J.B.
1975: Zonation of intertidal biomass and related benthic data from Sturgeon and Roberts Banks, Fraser River estuary, British Columbia; Environment Canada Fisheries and Marine Services, Technical Report No. 468, 150 p.
Levings, C.D., Armour, R., and McDaniel, N.G.
1978: A trench through mudflat communities of macroinvertebrates on Roberts Bank, Fraser River delta, B.C.; Department of Fisheries and Oceans, Fisheries and Marine Services, Manuscript Report No. 1501, 51 p.
Lingberg, S.E. and Harriss, C.
1974: Mercury enrichment in estuarine plant detritus; Marine Pollution Bulletin, v. 5, p. 93–94.
Lion, L.W., Altmann, R.S., and Leckie, J.O.
1982: Trace-metal adsorption characteristics of estuarine particulate matter: evaluation of contributions of Fe/Mn oxide and organic surface coatings; Environmental Science and Technology, v. 16, p. 660–666.
Luoma, S.N. and Bryan, G.W.
1981: A statistical assessment of the form of trace metals in oxidized estuarine sediments employing chemical extractants; Science of the Total Environment, v. 17, p. 165–196.
Luoma, S.N. and Davis, J.A.
1983: Requirements for modelling trace metal partitioning in oxidized estuarine sediments; Marine Chemistry, v. 12, p. 159–181.
Luoma, S.N., Ho, Y.B., and Bryan, G.W.
1995: Fate, bioavailability and toxicity of silver in estuarine environments; Marine Pollution Bulletin, v. 31, p. 44–54.
McGreer, E.R.
1979: Sublethal effects of heavy-metal contaminated sediment on the bivalve *Macoma Balthica* (L.); Marine Pollution Bulletin, v. 10, p. 259–262.
1981: Factors affecting the distribution of the bivalve *M. Balthica* (L.) on a mudflat receiving sewage effluent, Fraser River estuary, British Columbia; Marine Environmental Research, v. 7, p. 131–148.
Nagpal, N.K.
1995: Approved and working criteria for water quality; Water Quality Branch, Environmental Protection Department, Ministry of Environment, Lands and Parks, 45 p.
Nishimura, D.J.H., Piercey, G.E., Levings, C.D., Yin, K., and McGreer, E.R.
1996: Changes in fish communities and water chemistry after cessation of municipal sewage discharge near the Iona Island foreshore, Fraser River estuary, British Columbia; Canadian Technical Report of Fisheries and Aquatic Sciences, v. 2096, p. 17.
Nixon, S.W. and Pilson, M.Q.
1984: Nitrogen in estuarine and coastal marine ecosystems; *in* Nitrogen in the Marine Environment, (ed.) E.J. Carpenter and D.G. Capone; Academic Press, New York, New York, p. 565–647.
Otte, G. and Levings, C.D.
1975: Distribution of Macroinvertebrate Communities on A Mud Flat Influenced by Sewage – Fraser River Estuary, British Columbia; Fisheries and Marine Services Technical Report, no. 476, 79 p.
Pinckney, J. and Zingmark, R.G.
1991: Effects of tidal stage and sun angles on intertidal benthic microalgal productivity; Marine Ecology Progress Series, v. 76, p. 81–89.
Rosenfeld, J.K.
1979: Ammonium adsorption in nearshore anoxic sediments; Limnology and Oceanography, v. 24, p. 356–364.
Rybarczyk, H., Desprez, M., Ducrotoy, J.P., Olivesi, R., Delesmont, R., Jamet, F., and Elkaim, B.
1993: Dynamics of nutrients and faecal bacteria in a macrotidal estuary, the Bay of Somme (France); Netherlands Journal of Aquatic Ecology, v. 27, p. 395–404.
Samant, H.S., Doe, K.G., and Vaidya, O.C.
1990: An integrated chemical and biological study of the bioavailability of metals in sediments from two contaminated harbours in New Brunswick, Canada; Science of the Total Environment, v. 96, p. 253–268.
Santschi, P., Hohener, P., Benoit, G., and Buchholtz-ten Brink, M.
1990: Chemical processes at the sediment-water interface; Marine Chemistry, v. 30, p. 269–315.
Shea, D.
1988: Development of national sediment quality criteria; Environmental Science and Technology, v. 11, p. 1256–1261.
Stephens, K., Fulton, J.D., and Kennedy, O.D.
1969: Summary of biological oceanographic observations in the Strait of Georgia, 1965–1968; Fisheries Research Board of Canada, Technical Report, 110, 125 p.
Swain, L.G. and Holms, G.B.
1985: Water quality and objectives, Fraser River-delta area, Fraser River sub-basin from Kanaka Creek to the mouth, Technical Appendix; B.C. Ministry of Environment, 214 p.
Tabata, S.
1972: The movement of Fraser River-influenced surface water in the Strait of Georgia as deduced from a series of aerial photographs; Marine Sciences Branch, Pacific Region, Pacific Marine Science Report, v. 72-6, 69 p.
Tabata, S., Giovando, L.F., and Devlin, D.
1971: Current velocities in the vicinity of the Greater Vancouver Sewerage and Drainage District's Iona Island outfall, 1968; Fisheries Research Board of Canada, Technical Report 263, 110 p.
Tessier, A., Campbell, P.G.C., Auclair, J.C., and Bisson, M.
1984: Relationships between the partitioning of trace metals in sediment and their accumulation in the tissues of the freshwater mollusc *Elliptio Complanata* in a mining area; Canadian Journal of Fisheries and Aquatic Science, v. 41, p. 1463–1471.
Tessier, A., Carignan, R.C., and Belzile, N.
1994: Processes occurring at the sediment-water interface: emphasis on trace elements; *in* Chemical and Biological Regulation of Aquatic Systems, (ed.) J. Buffle and R.R. Devitre; CRC Press, Inc., Boca Raton, Florida, p. 137–173.
Thomson, R.E.
1975: Longshore current generation by internal waves in the Strait of Georgia; Canadian Journal of Earth Sciences, v. 12, p. 472–488.
Turekian, K.K.
1977: The fate of metals in the ocean; Geochimica et Cosmochimica Acta, v. 41, p. 1139–1144.
Varela, M. and Penas, E.
1985: Primary production of benthic microalgae in an intertidal sand flat of the Ria de Arosa, NW Spain; Marine Ecology Progress Series, v. 25, p. 111–119.

Waldichuk, M.
1984: Sewage pollution in British Columbia in perspective; *in* Workshop on Municipal Marine Discharge – 1984; Environmental Protection Service – Pacific Region, Burnaby, British Columbia, 50 p.

Watson, P.G., Freckers, P.E., and Howland, R.J.M.
1993: Benthic fluxes of nutrients and some trace metals in the Tamar estuary, SW England; Netherlands Journal of Aquatic Ecology, v. 27, p. 135–146.

Yin, K., Harrison, P.J., Pond, S., and Beamish, R.J.
1995a: Entrainment of nitrate in the Fraser River plume and its biological implications, I. Effects of salt wedge; Estuarine Coastal and Shelf Sciences, v. 40, p. 505–528.
1995b: Entrainment of nitrate in the Fraser River plume and its biological implications, II. Effects of spring vs neap tides and river discharge; Estuarine Coastal and Shelf Sciences, v. 40, p. 529–544.
1995c: Entrainment of nitrate in the Fraser River plume and its biological implications, III. Effects of winds; Estuarine Coastal and Shelf Sciences, v. 40, p. 545–558.

Knowledge of fish ecology and its application to habitat management

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Abstract: Information on fish habitat in the lower Fraser River and estuary downstream from Agassiz is presented with emphasis on geophysical factors that may be affecting fish ecology. The application to fisheries management is considered. The lower Fraser River and estuary provides habitat to support over 50 species of fish. Brief synopses are given of the ecology of commercially and ecologically significant fish. Fish communities in Boundary Bay and on Roberts Bank tend to be dominated by species adapted to marine conditions. Some brackish-water species are found in the salt wedge and on Sturgeon Bank. Our knowledge of fish ecology in the lower Fraser River and estuary is based on a patchwork of studies. To enable good management of this world-class estuary into the twenty-first century, it is prudent for stakeholders to foster ongoing programs of integrated fisheries ecosystem research in this area.

Résumé : Cet article présente l'information disponible sur l'habitat du poisson dans le bas Fraser et son estuaire en aval d'Agassiz, en soulignant les facteurs géophysiques susceptibles d'influer sur l'écologie du poisson. On y examine aussi les applications possibles pour la gestion des pêches. Le bas Fraser et son estuaire servent d'habitat à plus de 50 espèces de poissons; cet article présente un bref synopsis de l'écologie des poissons ayant une importance commerciale ou écologique. Les communautés de poisson des régions de la baie Boundary et du banc Roberts ont tendance à être dominées par des espèces adaptées aux conditions marines. On trouve certaines espèces d'eau saumâtre dans le coin salé et dans la région du banc Sturgeon. Notre connaissance de l'écologie du poisson dans le bas Fraser et son estuaire est fondée sur un ensemble d'études disparates. Afin d'assurer une bonne gestion de cet estuaire d'importance mondiale au XXI^e siècle, il serait prudent pour les intéressés de favoriser des programmes permanents de recherche intégrée sur l'écologie des pêches dans la région.

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INTRODUCTION

This paper provides an overview of information on fish habitat in the lower Fraser River and estuary, downstream from Agassiz, with emphasis on geophysical factors that may be affecting fish distribution. The knowledge and data are placed in the context of their application to fish habitat management. The lower Fraser River and estuary provide critical habitats for numerous commercially and ecologically significant fish species. The influence of habitat on fish production is well recognized by ecologists. Consequently, agencies such as Fisheries and Oceans Canada, which are mandated to manage fish habitat, have conducted, sponsored, or otherwise supported projects to increase our knowledge of the estuary. Applied ecological science is needed to determine the functional relationships between physical structures, estuarine and fluvial processes, and fish production. These relationships are needed to measure the importance of various habitat types. Management schemes, such as the Fraser River Estuary Management Program, were established on the basis of such ecological knowledge and continue to rely on new scientific information to set policy.

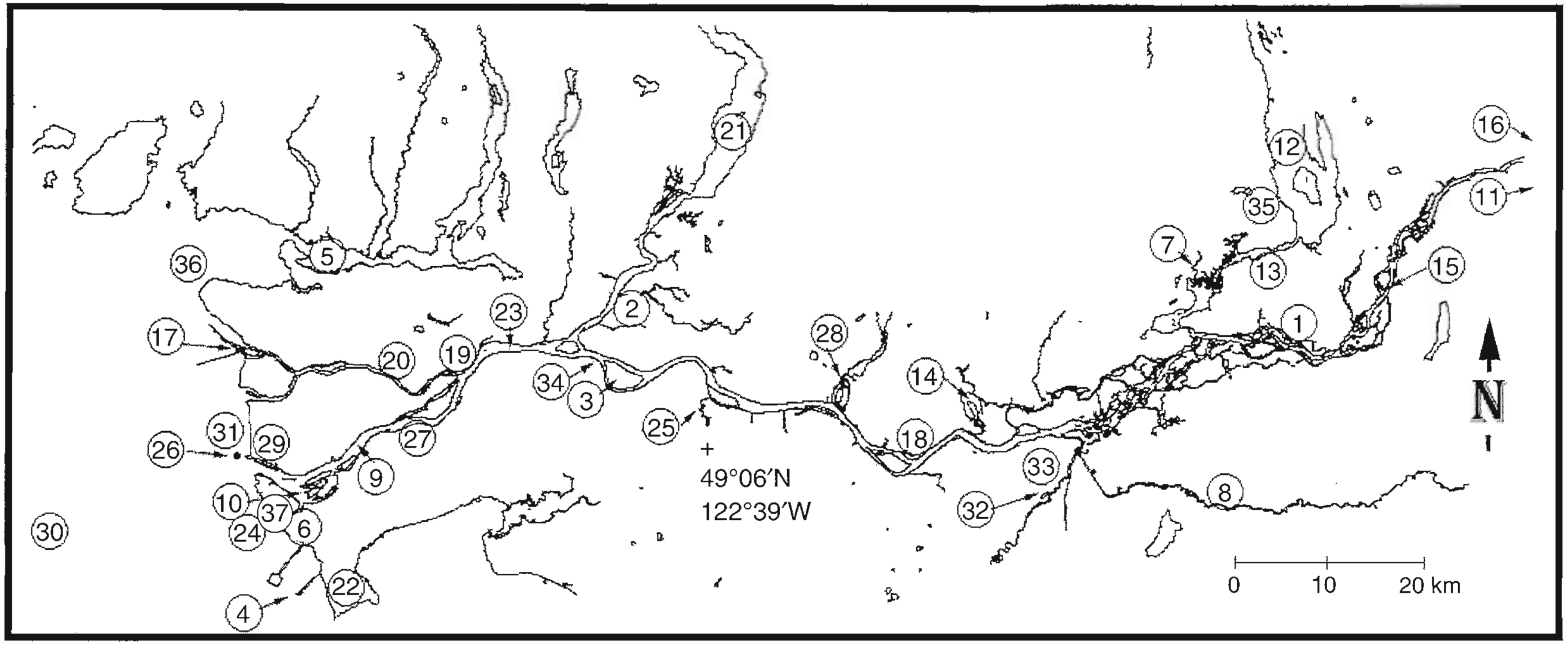
Many of the commercially significant fish species found in the lower Fraser River and estuary use multiple habitats to complete their life cycle, making definition of species-specific critical habitats exceedingly complex. For example, salmon (*Oncorhynchus* spp.) spawn in freshwater and complete a large portion of their life cycle in the northeast Pacific Ocean; however, the time spent rearing (growth in nursery habitat) in either fresh water (steelhead trout, *O. mykiss*, up to 5 years; pink salmon, *O. gorbuscha*, a few days) or the estuary (chinook salmon, *O. tshawytscha*, up to three months) varies considerably within and between species. The interrelations between survival in fresh water, estuary, and ocean are poorly understood (Bradford and Levings, 1997). In several instances even basic biological information, such as spawning locations, is unknown for the noncommercial, but numerically dominant fish (e.g. minnows, family Cyprinidae). In comparison to other major estuaries on the west coast of North America such as the Sacramento–San Joaquin estuary (Conomos, 1979; Interagency Ecological Program for the Sacramento–San Joaquin Estuary, 1997), detailed ecological information from the Fraser River estuary is very limited.

Fish habitats considered in this review extend from Agassiz, approximately 115 km from the mouth of the Fraser River, to the Strait of Georgia (Fig. 1), and include major tidal tributaries that enter the river in these reaches, as well as Sturgeon and Roberts banks. Because many of the smaller tributaries drain the floodplain of the lower river, these habitats also are mentioned. Northcote (1974) provided the first summary of knowledge of fish ecology in the estuary and lower river. Some aspects of estuarine ecology were included in papers which dealt with the entire Fraser River watershed, such as Northcote and Larkin (1989). There also have been a few papers that give summary details about the fish ecology of particular sectors of the estuary and lower river such as outer Burrard Inlet (Levings, 1973; Macdonald and Chang, 1993), Sturgeon and Roberts banks (Gordon and Levings, 1984), tidal marsh habitat near Ladner (Levy and Northcote, 1982), and a comparison of the fish community in several tributaries (Alouette, Salmon, and Chilliwack rivers) (Hartman, 1968). The scope of this review is limited to species that are thought to be ecologically or commercially significant. It should be recognized that this is a somewhat biased approach because detailed biological data are not available for the majority of fish species present in the study area. Because of concerns for biodiversity (Harding and McCullum, 1994), it is likely that species not mentioned in detail in this paper also are important. For example, McPhail and Carveth (1993) listed 45 species of freshwater or anadromous (fish that spawn in fresh water, migrate to sea as juveniles, and then return to the river as adults) fish from the Fraser River and tributaries below the Fraser Canyon, of which ten were described as introduced and four were known from single specimens only. Gordon and Levings (1984) found 52 species of marine fish from western Roberts Bank; this is likely a minimum number because smaller individuals of noncommercial fish such as cottids were not thoroughly identified in these surveys. Unfortunately, lack of base data and detailed knowledge of Pacific estuaries in general (Levings, 1994a) make it is difficult for ecologists to pass judgment on the biodiversity of the fish communities.

GENERAL PHYSICAL AND BIOLOGICAL FACTORS INFLUENCING FISH ECOLOGY IN THE LOWER FRASER RIVER AND ESTUARY

Fish ecology in estuaries and large rivers is strongly controlled by the interaction of depth, tides, temperature, sediment type, and fluctuations in river discharge. In addition, biological factors such as predation (e.g. Tompkins and Levings, 1991) and food-web structure (Power, 1990) have likely influenced the adaptive features of individual species. Behavioural interactions and competition between different species, such as chinook salmon and stickleback (*Gasterosteus aculeatus*) (Sambrook, 1991), also may be an influence shaping fish communities. In the intertidal zone, the floodplain, and shallow subtidal regions, water levels and depths determine whether or not particular habitats are accessible by fish. For these reasons, depth and height over chart datum or lowest normal water level have been used as primary factors to describe fish habitats — low, middle, and high intertidal zones which divide the beach into biophysical units. In the north arm of the estuary and other channels in the estuary and lower river, these zones correspond to the biological zonation described in Levings et al. (1991) (Fig. 2).

The difference between water depth at extreme low tide and high tide, or tidal range, decreases as one moves upstream in the river. At the mouth of the river, the tidal range is about 5 m; it decreases to a few centimetres at Chilliwack during low river runoff. River discharge becomes a major controlling factor for water levels at upstream reaches and in tributaries. On the main stem of the Fraser River, however, habitat water depth on the river margins can be described relative to chart datum provided on hydrographic charts. The landward boundary of fish habitat on the floodplain of the Fraser River is poorly described because the extent of flooding during



1 - Agassiz
2 - Alouette River
3 - Barnston Island
4 - British Columbia Ferry Corporation Tsawwassen terminals
5 - Burrard Inlet
6 - 'Canoe Pass'
7 - Chehalis River
8 - Chilliwack River
9 - Deas Slough
10 - Duck–Barber–Woodward island complex
11 - Fraser Canyon
12 - Harrison Lake
13 - Harrison River
14 - Hatzic Lake
15 - Herrling Island
16 - Hope
17 - Iona Island
18 - Mission
19 - New Westminster
20 - North arm
21 - Pitt Lake
22 - Point Roberts
23 - Queens Reach
24 - Roberts Bank
25 - Salmon River (at Langley)
26 - Sand island (at Steveston Bend)
27 - South arm
28 - Stave River
29 - Steveston
30 - Strait of Georgia
31 - Sturgeon Bank
32 - Location of former 'Sumas Lake'
33 - Sumas Mountain
34 - 'Surrey Bend'
35 - Weaver Creek
36 - Point Grey
37 - Westham Island

Figure 1*. Map of the study area showing the locations and fish habitats mentioned in the text. As noted in the text, 'Sumas Lake' has been drained. Hope and the Fraser Canyon are located upstream of the study area.*

freshet has not been mapped. In addition, in undyked areas (e.g. the mouths of tributary areas such as Chehalis River; Fig. 1) the importance of upland regions to fish habitat (e.g. detrital production from wetland forests) has not been investigated in the Fraser River estuary (Levings, 1994b; Kistritz et al., 1996).

As in most estuaries, the food web of the lower Fraser River ecosystem is detritus-based, with much of the production derived by bacteria living on detrital organic material; this process is known as heterotrophy (Seki et al., 1988). A stylized scheme of the energy sources relative to intertidal and floodplain biota and sediments is given in Figure 3. The ultimate source of carbon in the web is a mixture of material from shoreline vascular plants (Kistritz et al., 1996), benthic

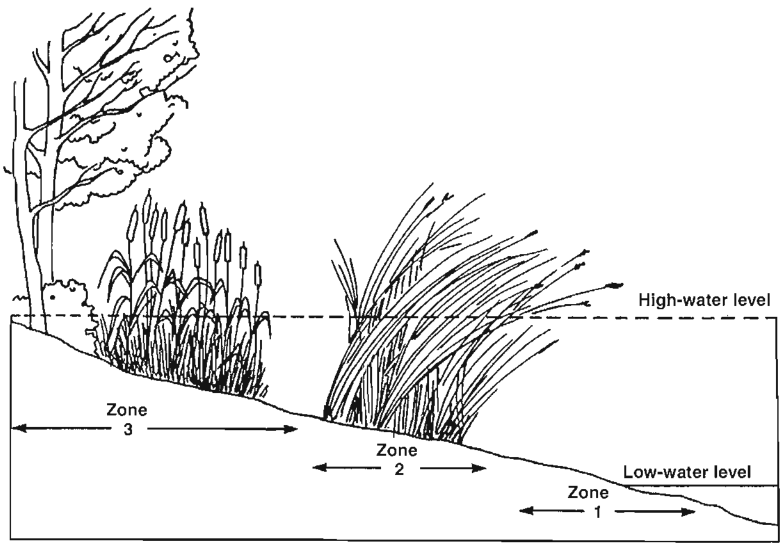


Figure 2.

*Vertical profile and zoning of brackish-water and freshwater fish habitats on the estuary of the Fraser River (Levings et al., 1991). Plants are typically riparian plants such as alder (*Alnus rubra*) and cattails (*Typha latifolia*) in zone 3, and Lyngbyei's sedge (*Carex lyngbyei*) in zone 2. Zone 1 is unvegetated sand flats or mud flats, frequently with algae such as diatoms.*

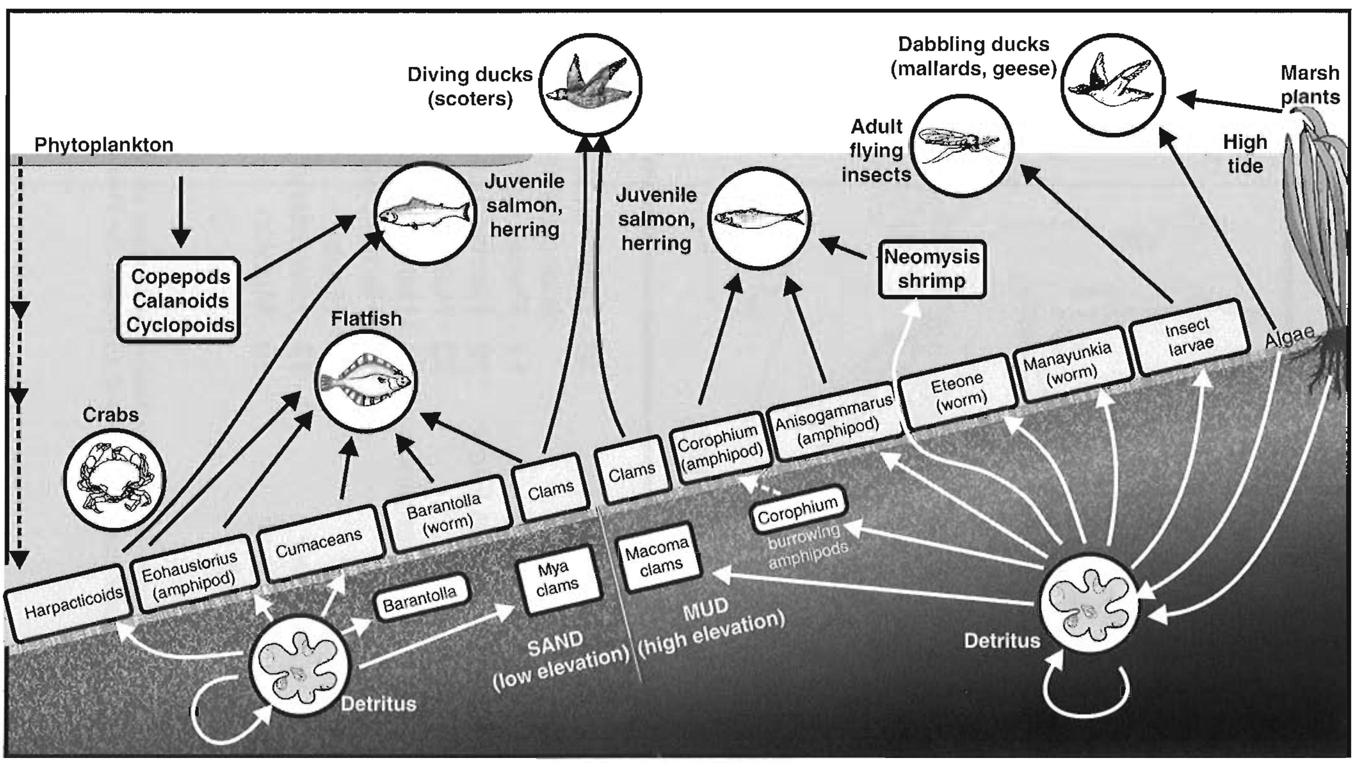


Figure 3. *A stylized version of estuarine food webs at the Fraser River estuary, depicting typical flora and fauna found along a vertical gradient from high to low tide and offshore. Detritus is the combination of decomposing plant material and bacteria fed upon by invertebrates such as bivalves, amphipods (scuds), and other crustaceans, which in turn are used as food by fish, crabs, and birds.*

algae living on the bottom substrate (Northcote et al., 1975; Pomeroy and Levings, 1980) (microphytes), and riparian vegetation living on the banks of rivers or streams (Ward et al., 1992) — very little is produced by pelagic phytoplankton, single-celled photosynthetic organism floating in water, because of light limitation in the water column of the river. An exception may be some parts of Sturgeon and Roberts banks, where carbon produced from phytoplankton may be brought onto the banks from the Strait of Georgia (Bendell-Young et al., 2004).

The supply of detritus from the estuary's shallow-water shorelines and marshes was first documented by Kistritz et al. (1983). Use of the detritus by invertebrates for secondary production in the estuary was investigated for scuds (gammarid amphipods) by Pomeroy and Levings (1980) and Levings (1994b). A comparison of the abundance of fish-food organisms such as harpacticoid copepods living on the bottom or plants growing on the banks showed that key species used as food were more abundant on Roberts Bank than on Sturgeon Bank (Bravender et al., 1993), probably because extensive beds of eelgrass (*Zostera marina*) are present in the former area. The invertebrates also are eaten by important forage fish species in the estuary, such as herring (*Clupea harengus pallasi*), sand lance (*Ammodytes hexapterus*), eulachons (*Thaleichthys pacificus*), smelt (Longfin smelt (*Spirinchus thaleichthys*) and surf smelt (*Hypomesus pretiosus pretiosus*)), which in turn are prey for vertebrate predators such as adult salmonids, marine mammals, and seabirds. Very little is known about freshwater food webs in the reaches above Chilliwack where algae attached to shoreline cobbles may be a significant carbon source; such algal growth can only occur when turbidity levels are low enough to permit photosynthesis (Richardson and Levings, 1996).

The foundation of fish-habitat management plans in the Fraser River estuary emphasizes food and refuge requirements for juvenile salmon and rests on the sustainability of vegetation on the shorelines and floodplain. For assessment and inventory purposes, vegetation is used as surrogate for high-quality fish habitat, because the abundance of fish-food invertebrates is tightly coupled with marsh-plant communities and eelgrass beds in the estuary (Bravender et al., 1993; Whitehouse et al., 1993). This coupling is the basis for the high, medium, and low ecological rating values attached to shoreline segments in the areas managed by the Fraser River Estuary Management Program (unpub. report, 1997). Although several factors such as prey shape, colour, and behaviour are known to determine the acquisition of food by juvenile salmon (Higgs et al., 1995), it is clear that abundance of a prey species is a key factor. This was shown specifically for harpacticoid copepods and chum salmon fry on Roberts Bank by D'Amour (1988). The types of invertebrate species in the lower Fraser River vary with distance from the sea, so salinity is an obvious major factor shaping the invertebrate communities. The types of prey species available to fish are, therefore, a reflection of distance upstream from the Strait of Georgia (e.g. oligochaete worms; Chapman and Brinkhurst (1981)), and this is mirrored in fish diets. For example, marine plankton, particularly harpacticoid and calanoid copepods, was important in the diet of young chinook on Roberts Bank (Levings, 1985). Because of the pervasive influence of fresh water in the surface layer in the rest of the estuary and lower river, freshwater invertebrates, especially larval and adult midges, are major food items of young chinook in the lower river areas. This has been shown by food studies for juvenile chinook on Sturgeon Bank (e.g. Levings, 1982a), the north arm (e.g. Levy et al., 1982; Levings et al., 1991), the tidal main stem river (e.g. Queens Reach; *see* below (Nishimura et al., 1995)), and the upstream reaches near Agassiz (Levings and Lauzier, 1991). As well as midges, insects with terrestrial affiliations such as bees, aphids, and springtails were eaten by juvenile chinook and chum salmon at Herrling Island and in tidal creeks or sloughs elsewhere in the lower Fraser River (Macdonald et al., 1990; Levings and Lauzier, 1991; Levings et al., 1995). Midges, mayflies, and stoneflies were dominant invertebrates in the littoral zone of the river near Agassiz (Richardson and Levings, 1996). Sockeye (*Oncorhynchus nerka*) and coho salmon fry and smolts are also dependent on insects produced on the shoreline and floodplain habitats (Birtwell et al., 1987; Levings et al., 1995).

ECOLOGY OF COMMERCIALLY AND ECOLOGICALLY SIGNIFICANT FISH

Salmon

Adult distribution and spawning habitats

Most returning adult salmon move from the Strait of Georgia and migrate upstream through the main channel of the river (south arm); however, before the main channel was trained and dykes built around the estuary islands, there were numerous distributary channels leading onto the Sturgeon and Roberts banks, and it is likely that at high tide adults moved through these channels in large numbers. The abundance and movement direction of migrating adult sockeye salmon in the trained reaches of the main river near Steveston has been related to local flow direction and velocities (Levy and Cadenhead, 1995). Channels which are still open, such as Canoe Passage, continue to be used by returning adults as migratory corridors.

Near Sumas Mountain, the sediment on the bed of the river channel and shoreline changes from sand to cobble and/or gravel. Cobble and/or gravel substrates with adequate water flow through the sediment interstices are required by salmon for spawning habitat. These substrates are used as spawning substrates by pink and chum salmon, for example between Chilliwack and Hope. The general locations of some of these spawning areas are shown in Figure 4. Chum salmon tend to use side channels and pink salmon mainly spawn in mid-river. The largest wild chinook salmon population in British Columbia spawns in the Harrison River (Fig. 1). Over the period 1984–1993, an average of 116 000 chinook spawned there (Fraser River Action Plan, unpub. report, 1995). A significant sockeye salmon population once spawned in this reach of the Harrison River, but the average in recent years is about 7000 fish (Department of Fisheries and Oceans, unpub. data, 1995). A major sockeye stock uses Pitt

River and Widgeon Slough for spawning, and this tidal lake is an important rearing area for this stock (Henderson et al., 1991). Numerous smaller tributaries in the lower reaches support spawning coho salmon, but downstream of Langley many of these streams have been destroyed by urbanization or drainage (Department of Fisheries and Oceans, unpub. map, 1996). Access to several of the larger rivers was partially or completely blocked by dams (e.g. Stave and Alouette rivers) and railways (e.g. Hatzic Lake and tributaries). In some instances, such as 'Sumas Lake', the entire lake was drained. Some of the loss of spawning habitat has been partially redressed by construction of artificial spawning channels for sockeye (e.g. Weaver Creek, tributary to Harrison River) or developed side-channel habitat for chum (e.g. Chehalis River mouth; Bonnell (1991)). Baseline quantitative data on the area of spawning gravel for various species in the lower Fraser River and tributaries are not published; however, Palmer's (1972) data enabled an estimate of about 42.5 ha for chum spawning habitat in the lower Fraser River and tributaries in 1968 (Table 1).

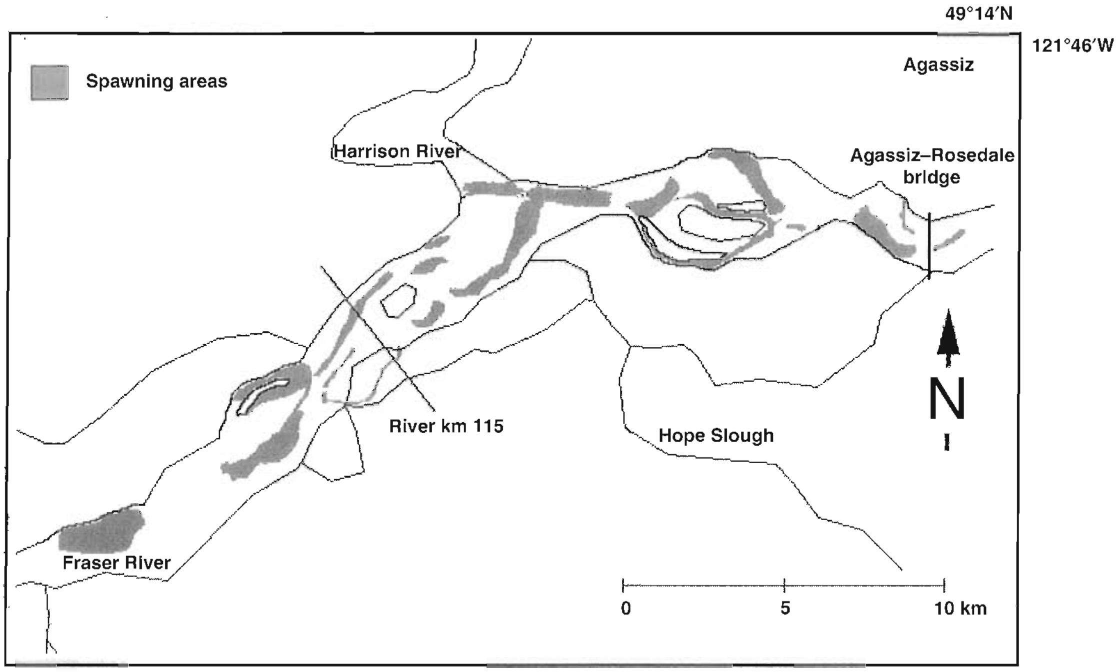


Figure 4. General location of spawning beds for pink and chum salmon (species combined) in the Fraser River between Rosedale and Herrling Island (digitized from an unpub. map developed by Department of Fisheries and Oceans and the International Pacific Salmon Fisheries Commission in 1961. The spawning beds were in the same general areas in 1996; Department of Fisheries and Oceans, unpub. data, 1996). This reach is upstream of the point where the river bed changes from sand to cobble and/or gravel. The cobble and/or gravel areas on the river margins in this reach also are used as winter habitat for juvenile chinook salmon (Levings and Lauzier, 1991).

Table 1. Estimates of natural spawning habitat for chum salmon available in the Fraser River below Hope in 1968 (data from Palmer, 1972). Areas estimated from the number of spawners were computed assuming each female fish required 0.4 m^2 to build a spawning nest.

Spawning ground	Area (m^2)	Comments
Harrison and Chehalis rivers	131 250	Measured
Squakum Creek	5850	Measured
Weaver Creek	8360	Measured
Stave River	62 700	Measured
Inches Creek	4180	Measured
Vedder River system	75 990	Estimated from spawner count
Fraser River, main stem	114 030	Estimated from spawner count
Minor tributaries of the Fraser River	22 820	Estimated from spawner count

Juveniles and rearing habitat

Distribution and influencing factors

The first survey of juvenile salmon in the estuary was conducted in 1971 on Sturgeon and Roberts banks by Goodman (1975) during impact assessment studies for proposed expansion of the Vancouver International Airport. Juvenile chinook, chum, pink, and coho salmon were sampled with a surface trawl and were found to be widespread over both Sturgeon and Roberts banks. There have been several more localized abundance surveys in more recent years. These have focused on the habitats between the British Columbia Ferry Corporation and Westshore Terminal Ltd. causeways (Levings et al., 1983; Macdonald, 1984; Levings, 1985), a low-tide embayment on western Sturgeon Bank (Levings, 1982a), and the vicinity of the Iona Island sewage outfall (Gordon and Levings, 1984; Nishimura et al., 1996).

Juvenile salmon, especially chinook, were found on Sturgeon and Roberts banks at low, middle, and high intertidal habitats (Goodman, 1975). This species appears to concentrate in low-tide refuges during extremely low tides (Levings, 1982a). While it is not known how far off the banks the fish move during a given tide cycle, there may in fact be considerable onshore-offshore movement. Numerous times each spring and summer, when Sturgeon and Roberts banks are almost completely dry during tides less than 0.5 m over chart datum, juvenile salmon move into habitats which remain watered during these periods (Levings, 1982a). Temperatures may be lower in these refuges relative to the main banks because these features hold water masses connected with the cooler waters of the Strait of Georgia (Gordon and Levings, 1984). Thus, elevations of the sand flats give an important index of fish habitat, yet there are very few recent data on intertidal surface topography. Recent data are important because the elevations of the sand flats and channels can vary significantly over relatively short time periods. Exceptions to this are the detailed elevation data provided for Sturgeon Bank by Feeney et al. (1994).

Water quality is also an important concern in the estuary as juvenile salmon undergo acclimation in the estuary, and they are adapting to gradually move from fresh to brackish conditions before completing physiological adaptation to life in seawater and moving to the Strait of Georgia. For example, dissolved oxygen was an important physico-chemical factor affecting distribution of juvenile salmon while the Iona Island sewage plant discharged waste water onto Sturgeon Bank. The decomposing sewage imposed a biological oxygen demand on the water masses, leading to decreased levels of dissolved oxygen. Mesa (1985) showed that juvenile chinook were less abundant in areas of low dissolved oxygen. The young salmon were under stress and more susceptible to bird predation, especially at low tide when water temperatures rose with a concomitant decrease in oxygen saturation of the water. As of 1988, the effluent has been discharged at 100 m off Sturgeon Bank, which led to an improvement in sediment and water quality and fish-habitat conditions in the formerly affected part of Sturgeon Bank (Nishimura et al., 1996).

Residency, feeding, and growth

Chinook salmon Chinook fry begin to appear on the main stem river shorelines in early March, have been caught as late as August, and are undergoing a rearing migration as they move downstream from the spawning grounds. The seasonal pattern of catches of juvenile salmon in the lower river and estuary suggests that many, perhaps most, juvenile chinook salmon residing in these areas are progeny of the large Harrison River stock. Chinook fry leave the Harrison River within one or two weeks after hatching. This wave of fish appears to move into Fraser River habitats below the confluence with the Harrison River in a week or two (Fig. 5). Chinook fry

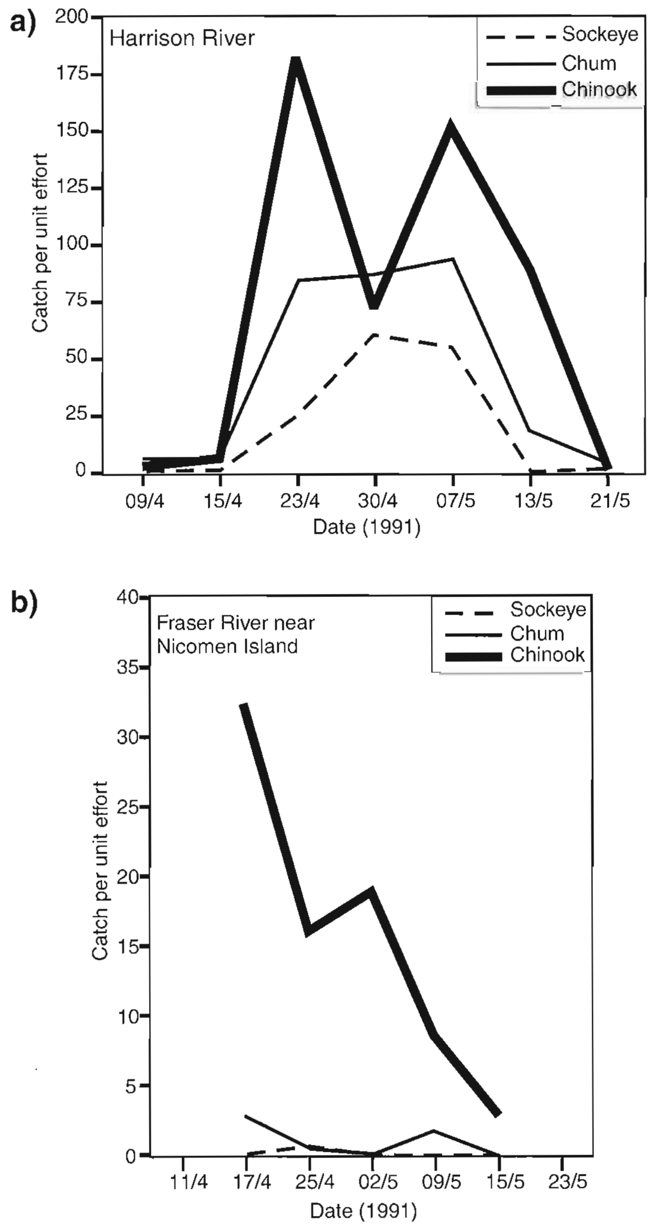


Figure 5. *Seasonal changes of juvenile sockeye, chum, and chinook salmon fry catches by beach seine* ***a)*** *in the Harrison River and* ***b)*** *on the main stem Fraser River (Nicomen Island, near Sumas Mountain, below the confluence of the Harrison and Fraser rivers)* (data from *Gregory et al., 1993).*

and/or smolts can be found on the Sturgeon and Roberts banks between March and late August, as documented in a number of studies (e.g. Levings, 1985).

More chinook fry may be reared on Sturgeon Bank, characterized by brackish water (<10‰) (Gordon and Levings, 1984), as this life history stage is adapted to the relatively low salinities found there. As they undergo adaptation to life in seawater and grow larger (Levings, 1985), the young chinook may move offshore to the Strait of Georgia or westward to Roberts Bank. Salinities are higher in the intercauseway area on western Roberts Bank because the Westshore Terminal Ltd. causeway inhibits the movement of river water to this part of the estuary. Short-term marking experiments with chinook fry on Sturgeon Bank showed that individual fish resided in low-tide refuges for at least two days (Levings et al., 1983). Radiotagged chinook smolts moved downstream through the Fraser River from Mission to New Westminster at an average speed of 2.3 km/h (Hvidsten et al., 1996). Chinook fry appear to live all winter in cobble shorelines above Chilliwack. Chinook fry were found by Levings and Lauzier (1991) in these habitats near Herrling Island, for example, between October and March.

The ecology of juvenile salmon rearing in the Duck–Barber–Woodward island complex was documented in a series of studies summarized in Levy et al. (1979), which showed that the morphology of tidal channels (i.e. depth, gradient, side slope, etc.) was an important determinant for juvenile salmon abundance. Data from this island complex showed that individual chinook fry remained in freshwater habitat for up to 30 days (Levy and Northcote, 1982). Some of the chinook fry in the Duck–Barber–Woodward island complex may undergo short-term migrations between the islands and the intertidal banks, but marking experiments have not been conducted to verify this. Upstream of New Westminster, fry are widely distributed in sloughs, side channels, and the mouths of tributaries (e.g. Brunette River; Murray and Rosenau (1989)). Tidal creeks are also important rearing areas in these reaches; chinook fry were found up to 1.5 km off the Fraser River main stem in a wetland area on the south side of the river at Surrey, locally known as 'Surrey Bend' (Levings et al., 1995).

Juvenile chinook salmon on Sturgeon and Roberts banks ate a wide variety of prey ranging from brackish-water invertebrates such as shrimp and scuds (mysids and gammarid amphipods) on Sturgeon Bank (Levings, 1982a) to herring and marine calanoid copepods on Roberts Bank (Macdonald, 1984). Freshwater and brackish-water invertebrates were major food items farther upstream in the estuary. Table 2 summarizes some previously unpublished data on stomach contents of chinook fry and smolts caught by surface trawling at least 50 m offshore, in the pelagic environment at Queens Reach. These data show that invertebrates such as chironomids, originating from vegetated shoreline habitats, were the most abundant organisms in the fish stomachs. Relatively few organisms produced in the water column of the river, such as cyclopoid or calanoid copepods, were used as food.

Table 2. Dominant types of invertebrates observed in stomachs of young chinook salmon caught by surface trawl at Queens Reach in spring 1988. Numbers in the table are percentages of stomach contents (numerical data) accounted for by each insect taxon. Fry: less than 50 mm length; smolts: more than 50 mm length (*data from* Nishimura et al., 1995).

Type of invertebrate	Fry (271 examined)	Wild or hatchery smolt (256 examined)	Hatchery smolt (23 examined)
Unidentified adult dipterans	1.83	4.71	1.95
Unidentified larval dipterans	1.70	1.31	0.31
Chironomid larvae	41.27	17.02	8.77
Chironomid pupae	11.54	0.00	6.35
Chironomid adults	11.86	10.21	17.50
Ceratopogonid larvae	1.05	0.00	0.44
Ceratopogonid adults	0.15	2.36	0.84
Unidentified Emphemeroptera nymphs	1.94	13.87	1.38
Heptageniidae nymphs	3.05	0.00	2.06
Unidentified Homoptera adults	1.17	10.99	5.71
Cicadellidae adult	0.24	0.0	1.83
Psyllidae adult	0.27	0.0	3.57
Hymenoptera adult	0.09	6.02	0.58
Plecoptera nymphs	0.78	7.33	1.89
Plecoptera adults	0.18	1.83	0.29
Psocoptera adults	0.0	3.14	0.09
Unidentified Trichoptera adults	0.09	4.97	0.12
Unidentified Hydropsychidae larvae	0.18	0.00	1.21
Collembola adults	1.91	0.79	0.32
Cladocera	1.37	0.00	11.58
Arachnida	0.42	3.93	1.55
Unidentified insecta	4.31	1.84	16.75
Nematoda	0.06	1.31	1.54
Coleoptera	0.03	1.05	0.97
Hemiptera	0.00	0.00	2.23

Chum salmon. Until recently, the downstream migration of chum fry was monitored each year by trapping at Mission, usually showing peak numbers in April. Their rearing migration through the lower reaches may take between 3 days and 16 days (Levings and Tompkins, 1985) with the variation possibly related to river discharge. Marking experiments in the Duck–Barber–Woodward island marshes indicated residence time of up to 11 days (Levy and Northcote, 1982), and at least 2 days in Deas Slough (Burger and Nishimura, 1996). Chum fry began to use the bank habitats in March and were caught until about May or June (Gordon and Levings, 1984; Macdonald, 1984). Fish caught later in spring may have been fish that had been rearing in the Strait of Georgia that had moved onto the banks at high tide. Marking experiments with chum fry were conducted on Roberts Bank and indicated residency of individual fry in the order of 1–3 days (Levings et al., 1983). At high tide, Macdonald (1984) found that juvenile chum were more widespread in the intercauseway area relative to other salmon species and were found throughout the intertidal zone (Fig. 6).

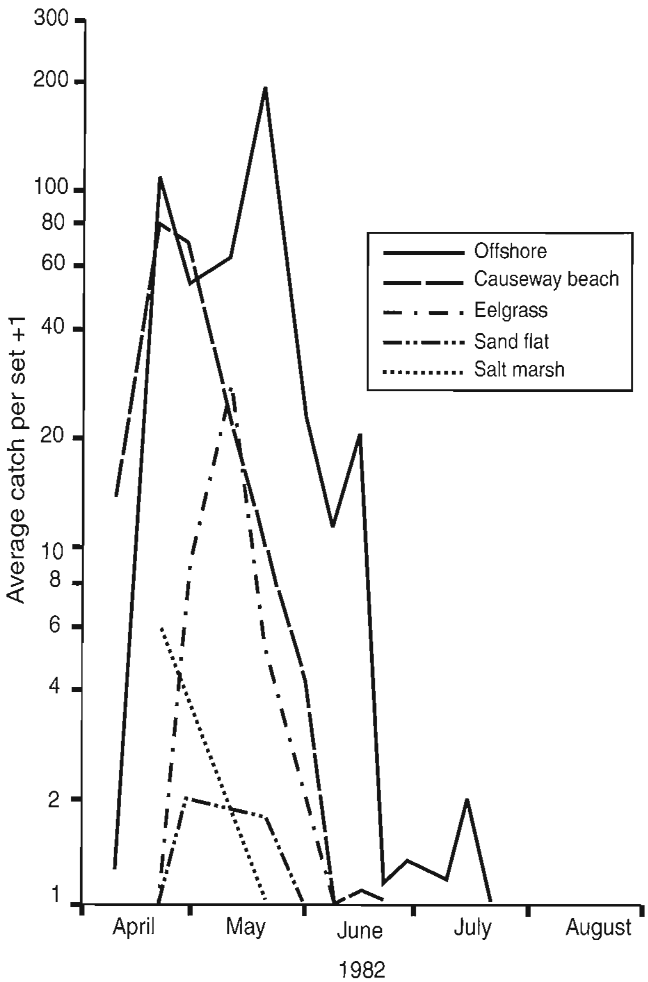


Figure 6. Seasonal change in catch pattern of chum fry caught by beach seine in various habitat types in the intercauseway area on Roberts Bank (Macdonald, 1984). The five zones indicated are from near low-tide level (offshore) to the high-tide limits (salt marsh).

Pink salmon Pink salmon fry move through the lower river and estuary quickly and do not reside in the study area for substantial periods (Levy and Northcote, 1982). There may be some movement of this species from the Strait of Georgia onto Roberts Bank (Gordon and Levings, 1984).

Sockeye salmon Very little is known about the ecology of juvenile sockeye salmon in the lower river. The fry appear to move through Queens Reach between May and June (Fig. 7), and in 1988 were more abundant on the north side of the river, possibly because they were moving out of the Pitt River. It is also possible that hydrological conditions such as current directions and speed were directing fry to the north shore. The origin of sockeye fry rearing in tidal freshwater habitats (e.g. 'Surrey Bend'); Levings et al. (1995)) and estuarine sloughs (e.g. Deas Slough; Birtwell et al. (1987)) is not known. Some of the fry may originate from a stock spawning in Pitt Lake, but most of the fry from this particular stock are thought to be reared in the lake (Henderson et al., 1991). All of the sockeye smolts produced in the entire Fraser River watershed must pass through the estuary on their way to the sea, and this produces a massive pulse of fish over a short period of time, depending on stock strength and freshwater survival. Peak migration of young sockeye through Queens Reach in 1988 was between April and June, mainly on the south side of the river (Fig. 7).

Coho salmon This species usually uses freshwater habitat for one year before smolting and migrating to the sea. As far as is known, the main stem of the Fraser River is not a major rearing habitat for coho fry; however, a few coho fry were caught on the main stem in Queens Reach (Levings, 1994b). Coho fry were observed in side-channel habitat near Herrling Island (Levings, unpub. data, March 9, 1984) and in tidal creeks near 'Surrey Bend' (Levings et al., 1995), but these were likely progeny of coho spawning locally. Hatchery-reared and wild coho smolts from numerous tributaries move to the ocean through the lower river. In 1993–1994, Richardson et al. (2000) found that coho juveniles (life stage not identified) were more abundant in the lower river relative to 1972–1973. Coho smolts were reported from Roberts Bank by several authors (e.g. Levings et al., 1983; Macdonald, 1984).

Steelhead and cutthroat trout

Steelhead

Little is known about the ecology of returning adult steelhead, but this species migrates through the lower river in late fall and winter. Steelhead spawn in some of the major tributaries in the lower river (e.g. Alouette River; Hartman (1968)). Rearing habitat is particularly important for this species because young steelhead rear for 2 or 3 years in tributary habitats (Hartman, 1968). Several of these tributaries have been degraded by urbanization, water diversion, and withdrawals that affected productivity of this species. The mainstem Fraser River from Agassiz to the estuary does not appear to be used by juveniles for rearing.

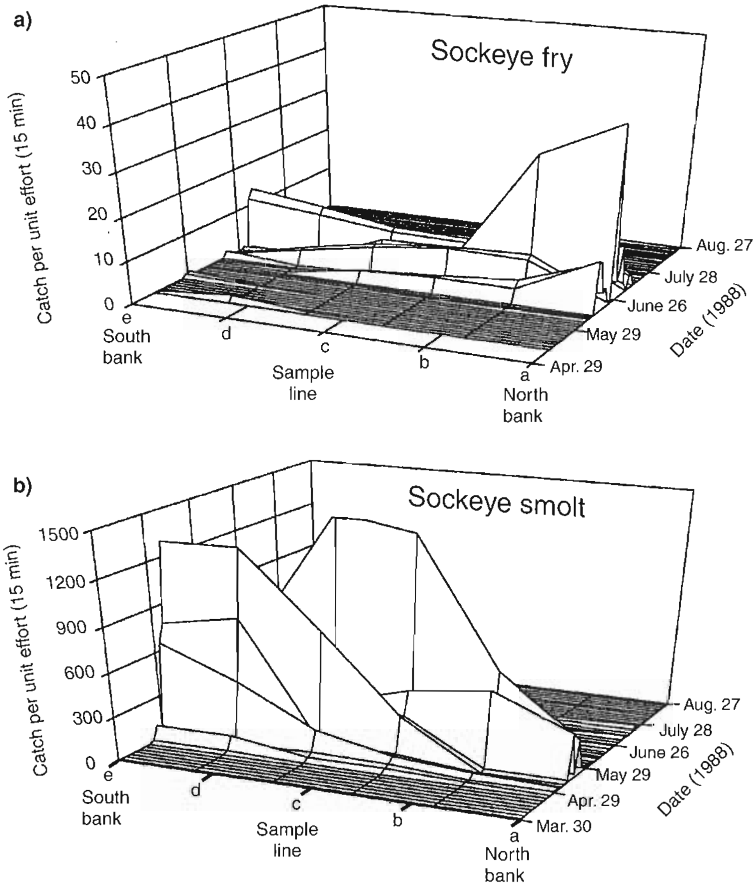


Figure 7.

***a)** Sockeye fry and **b)** smolt catches from surface trawling (standardized 15 minute tow) at Queens Reach, spring 1988. The trawl net was towed upriver on five transects parallel to shore. Transects a and e were approximately 50 m from the north and south bank, respectively; transects b, c, and d were spaced at approximately 100 m intervals* (data from *Whitehouse and Levings, 1989).*

Cutthroat trout

This species uses a wide variety of habitats in the lower Fraser River. Small streams, larger tributaries, the main-stem Fraser River, and the estuary are used for spawning and rearing. The nonanadromous form completes its total life cycle within first- or second-order streams, and the loss of these habitats, owing to urbanization (Department of Fisheries and Oceans, unpub. map, 1996), has led to the extinction of numerous stocks. Anadromous cutthroat trout also spawn in tributary streams, as well as on gravel bars of both main-stem (author's pers. observations, May 2, 1991) and slough habitats (author's pers. observations, March, 1958) in the reaches near Nicomen Island.

Herring, smelts, and their relatives

Herring

There may be some herring spawn deposited on eelgrass at Roberts Bank, but abundance has been so low in recent years that Department of Fisheries and Oceans herring-spawn observers no longer assess the area. Spawning still occurs regularly on Point Roberts and at Boundary Bay (Hay et al., 1989). There is no active commercial fishery in the estuary for herring, although decades ago there was a stock at Point Grey that was harvested (Williamson, 1930).

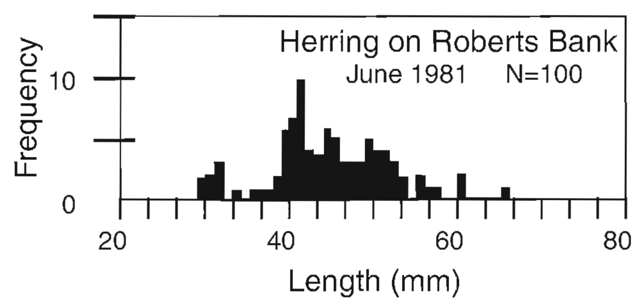


***Figure 8.** Length composition of juvenile herring caught in beach seines in the intercauseway area, Roberts Bank. As virtually no herring spawn on Roberts Bank, it is likely these young fish are from spawning populations on Point Roberts, or possibly the southern Gulf Islands (Levings, 1983).*

Juvenile herring were recorded from beach-seine and surface-trawl surveys conducted on Roberts and Sturgeon banks (e.g. Goodman, 1975; Greer et al., 1980; Gordon and Levings, 1984; Macdonald, 1984). Juvenile herring were usually more abundant on Roberts Bank, probably because this marine species has adapted to the higher salinity oceanographic regime of this bank. The stock origin of the juvenile herring in the estuary is not known; however, judging from size data (Fig. 8), Levings (1983) speculated they may be the progeny of fish that spawned on Point Roberts or the southern Gulf Islands. Judging from size changes in juvenile herring on Roberts Bank (Macdonald, 1984) over the spring-summer period, growth occurs in the estuary. It is likely that some of this growth occurs in the Strait of Georgia as the herring move between the intertidal zone on the banks and the pelagic area offshore. Macdonald (1984) found that juvenile herring caught in beach seines on western Roberts Bank were smaller than those from the stomachs of juvenile chinook salmon sampled at the same time, indicating size-selective predation. The feeding habits of juvenile herring in the estuary are not well known. Levings (1983) found that harpacticoid copepods were major items in herring stomach contents from Roberts Bank, indicating the linkage between herring and detritus via the food web, as shown in Figure 3.

Longfin and surf smelt

These are two species of smelt which migrate upstream through the lower Fraser River (Whitehouse and Levings, 1989; McPhail and Carveth, 1993). The longfin smelt has a resident population in Harrison and Pitt lakes. The surf smelt is pursued in an important recreational fishery in Burrard Inlet (Levy, 1982).

Sand lance

This is one of the most important forage species for adult salmon and other fish in the Strait of Georgia. The species was abundant in beach seines on Sturgeon and Roberts banks (Gordon and Levings, 1984). The sand lance uses outer Sturgeon Bank as a habitat; individuals of this species were dug from sand in the lower intertidal zone in February, 1992 (Levings, unpub. data, 1992).

Eulachon

This anadromous fish is one of the most abundant forage species in the lower river and estuary. During their upstream migration in the spring, eulachons are eaten by numerous species of seabirds, marine mammals, and fish (Rogers et al., 1990), and are also culturally significant to First Nations people (Drake and Wilson, 1992). Trawling data from Queens Reach showed adult eulachon were most abundant in the latter half of April and catches tended to be higher on the north shore of the river (Fig. 9). Spawning occurs in shallow water (<2 m) on sandy substrates up to 175 km upstream from the mouth of the Fraser River (Samis, 1977). Eulachon spawning success may, therefore, be sensitive to changes in substrate characteristics. After hatching, eulachon larvae drift downstream to the Strait of Georgia. Larval fish were abundant in plankton tows made in the river's bottom water, in the salt wedge near Steveston, and many of them likely were eulachon (Levings, 1980a).

Flatfish

Several species of flatfish have been caught in the estuary by various workers (e.g. Greer et al., 1980; Gordon and Levings, 1984), including sand dabs (*Citharichthys* spp.), representatives of the left-handed flounders (family Bothidae). The

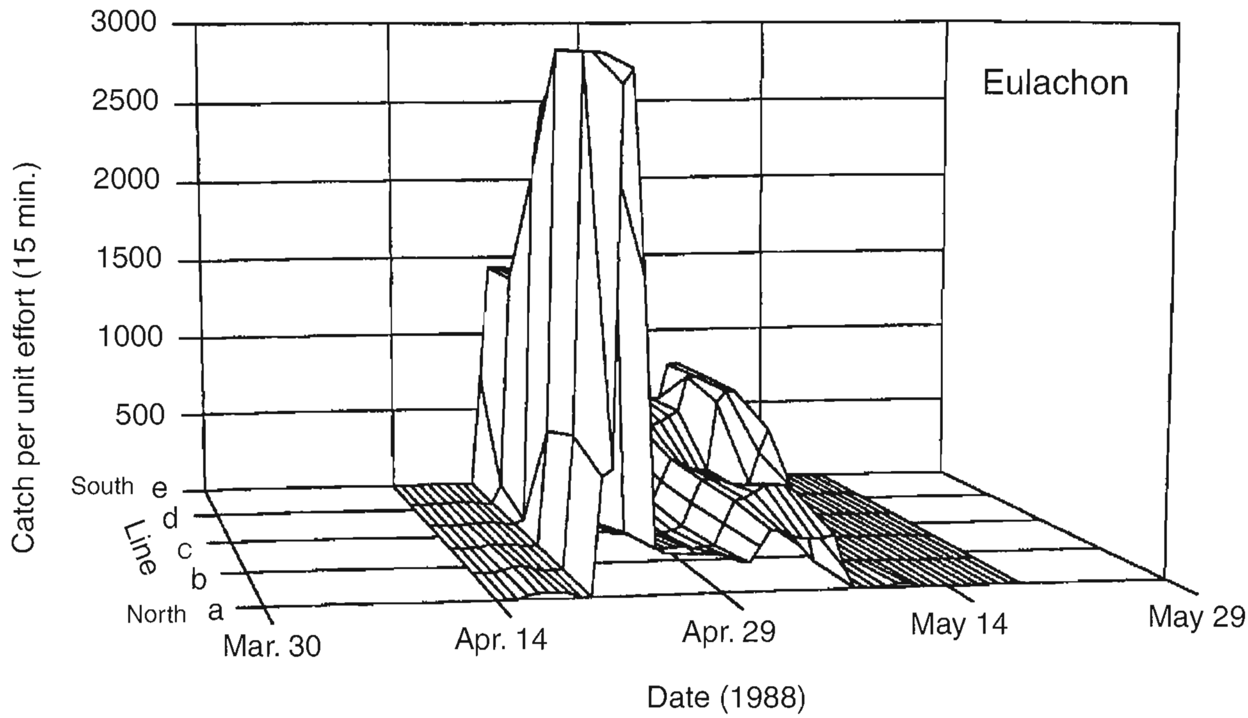


Figure 9. *Eulachon catches from surface trawling (standardized 15 minute tow) at Queens Reach, spring 1988. The trawl net was towed upriver on five transects parallel to shore. Transects a and e were approximately 50 m from the north and south bank, respectively; transects b, c, and d were spaced at approximately 100 m intervals (*data from *Whitehouse and Levings, 1989).*

other species are members of the Pleuronectidae, the right-handed flounders. More species of flatfish have been caught on Sturgeon and Roberts banks relative to the rest of the estuary, probably because most species of this marine fish taxa are adapted to the higher salinities characterizing these areas. English sole (*Pleuronectes vetulus*) and starry flounder (*Platichthys stellatus*) are the two most abundant species of flatfish in the estuary, with English sole more common on Roberts Bank relative to other areas of the estuary (Gordon and Levings, 1984). Both starry flounder and English sole were harvested by trawlers in the Strait of Georgia, including the Fraser River estuary, in the 1960s and earlier (Forrester and Ketchen, 1964), but stocks have declined significantly since then.

Because of the potential use of starry flounder as a sentinel species to detect contaminants, there have been a number of recent detailed studies on their ecology. Starry flounder are widely distributed and have been found on both Roberts and Sturgeon banks and upstream as far as Mission (Northcote, 1974; Nelson et al., 1994). Juvenile starry flounder were more abundant in the intertidal zone of the lower estuary and river. More adult and sexually mature fish were caught in the bottom waters of the river channels. These fish likely move to the Strait of Georgia for spawning in winter (Burger, 1995). The abundance of starry flounder was related to sediment type, as otter-trawl catches were higher on sand relative to mud substrates (Burger, 1995). Sand waves of up to 1.5 m have been reported in the Fraser River channels (Kostaschuk and Luternauer, 2004), so this species must be adapted to dynamic changes in the benthic habitat. The home range and migration rates of starry flounder were investigated using ultrasonic and radio tags on Sturgeon Bank, in the north arm, and in the vicinity of Barnston Island. Results showed that both adult and juvenile fish (>10 cm) moved about 500 m in 24 h. Although 237 starry flounder were tagged in the lower river with conventional external tags, none were recaptured during trawling or beach seining. The radio tagging showed that juvenile starry flounder moved downstream from Barnston Island in a unidirectional migration in March (Fig. 10; Nelson and Alexander (1995)), whereas more mature individuals, tracked using ultrasonic tags, showed more upstream and downstream movements (Nelson et al., 1994).

The growth rate of starry flounder from Sturgeon Bank and the lower Fraser River was determined from otolith analyses (otoliths are calcium deposits in the inner ear of fish; rings of protein are deposited in the otoliths each year, enabling age estimates to be done on the fish); on average, starry flounder reach about 9 cm in their first year. The oldest

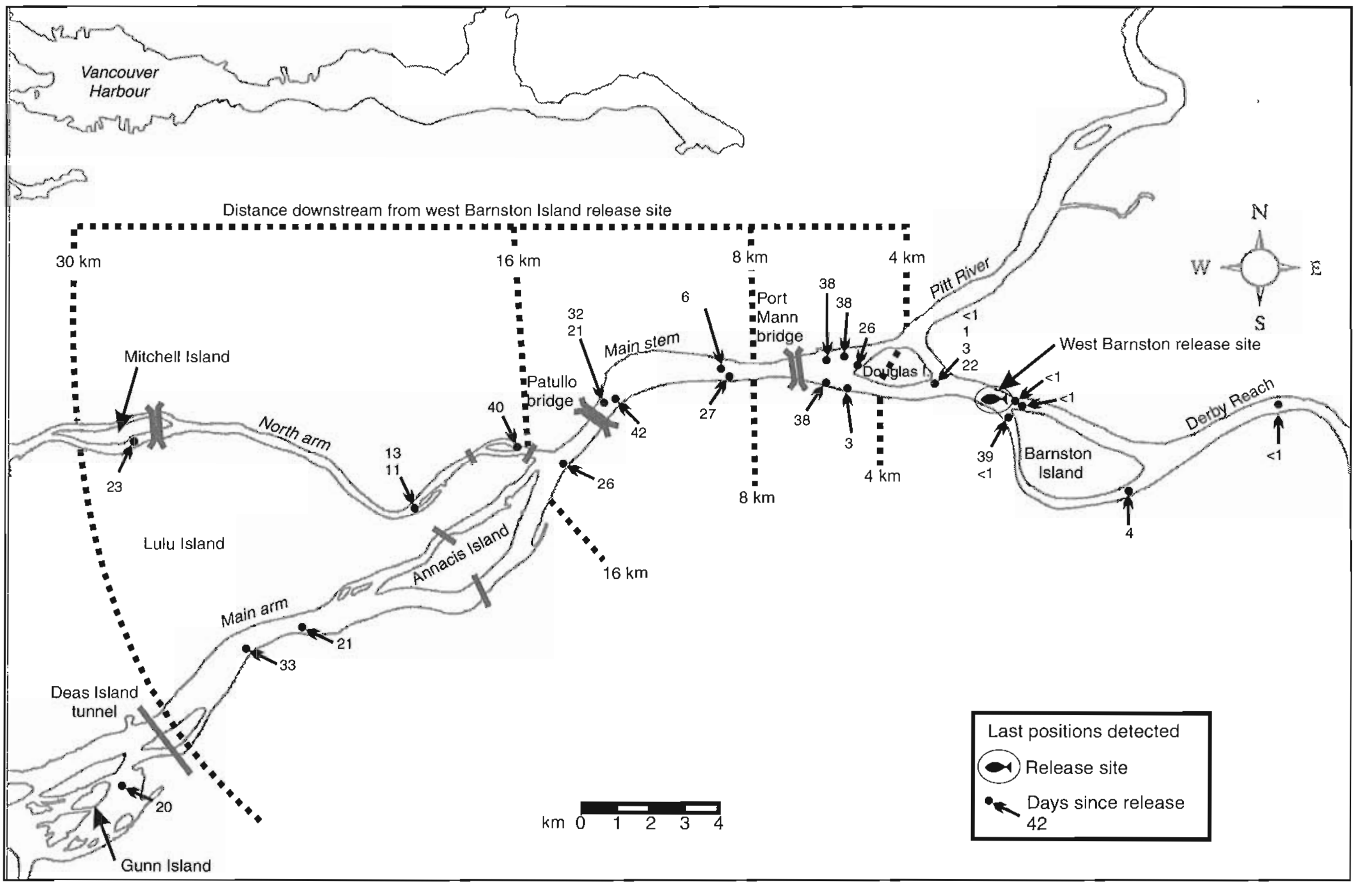


Figure 10. Migration routes for starry flounder in the lower Fraser River in February and March 1994. The fish were equipped with radio tags, released near Barnston Island, and then tracked by fixed or mobile radio signal receivers (Nelson and Alexander, 1995).

fish reported in the data set was over 9 years old. Starry flounder in tidal freshwater habitats near Barnston Island ate almost exclusively chironomid larvae, whereas fish from the brackish reaches in the north arm fed on polychaetes, amphipods, and bivalves (Fig. 11).

Cyprinids (minnows), Catostomids (suckers), and other freshwater species

Beach-seine catches in the lower Fraser River are frequently dominated by members of the minnow family, which is represented by nine species (McPhail and Carveth, 1993). As an example, Table 3 gives a summary of beach-seine data from the Herrling Island area, showing that dace (*Rhinichthys* spp.) and peamouth (*Mylocheilus caurinus*) accounted for about 63% of the fish caught in surveys during spring and summer 1987. Carp (*Cyprinus carpio*), black crappie (*Poxomis nigromaculatus*), and brassy minnows (*Hypognatus hankonsoni*) are found in the lower river, particularly in off-channel habitats such as sloughs. Carp and black crappie were introduced from elsewhere in the world and are outside their natural range. In general, cyprinids are less abundant on Sturgeon Bank and are rare on western Roberts Bank, as almost all members of the group are not tolerant of salt water. An exception is the peamouth, which is known to have some osmoregulatory abilities (Clark and McInerney, 1974) and may have colonized some lakes on Vancouver Island by migrating in the Fraser River plume, which can extend to the island's shorelines during freshet. The most common species of sucker in the lower Fraser River is the large-scale sucker (*Catostomus macrocheilus*) (McPhail and Carveth, 1993). Populations of this species appear to be relatively stable in the lower Fraser River as there was little difference in the density of large-scale sucker populations between 1972–1973 and 1993–1994 (Richardson and Healey, 1996).

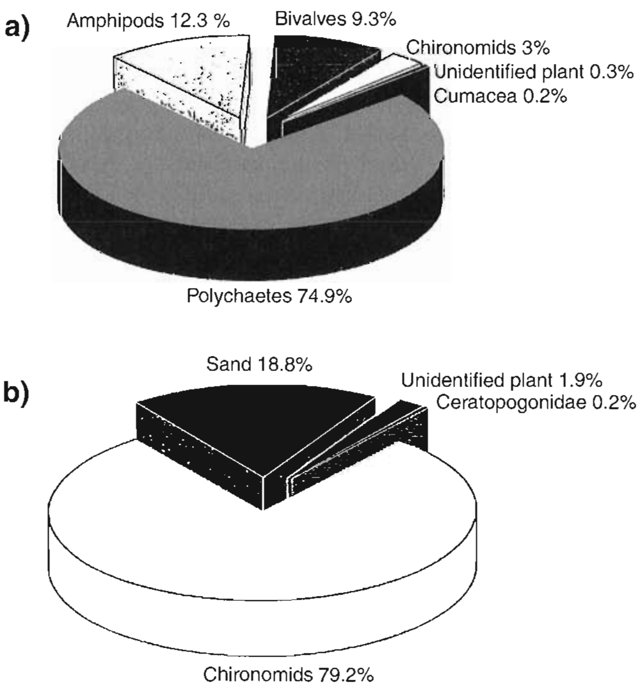


*Figure 11. Stomach contents of starry flounder caught by otter trawl **a)** in the north arm (brackish habitat) and **b)** near Barnston Island (freshwater habitat) (Burger, 1995). Data are based on a relative importance index. Stomach contents in the freshwater habitat were dominated by insect larvae, but fish in the brackish area consumed a variety of marine and estuarine invertebrates such as polychaete worms and amphipods (scuds).*

Table 3. Per cent abundance of various fish species caught in beach seines between June and September 1987 near Herrling Island, lower Fraser River (*data from* Brown et al., 1989). Only species accounting for at least 1% of the total catch (5109 fish) are shown.

Species	Percentage of catch
Sockeye fry and smolts	1.3
Chinook fry and smolts	14.0
Peamouth	5.3
Northern pike minnow	1.6
Long nose dace	35.5
Redside shiner	27.6
Bridgelip sucker	3.0
Prickly sculpin	2.8

There are very few specific data on residency, feeding, or rearing of any minnow, sucker, or other freshwater fish species in the lower Fraser River. Bartnik (1973) mentioned that peamouth spawned in the Alouette River. Northcote et al. (1979) showed that the diet of cyprinids such as peamouth and redside shiners was dominated by insects. Leopard dace (*Rhinichthys falcatus*) and longnose dace (*Rhinichthys cataractae*) also fed on aquatic insects, but the latter species preferred habitats characterized by faster flowing water (Gee and Northcote, 1963). The only recently published data on feeding of a cyprinid in the lower Fraser River are from diet studies of northern pike minnow (*Ptychocheilus oregonensis*) in the Chilliwack area. Gregory and Levings (1998) showed that this species primarily fed on fish, including juvenile salmon and cottids.

The Salish sucker (*Catostomus* sp.) and the Nooksack dace (*Rhinichthys* sp.), both reported from streams on the Fraser River floodplain, may be endangered species. The Salish sucker has been reported only from headwaters of the Salmon River, near Langley. Both the Salish Sucker and the Nooksack dace were listed as species of regional concern by McPhail and Carveth (1992). These authors stated that excessive siltation in small streams, sometimes caused by land clearing and construction during urbanization, is the greatest threat to the continued existence of these species.

Sticklebacks

Sticklebacks are one of the most abundant fish in the estuary, reaching densities of 20 fish/m^2 in the side channels of the Duck–Barber–Woodward island complex area in spring (Sambrook, 1991). Peak abundance of sticklebacks on Sturgeon and Roberts banks was observed in the autumn (Gordon and Levings, 1984). This species is represented in the lower

Fraser River by an anadromous and a nonanadromous form which are genetically distinct (McPhail and Carveth, 1993). Sticklebacks spawn in vegetation such as marsh plants and therefore are one of the fish species in the lower river (e.g. Salmon River at Langley; Virgil and McPhail (1994)) and estuary that are tightly linked to vegetation.

Sculpins

Staghorn sculpin (*Leptocottus armatus*) were the numerically dominant sculpins on Roberts and Sturgeon banks in survey data reported by Gordon and Levings (1984); however, their data do not include some of the abundant marine sculpins such as *Oligocottus* sp. that are difficult to identify in the field. Staghorn sculpin also are found in the inner estuary, but the dominant sculpin in the tidal freshwater reaches of the river is prickly sculpin (*Cottus asper*) (McPhail and Carveth, 1992). Little is known of the life history and ecology of either of these species in the Fraser River, but both are known to feed extensively on insects and crustaceans (Northcote et al., 1979). The prickly sculpin also is known as a predator of juvenile chum salmon, and according to Jones (1986) may influence chum salmon population dynamics.

Other anadromous species

White sturgeon

White sturgeon (*Acipenser transmontanus*) live in channel habitats of the river and estuary and are rarely caught in the intertidal zone. The white sturgeon is the largest fish species occurring in the lower Fraser River and estuary — the largest recorded fish caught weighed about 636 kg. There is great interest in the ecology of this species, especially since 1993 and 1994 when over 30 very large dead sturgeon (up to 4 m length) were found on beaches between Roberts Bank and Lillooet (Glavin, 1994). The causes of these deaths are not known. The white sturgeon is the only estuarine fish species in Canada to be listed in *1996 IUCN (International Union for the Conservation of Nature) Red List of Threatened Animals*, indicating the 'threatened' status of the species. This species is the oldest and slowest growing fish in the lower Fraser River, with large specimens aged well over 100 years. Basic data on growth rates, feeding, a history of the fishery, and data on distribution in the lower Fraser River are given in Semakula and Larkin (1968), Northcote et al. (1978), and Echols (Echols, 1995). Perrin et al. (2003) recently described the spawning habitats of white sturgeon in the lower Fraser River. Subadult white sturgeon appear to prefer off-channel habitats (such as Hatzic Slough) during the late spring and summer (E.D. Lane and M.L. Rosenau, unpub. report, 1992). White sturgeon feed on benthic organisms including insect larvae. Lamprey are used as bait for this species of white sturgeon in the sports fishery.

Lampreys

Three species of lamprey occur in the lower Fraser River and its tributaries, namely the Pacific lamprey (*Entosphenus tridentatus*), the western brook lamprey (*Lampetra richardsoni*), and the river lamprey (*Lampetra ayresi*). The juvenile stages of the Pacific lamprey, known as ammocoetes, are very abundant in the sand substrates in the intertidal and channel habitats of the river. Based on surface trawl catches in spring 1988 at Queens Reach, Beamish and Levings (1991) estimated that three million juvenile Pacific lamprey migrated to sea through the lower Fraser River. The western brook and river lamprey live in the smaller tributaries of the lower river. Pacific lamprey spawn in tributaries above Hope (Beamish and Levings, 1991). Ammocoetes, young lamprey larvae in freshwater, rear in the substrates throughout the lower Fraser River or their spawning river and after several years become physiologically prepared for life in the sea. They then move downstream to the Strait of Georgia where they live as predatory adults before returning upstream to spawn.

STATUS OF HABITATS: EXAMPLES OF LOSSES AND GAINS

Context

An analysis of fish habitat loss and gain in the lower Fraser River needs to be put in the context of geological and hydrological factors. Vegetation and substrates are usually used as surrogates for estimating (quantifying) high-quality fish habitat for management purposes (*see* above); however, as explained by Adams and Williams (2004) and Levings and Nishimura (1996), establishment and maintenance of the dynamic equilibrium of plant communities inevitably must consider natural sedimentation patterns, river discharge regime, sea-level rise, and flow patterns. Overlying these natural factors are those related to urbanization and industrialization, for example, dredging, filling, dyking, and port construction. All of these activities have led to loss of fish habitat in the intertidal zone or on the floodplain. Table 4 provides an overview of the current status of habitat as affected by various industrial activities for fish in the lower Fraser River and estuary.

Geology and hydrology are also major factors controlling the most important attribute of habitat for fish: water-column living space. For example, the availability of shallow water in estuaries is thought to provide juvenile salmon with protection from larger fish predators found offshore (Macdonald et al., 1988). A quantitative analysis of fish habitat in the lower Fraser River and estuary, therefore, should include data on area (hectares, square kilometres) at specific intertidal elevations to approximately -10 m below chart datum, but there are few data available. Because there are ecologically important fish species such as eulachon that use shallow areas as spawning habitat and because all fish must move offshore when intertidal areas dewater, quantification of the shallow-water habitat is important. This analysis should include vegetated and unvegetated habitats. Further upstream, gravel bars on the main stem are used as spawning habitat for chum and pink salmon (Fig. 4), and as winter habitat for chinook salmon (Levings and Lauzier, 1991), depending on season and river discharge. Conversion of these shallow or seasonally flooded areas to developed or reclaimed land has an obvious negative effect on the habitat of these species.

Losses

A quantitative analysis of fish-habitat change using vegetation as a surrogate in the entire lower Fraser River and estuary cannot be conducted because of the differences in vegetation classification systems that various authors have used (e.g. Kistritz et al., 1996). An estimate of the distribution of some of the original vegetation in the area, which probably is a reasonable reflection of several types of fish habitat, was

Table 4. General status of spawning and rearing habitats in the lower Fraser River and estuary for 17 selected fish species. Fish species listed are those judged to be ecologically or commercially significant based on current knowledge.

Taxa	Status of habitats in estuary and/or floodplain	Status of habitats in lower river and tributaries
Chinook salmon	Significant loss of rearing habitat (wetlands, shallow-water habitat) especially in the north arm	Condition of major spawning ground in Harrison River not known; winter rearing habitats above Mission functioning; loss of spring rearing habitat on main stem river below Mission
Chum salmon	Significant loss of rearing habitat (wetlands, shallow-water habitat) especially in the north arm	Some spawning grounds in tributaries affected by low flow and urbanization; some new spawning channels built (Bonnell, 1991); spawning grounds on main stem above Chilliwack functioning
Coho salmon	Significant loss of winter rearing habitat in small floodplain tributaries; summer drought	Many spawning grounds in tributaries affected by low flow and urbanization
Pink salmon	Move to sea quickly	Spawning habitats on main stem above Chilliwack functioning
Sockeye salmon	Significant loss of fry habitats for river rearing stocks	Condition of spawning ground on Harrison River not known; Weaver Creek spawning channel built to compensate for flood damage of natural spawning area; logging implicated; Pitt and Harrison lakes functioning
Steelhead	Somewhat similar to coho (above)	Somewhat similar to coho (above)
Cutthroat	Not documented	Spawning habitats on main stem above Chilliwack functioning; much stream habitat damaged by urbanization
Herring	Eelgrass beds in intercauseway area on Roberts Bank appear suitable for spawning; not clear why spawning numbers reduced in this area	Not applicable
Surf smelt	Not documented	Spawning habitat (e.g. Spanish Banks) functioning
Eulachon	Not documented	Spawning substrates functioning, but dredge-spoil disposal and intertidal log storage could affect sediment quality
Starry flounder	Loss of shallow-water habitat	Loss of shallow-water habitat
English sole	Loss of shallow-water habitat	Not applicable
Peamouth	Loss of shallow-water habitat	Loss of shallow-water habitat
Suckers	Not documented	Loss of tributary habitats for endangered Salish sucker is of concern
Stickleback	Not documented	Loss of wetland habitat in tidal creeks and floodplain may have reduced spawning and rearing areas
White sturgeon	Not documented	Dredging in river channels may affect spawning and rearing areas; poorly documented
Lampreys	Dredge-spoil disposal and intertidal log storage could affect rearing habitats of Pacific lamprey	Loss of tributary spawning habitats for western brook lamprey

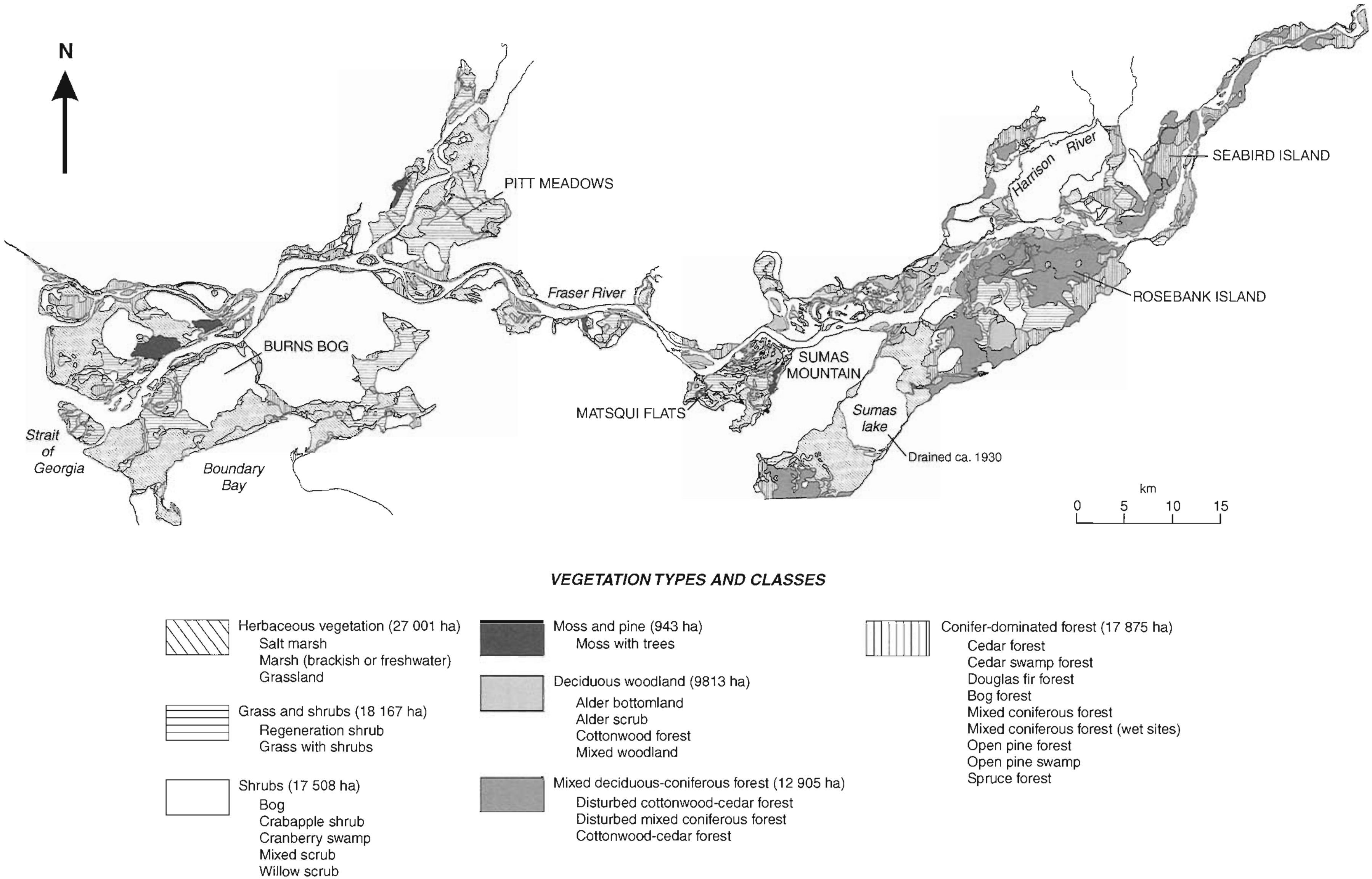


Figure 12. *The vegetation of the floodplain of the Fraser, Serpentine, and Nicomekl rivers, 1859–1890, excluding Sturgeon and Roberts banks and Boundary Bay* (from *North and Teversham, 1984). Numbers in brackets following codes for vegetation units indicate area in square kilometres.*

developed from surveyor's records of the Royal Engineers by North and Teversham (1984). The authors plotted these surveys onto a map with a reconstruction of the shoreline as it was prior to dyking (Fig. 12). As described in Levings and Thom (1994), Department of Fisheries and Oceans (unpub. map, 1996), Kistritz et al. (1996), and Boyle et al. (1997), there have been major losses in fish habitat in the lower Fraser River, especially salt marshes, wetlands of all types in the north arm, off-channel habitat such as wetland forest and lakes (e.g. 'Sumas Lake'), and sloughs and small tributaries such as floodplain tidal creeks. Excluding Sturgeon and Roberts banks and Boundary Bay (total about 244 km^2), there were originally approximately 1032 km^2 of vegetated habitat. Some of the reasons for losses of these wetland habitats are given in Table 5. Large areas of intertidal unvegetated habitat such as sand and gravel bars have been lost due to dyking and port construction. Causeways and training walls on Sturgeon Bank have led to wave focusing, creating a high-energy environment that has apparently prevented marsh colonization in the sector between the north arm and Iona Island jetties (Levings, 1980b).

Over the past few decades it has been difficult to conserve shallow-water habitat, both vegetated and unvegetated, in the lower Fraser River while at the same time maintaining functioning urban and agricultural centres and transportation links. Fish habitats such as marshes are inevitably compromised, but fish-habitat management policy in the past 15 years or so has required mitigation, compensation, and restoration

Table 5. Reasons for habitat loss and measures which could lead to regaining areas of nine critical fish-habitat types in the lower Fraser River and estuary.

Fish habitat type	Reasons for loss	Measures which could lead to gain or restoration	Examples of loss or gain
Brackish marsh	Dyking, urbanization, filling, wave erosion, reduced sediment supply, shoreline armouring using riprap revetment	Transplant, lowering of elevation, wave barrier, removal of fill or debris; marsh benches	Numerous, *see* Pomeroy et al. (1981); Kistritz (1996); Levings and Nishimura (1996); Adams and Williams (2004)
Salt marsh	Dyking, urbanization, filling, wave erosion, reduced sediment supply, shoreline armouring using riprap revetment	Raising of elevation, other measures as above, removal of fill	Iona triangle, Pomeroy and Levings (1980); sand island at Steveston bend
Intertidal and shallow unvegetated	Conversion to marsh by transplant, dredging, filling, urbanization	Channelization using backhoe or dredge; removal of fill	Numerous; *see* Levings and Nishimura (1996); Kistritz (1996); Adams and Williams (2004)
Subtidal/ channel	Dredging, channelization, filling	Channelization using backhoe or dredge; removal of fill	Macdonald Slough; *see* Levings and Nishimura (1996); Burnaby Bend; (Department of Fisheries and Oceans, unpub. data, 1996)
Slough/tidal creeks, tributary streams	Dyking, urbanization, low flow, filling	Channelization using backhoe or dredge; removal of fill; restoration of culverted portions of small streams, removal of barrier at upstream of sloughs, fish-protection flows	Alouette River; *see* Levings and Nishimura (1996); Burnaby Bend; (Department of Fisheries and Oceans, unpub. data, 1996)
Off-channel ponds and lakes	Agriculture, urbanization	Dyke breaching and reflooding; floodgates with proper flaps	Hatzic Lake floodgate
Wetland forest	Agriculture, urbanization	Dyke breaching and reflooding, transplanting	None, but some riparian replanting in several areas
Gravel spawning habitat	Agriculture, urbanization, gravel removal, tow-boat erosion, scraper dredging	Spawning channel construction, buffer zones, leave strips	Chehalis Flats (Bonnell, 1991)
Eelgrass	Port construction, filling, erosion	Transplant, improvement of light penetration, reduction of current through installation of weirs	Roberts Bank (Harrison and Dunn, 2004)

(Adams and Williams, 2004). Engineering structures such as dykes, shipping channels, port terminals, and bridges began to be built in the lower river in the 1880s, and these types of development have continued to the present time. Maintenance dredging and river training are necessary to keep shipping channels functional for deep-sea vessels and have effects on the general morphology of the estuary (Kostaschuk and Luternauer, 2004). As described above, an analysis of the area (e.g. hectares) at specific intertidal and shallow subtidal elevations (relative to chart datum) in the estuary has not been conducted, but might be done in the lower river using the base-line maps provided by Johnson (1921). Because so much intertidal and shallow-water estuarine habitat has been lost by land filling in the estuary, mostly using sand dredged from channels, the area at specific elevations may be a better currency for assessment of fish habitat loss or gain. Suction dredging used to maintain shipping channels has the potential to kill millions of young salmon and other fish, but damage can be controlled through the use of timing restrictions and equipment siting; however, there are indirect ecosystem effects such as changes in channel configuration and depths which can occur in estuaries that are frequently dredged (Levings, 1982b; Kostaschuk and Luternauer, 2004). The increased river velocities arising when river channels are trained to become self-scouring were a major issue when extension of training walls in the lower Fraser River near Steveston was considered in the 1970s. There was concern that young salmon would be denied access to low-velocity backwater areas if they were built. In addition, access to Sturgeon bank by young salmon moving out of the south arm was thought to be reduced by the Steveston north jetty. Water flows over the jetty from the river to the bank only on high tides (Envirocon, 1980a; Levings, 1980b). For this reason, in 1978, three breaches, each about 5 m wide, were made in the jetty by removing riprap.

The effects of log storage on fish habitats in the intertidal zone of the estuary were investigated by Levy et al. (1982) in the Point Grey area. Although, in the opinion of these authors, direct effects on fish were equivocal, their studies and data from other studies provided sufficient information to develop a Fraser River Estuary Management Program policy for keeping stored logs off the intertidal zone.

On Roberts Bank, especially in the intercauseway area between the British Columbia Ferry Corporation Tsawwassen ferry terminal causeway and the Westshore Terminals Ltd.–Deltaport causeway, there has been significant loss of subtidal habitat due to port and dyke construction (Kistritz, 1996). There also has been direct loss of eelgrass on Roberts Bank due to port construction (Levings, 1985). A dyke constructed seaward of one of the remaining salt marshes in the estuary (Bernard and Bartnik, 1987) may have reduced wave erosion, but the structure also led to the permanent loss of shallow-water habitat (R.U. Kistritz, G. Williams, and J. Scott, unpub. map manuscript, Fraser River Estuary Management Program, 1992).

Gains and restoration initiatives

One of the recent gains in fish habitat on eastern Sturgeon Bank was the recovery of fish habitat from sewage pollution, by discharging the effluent beyond the tidal flats in the deeper waters of the Strait of Georgia (Bendell-Young et al., 2004). As documented by Nishimura et al. (1996), fish abundance and diversity is higher in the area now relative to the 1980s, when primary treated sewage was discharged in the Iona Island area.

On western Sturgeon Bank and eastern Roberts Bank, wetland habitat in the middle intertidal and upper intertidal zones is increasing due to natural sedimentation and progradation (Hutchinson et al., 1989). In a few specific instances, industrialization has led to habitat creation. A dredged sand island, originally created in 1980 from sand pumped from the river bed at Steveston Bend, was initially transplanted with sedges (Envirocon, 1980b), but has now been colonized by dune grass and salt-marsh plants. The island is nearly totally flooded at high tide. A salt marsh (about 0.5 ha) was documented on this sand island in 1996 (Fig. 13, 14). Farther upstream, it is likely that brackish marshes behind the training wall near Steveston resulted from the colonization of dredge-sand islands (Wiley, 1984).

Artificial beaches of sand, gravel, and cobble were created by Westshore Terminals Ltd. on Roberts Bank, thus creating a small area of shallow-water habitat in an area formerly characterized by deep water only. These beaches were sampled in 1984, about a decade before one of the recent phases of the port expansion. Juvenile chum were caught on the beaches (Levings, 1985), and substrate was colonized by eelgrass and harpacticoid copepods, important prey for juvenile salmon, as previously mentioned. According to Harrison and Dunn (2004), the expansion of eelgrass in the intercauseway area has been the result of causeway construction as the structures deflect fresh water and sediment from the river. Some of the eelgrass expansion has been attributable to invasion by an introduced species (*Zostera japonica*) (Harrison and Dunn, 2004). Kelp beds developed on riprap revetment around the rim of a dredged borrow pit on western Roberts Bank (Miller and Hensel, 1982). In 1993, marsh plants were transplanted on the north side of the Tsawwassen causeway to compensate for losses owing to expansion of a ferry-terminal parking area (Fraser River Estuary Management Program project files; Adams and Williams (2004)).

There have been approximately 40 fish-habitat restoration or compensation projects conducted in the north and south arms of the lower river and in the main stem upstream (Adams and Williams, 2004). According to Kistritz (1996), the projects have resulted in a net gain of about 6 ha in marsh habitat, but this has been at the expense of sand-flat and mud-flat habitat. The implications of this 'like for unlike' change in fish habitat are difficult to predict with our present knowledge of fish ecology in the Fraser River estuary. The ecological performance of some of the marsh-transplant projects from a fish-habitat viewpoint was recently evaluated. The studies found mixed success, as described in Levings and Nishimura (1996). Elevation in the intertidal zone was found to be one of the major factors influencing the suitability of compensation and restoration projects because this key parameter affects availability of fish habitat. In addition, if habitats are out of water too much of the time, living areas for piscivorous birds can be enhanced. Developments such as sand islands are of concern in this regard.

There is clearly a requirement for fish-habitat restoration in the lower Fraser River and estuary, especially in reaches near New Westminster where marshes are almost totally absent, resulting in deficits of fish-food organisms such as midges (Whitehouse et al., 1993). Healey and Richardson (1996) recently estimated that about 2.5 times as much carbon was being provided by the historical vegetation relative to the present; however, the role of the original vegetation (Fig. 12) in provision of fish habitat is not clear; an explicit interpretation of the implications of habitat loss for ecosystems supporting fish is difficult with present knowledge.

Because of differences in methodology used for classifying and quantifying habitats, it is difficult to make direct comparisons of the status of the fish habitats of the Fraser River estuary with other large estuaries on the west coast of North America; however, on an 'urbanization' gradient from California to Alaska, it is likely that the Fraser River estuary has lost comparable amounts of fish habitat relative to other estuaries close to large cities in this region. Chinook salmon-rearing habitat (marshes, sloughs, and tidal freshwater channels) may be used for comparison. Most authorities estimate that 70–90% of wetlands have been lost in the lower Fraser River area. Boyle et al. (1997) estimated that the area of fen and swamp-bog-marsh habitat in the lower Fraser River delta decreased from 83 100 ha to 12 000 ha between 1820 and 1990. The Sacramento–San Joaquin river estuary in California has lost about 70% of these kinds of chinook habitat, according to Yoshiyama et al. (1996). On the other hand, the undeveloped Stikine River estuary in southeast Alaska showed a gain in marsh habitat of 522 ha between 1948 and 1979 (Simenstad et al., 1997).

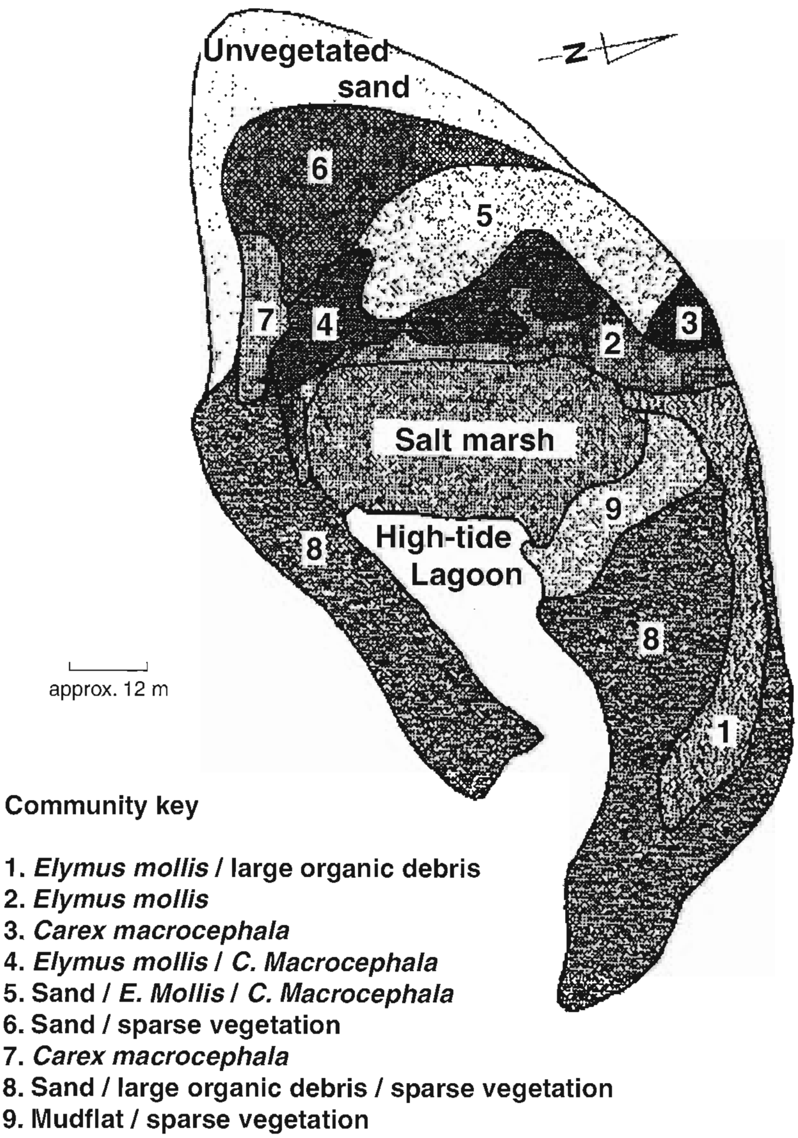


Figure 13.

Vegetation map of a sand island created from dredged material at Steveston Bend. Data obtained in October, 1996 (Durrance, 1997).

*Figure 14. Photographs showing salt-marsh vegetation on the sand island, autumn 1996 (photograph courtesy of Bertrand Groulx, GSC). **a)** Water in right foreground is in high-tide lagoon. GSC 2003-500A, B; **b)** Sand island looking to southeast at low tide; the lagoon is dry. GSC 2003-501*

Society continues to show concern about habitat loss and its relevance to the management of Fraser River estuary fish habitats; however, there is currently relatively little investment in research to document the dynamics of changes in these biophysical units, which are built and maintained by geological, hydrological, and botanical processes and the functional relationship of these changes to fish production. This is certainly true when other major estuaries on the west coast of North America are compared. For example, there are multimillion-dollar research programs currently underway at both the Sacramento–San Joaquin and Columbia river estuaries. Most of the effort of these programs is targeted to improve knowledge of how fish habitat functions in the tidal rivers and their estuaries, especially to support chinook salmon. While the first evidence in British Columbia of juvenile salmon use of estuaries was documented in the Fraser River estuary by Goodman (1975), this finding stimulated several detailed ecosystem studies at other, smaller estuaries in British Columbia (e.g. Nanaimo, Squamish; Levings (1997)). Subsequently, work on these smaller areas established the current ecological paradigm used to manage fish habitats in the Fraser River, but only by extrapolation. Most of the studies in the lower Fraser River and estuary have produced snippets of information, and data cannot be integrated because of timing and/or spatial differences in sampling. There never has been a comprehensive ecological study of fish habitats in the lower Fraser River and estuary, and in the opinion of this author such a study is needed to make sure proper and informed environmental management is achieved into the twenty-first century. An integrated study should consider the ecological linkages between the tributaries on the floodplain, the main-stem Fraser River, and the estuary, because land use on the delta affects these three ecosystems. Scientific knowledge is not static, and it would be prudent for policy makers, for example, those involved in the Fraser River Estuary Management Program, to foster detailed ecological research on fish habitats in the Fraser River estuary.

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REFERENCES

Adams, M.A. and Williams, G.L.
2004: Tidal marshes of the Fraser River estuary: composition, structure, and a history of marsh creation efforts to 1997; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Bartnik, V.G.
1973: Behavioural ecology of the Longnose Dace (Pisces, *Rhinichthys cataractae*, Cyprinidae); Ph.D. thesis, Department of Zoology, University of British Columbia, Vancouver, British Columbia, 163 p.

Beamish, R.J. and Levings, C.D.
1991: Abundance and freshwater migrations of the anadromous parasitic lamprey (*Lampetra tridentata*) from a tributary of the Fraser River, British Columbia; Canadian Journal of Fisheries and Aquatic Sciences, v. 48, p. 1250–1263.

Bendell-Young, L., Yin, K., Thomas, C., Harrison, P.J., Feeney, T., Arvai, J.L., Levings, C.D., and Ross, L.
2004: Biogeochemistry of the intertidal area of the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Bernard, D.J. and Bartnik, V.G.
1987: Tsawwassen Indian Reserve Flood Control Works. Post-project Environmental Analysis; Environment Canada, Inland Waters and Lands, Pacific and Yukon Region, Vancouver, British Columbia, 31 p.

Birtwell, I.K., Nassichuk, M.D., and Buene, H.
1987: Underyearling Sockeye Salmon (*Oncorhynchus nerka*) in the estuary of the Fraser River; *in* Sockeye Salmon (*Oncorhynchus nerka*) Population Biology and Future Management, (ed.) H.D.L. Smith, L. Margolis, and C.C. Wood; Canadian Special Publication, Fisheries and Aquatic Sciences, v. 96, p. 25–35.

Bonnell, R.G.
1991: Construction, operation, and evaluation of groundwater-fed side channels for Chum Salmon in British Columbia; American Fisheries Society Symposium, v. 10, p. 109–124.

Boyle, C.A., Lavkulich, L., Schreier, H., and Kiss, E.
1997: Changes in land cover and subsequent effects on lower Fraser Basin ecosystems from 1827 to 1990; Environmental Management, v. 21, p. 185–196.

Bradford, M.J. and Levings, C.D.
1997: Report on the Workgroup "Partitioning Survival"; *in* Proceedings, Workshop on Estuarine and Ocean Survival of Northeastern Pacific Salmon, (ed.) R.L. Emmett and M.H. Schiewe; Newport, Oregon, March 21, 1996; National Oceanic and Atmospheric Administration Technical Memorandum, National Marine Fisheries Service–Northwest Fisheries Science Center, NMFS-NWFSC-29, p. 279–281.

Bravender, B.A., Levings, C.D., and Brown, T.J.
1993: A comparison of meiofauna available as fish food on Sturgeon and Roberts bank, Fraser River estuary, British Columbia; Canadian Fisheries and Aquatic Sciences, Technical Report 1904, 40 p.

Brown, T.J., Whitehouse, T.R., and Levings, C.D.
1989: Beach seine data from the Fraser River at North Arm, Main Arm, and Agassiz during 1987-88; Canadian Fisheries and Aquatic Sciences, Data Report 737, 134 p.

Burger, L.
1995: Catch and biological data for Starry Flounder (*Platichthys stellatus*) in the Fraser River estuary; *in* Studies of the Starry Flounder in the Fraser River, 1992-94, (ed.) T.C. Nelson; Fraser River Estuary Management Program, Technical Report WQM 95-02; Fraser River Estuary Management Program, New Westminster, British Columbia, p. III-1–III-36.

Burger, L.F. and Nishimura, D.J.H.
1996: Chum fry residency and stomach content analysis at transplanted marsh habitat sites in the Fraser River estuary; *in* Created and Restored Sedge Marshes in the Lower Fraser River and Estuary: an Evaluation of Their Functioning as Fish Habitat, (ed.) C.D. Levings and D.J.H. Nishimura; Canadian Technical Report of Fisheries and Aquatic Sciences, no. 2126, p. 103–126.

Chapman, P.M. and Brinkhurst, R.O.
1981: Seasonal changes in the interstitial salinities and seasonal movements of subtidal benthic invertebrates in the Fraser River estuary; B.C. Estuarine Coastal Shelf Science, v. 12, p. 49–66.

Clark, D.W. and McInerney, J.E.
1974: Emigration of the Peamouth, *Mylocheilus caurinus*, across a dilute seawater bridge: an experimental zoogeographic study; Canadian Journal of Zoology, v. 52, p. 457–469.

Conomos, T.H. (ed.)
1979: San Francisco Bay: the Urbanized Estuary; Pacific Division of the American Association for the Advancement of Science, 493 p.

D'Amour, D.
1988: Vertical distribution and abundance of natant harpacticoid copepods on a vegetated tidal flat; Netherlands Journal of Sea Research, v. 22, p. 161–170.

Drake, A. and Wilson, W.
1992: Eulachon: a fish to cure humanity; University of British Columbia Museum of Anthropology, Note #32, University of British Columbia, Vancouver, British Columbia, 28 p.

Durrance, C.
1997: Sand Island - Salt Marsh Vegetation Assessment; Department of Fisheries and Oceans, West Vancouver, B.C.; February 9 1997, 8 p + figures, appendices.

Echols, J.C.
1995: Review of Fraser River Sturgeon, *Acipenser transmontanus*; Fisheries and Oceans, Fraser River Action Plan, Vancouver, British Columbia, 33 p.

Envirocon
1980a: Environmental Impact Assessment of Repairs to the Steveston North Jetty; Public Works Canada, Vancouver, B.C.; February 1980, 270 p. + figs.
1980b: Fraser River Habitat Development Program, Addendum to the Criteria Summary Report; Departments of Supply and Services, Fisheries and Oceans, Canadian Wildlife Service, and Public Works, Vancouver, B.C., June 1980, 38 p. + app.

Feeney, T.D., Amos, C.L., and Luternauer, J.L.
1994: Sediment pollution regime on the northern tidal flats, Fraser River delta, British Columbia, Canada; *in* Proceedings, Coastal Zone Canada 1994; Halifax, Nova Scotia, September 20–23, 1994, Coastal Zone Association of Canada, v. 4, p. 1273–1287.

Forrester, C.R. and Ketchen, K.S.
1964: A review of the Strait of Georgia trawl fishery; Bulletin of Fisheries Research Board of Canada, v. 139, 78 p.

Gee, H.H. and Northcote, T.G.
1963: Comparative ecology of two sympatric species of Dace (*Rhinichthys*) in the Fraser River system, British Columbia; Journal of Fisheries Research Board of Canada, v. 20, p. 105–118.

Glavin, T.
1994: A Ghost in the Water; New Star Books, Vancouver, British Columbia, 78 p.

Goodman, D.
1975: A synthesis of the impacts of proposed expansion of the Vancouver International Airport and other developments on the fisheries resources of the Fraser River estuary; Department of Environment, Fisheries and Marine Service, Vancouver, British Columbia (2 volumes).

Gordon, D.K. and Levings, C.D.
1984: Seasonal changes of inshore fish populations on Sturgeon and Roberts Bank, Fraser River estuary, British Columbia; Canadian Fisheries and Aquatic Sciences, Technical Report 1240, 81 p.

Greer, G.L., Levings, C.D., Harbo, R., Hillaby, B., Brown, T., and Sibert, J.
1980: Distribution of fish species on Roberts and Sturgeon Bank recorded in seine and trawl surveys; Canadian Fisheries and Aquatic Sciences, Manuscript Report 1596, 51 p.

Gregory, R.S. and Levings, C.D.
1998: Turbidity reduces predation on migrating juvenile Pacific Salmon; Transactions of the American Fisheries Society, v. 127, p. 275–285.

Gregory, R.S., Whitehouse, T.R., and Levings, C.D.
1993: Beach seine catches, lengths, weights, and stomach content data of salmonids and other fishes from the Harrison and Fraser Rivers, April and May 1991; Canadian Fisheries and Aquatic Sciences, Data Report 902, 85 p.

Harding, L.E. and McCullum, E. (ed.)
1994: Biodiversity in British Columbia; Environment Canada, Canadian Wildlife Service, Ottawa, Ontario, 426 p.

Harrison, P.G. and Dunn, M.
2004: Fraser River delta seagrass ecosystems, their distributions and importance to migratory birds; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Hartman, G.F.
1968: Growth rate and distribution of some fishes in the Chilliwack, South Alouette and Salmon Rivers; B.C. Fish and Wildlife Branch, Management Publication No. 11, 33 p.

Hay, D.E., McCarter, P.B., Kronlund, R., and Roy, C.
1989: Spawning areas of British Columbia herring: a review, geographical analysis and classification. Volume V: Strait of Georgia; Canadian Fisheries and Aquatic Sciences, Manuscript Report 2019, 268 p.

Healey, M.C. and Richardson, J.S.
1996: Changes in the productivity base and fish populations of the lower Fraser River (Canada) associated with historical changes in human occupation; Archives for Hydrobiologie, Supplement 113, Large Rivers, v. 10, no. 1–4, p. 279–290.

Henderson, M.A., Diewert, R.E., Hume, J., Shortreed, K., Levy, D.A., and Morton, K.
1991: The carrying capacity of Pitt Lake for juvenile Sockeye Salmon (*Oncorhynchus nerka*); Canadian Fisheries and Aquatic Sciences, Technical Report 1797, 61 p.

Higgs, D.A., Macdonald, J.S., Levings, C.D., and Dosanjh, B.
1995: Nutrition and feeding habits of Pacific Salmon (*Oncorhynchus* spp.) in relation to life history stage; *in* Physiological Ecology of Pacific Salmon, (ed.) R. Brett, W.C. Clarke, K. Groot, and L. Margolis; University of British Columbia Press, Vancouver, British Columbia, 510 p.

Hutchinson, I., Prentice, A.C., and Bradfield, G.
1989: Aquatic plant resources of the Strait of Georgia; *in* The Ecology and Status of Marine and Shoreline Birds in the Strait of Georgia, British Columbia, (ed.) K. Vermeer and R.W. Butler; Special Publication, Canadian Wildlife Service CW66-98/1987E, Ottawa, Ontario, p. 50–60.

Hvidsten, N.A., Levings, C.D., and Grout, J.
1996: A preliminary study of hatchery Chinook Salmon smolts migrating in the lower Fraser River, determined by radiotagging; Canadian Fisheries and Aquatic Sciences, Technical Report 2085, 9 p. + figures.

Interagency Ecological Program for the Sacramento-San Joaquin Estuary
1997: Newsletter of California Department of Water Resources, Sacramento, California, v. 10, no. 2, 47 p.

Johnson, W.A.
1921: Sedimentation of the Fraser River delta; Geological Survey of Canada, Memoir 125, p. 46.

Jones, M.L.
1986: The influence of natural predation on the population dynamics of Pacific Salmon: an experimental study; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 184 p.

Kistritz, R.U.
1996: Habitat compensation, restoration and creation in the Fraser River estuary: are we achieving a no-net-loss of fish habitat?; Canadian Fisheries and Aquatic Sciences, Manuscript Report 2349, 70 p.

Kistritz, R.U., Hall, K.J., and Yesaki, I.
1983: Productivity, detritus flux, and nutrient cycling in a *Carex lyngbyei* tidal marsh; Estuaries, v. 6, p. 227–237.

Kistritz, R.U., Scott, K.J., and Levings, C.D.
1996: Changes in fish habitat in the lower Fraser River analyzed by two wetland classification systems; *in* Created and Restored Sedge Marshes in the Lower Fraser River and Estuary: an Evaluation of their Functioning as Fish Habitat, (ed.) C.D. Levings and D.J.H. Nishimura; Canadian Fisheries and Aquatic Sciences, Technical Report 2126, p. 1–38.

Kostaschuk, R.A. and Luternauer, J.L.
2004: Sedimentary processes and their environmental significance: lower main channel, Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Levings, C.D.
1973: Sediments and abundance of *Lycodopsis pacifica* (Pisces, Zoarcidae) near Point Grey, B.C., with catch data for associated demersal fish; Fisheries Research Board Canada, Technical Report 393, 32 p.
1980a: Vertical distribution and abundance of epibenthos and macrozooplankton in the lower Fraser estuary; Canadian Fisheries and Aquatic Sciences, Data Report 241, 59 p.
1980b: Consequences of training walls and jetties for aquatic habitats at two British Columbia estuaries; Coastal Engineering, v. 4, p. 111–136.
1982a: Short-term use of a low tide refuge in a sandflat by juvenile chinook (*Oncorhynchus tshawytscha*), Fraser River estuary; Canadian Fisheries and Aquatic Sciences, Technical Report 1111, 33 p.
1982b: The ecological consequences of dredging and dredge spoil disposal in Canadian waters; National Research Council of Canada, Associate Committee on Scientific Criteria for Environmental Quality; NRCC Publication 18130, 141 p.
1983: Some observations of juvenile herring at the Fraser River estuary, B.C.; *in* Proceedings, Fourth Pacific Coast Herring Workshop, (ed.) K. Buchanan; October 7–8, 1981; Canadian Fisheries and Aquatic Sciences, Manuscript Report 1700, p. 91–104.
1985: Juvenile salmonid use of habitats altered by a coal port in the Fraser River estuary, British Columbia; Marine Pollution Bulletin, v. 17, p. 248–254.
1994a: Science and management needed to maintain salmon production in estuaries of the northeast Pacific; *in* Proceedings, Joint Symposium of Estuarine Research Federation and Estuarine and Coastal Sciences Association, (ed.) K. Dyer and R.J. Orth; September 14–18, 1992, Plymouth, England; Olsen and Olsen, Denmark, p. 417–421.
1994b: Life on the edge: structural and functional aspects of Chinook and Coho rearing habitats on the margins of the lower Fraser River; *in* Proceedings, 1994 North East Pacific Chinook and Coho Salmon Workshop, Eugene, Oregon, November 7–10, 1994; p. 139–147.
1997: An overview of the science supporting marine and estuarine fish habitat management in Pacific region, with emphasis on research on physical changes; *in* Proceedings of the DFO Workshop on Research Priorities to Improve Methods for Assessing Productive Capacity for Fish Habitat Management and Impact Assessment, (ed.) C.D. Levings, C.K. Minns, and F. Aitkens; Sidney, B.C., May 13–15, 1996; Canadian Fisheries and Aquatic Sciences, Technical Report 2147, p. 95–101.

Levings, C.D. and Lauzier, R.B.
1991: Extensive use of the Fraser River basin as winter habitat by juvenile Chinook Salmon (*Oncorhynchus tshawytscha*); Canadian Journal of Zoology, v. 69, p. 1759–1767.
Levings, C.D. and Nishimura, D.J.H. (ed.)
1996: Created and restored sedge marshes in the lower Fraser River and estuary: an evaluation of their functioning as fish habitat; Canadian Fisheries and Aquatic Sciences, Technical Report 2126, 143 p.
Levings, C.D. and Thom, R.M.
1994: Habitat changes in Georgia Basin: implications for resource management and restoration; *in* Review of the Marine Environment and Biota of Strait of Georgia, Puget Sound, and Juan de Fuca Strait, (ed.) R.C.H. Wilson, R.J. Beamish, F. Aitkens, and J. Bell; Proceedings, BC/Washington Symposium on the Marine Environment, January 13–14, 1994; Canadian Fisheries and Aquatic Sciences, Technical Report 1948, p. 330–351.
Levings, C.D. and Tompkins, A.
1985: Habitats of Fraser River chum – an overview; *in* Proceedings, 1985 Northeast Pacific Pink and Chum Salmon Workshop, (Rapporteur) B.G. Shepherd; Department of Fisheries and Oceans, Vancouver, British Columbia, p. 162–167.
Levings, C.D., Boyle, D.E., and Whitehouse, T.R.
1995: Distribution and feeding of juvenile salmon in freshwater tidal creeks, lower Fraser River, British Columbia; Fisheries Management and Ecology, v. 2, p. 299–308.
Levings, C.D, Conlin, K., and Raymond, B.
1991: Intertidal habitats used by juvenile Chinook (*Oncorhynchus tshawytscha*) rearing in the North Arm of the Fraser River estuary; Marine Pollution Bulletin, v. 22, p. 20–26.
Levings, C.D., Greer, G.L., and Miller, P.
1983: Results of preliminary mark-capture experiments with juvenile salmonids on Sturgeon and Roberts Bank, Fraser River estuary; Canadian Fisheries and Aquatic Sciences, Manuscript Report 1684, 27 p.
Levy, D.A.
1982: Biology and management of Surf Smelt in Burrard Inlet, Vancouver, B.C.; University of British Columbia, Westwater Research Centre, Technical Report 28; Vancouver, British Columbia, 48 p.
Levy, D.A. and Cadenhead, A.D.
1995: Selective tidal stream transport of adult Sockeye Salmon (*Oncorhynchus nerka*) in the Fraser River estuary; Canadian Journal of Fisheries and Aquatic Sciences, v. 52, p. 1–12.
Levy, D.A. and Northcote, T.G.
1982: Juvenile salmon residency in a marsh area of the Fraser River estuary; Canadian Journal of Fisheries and Aquatic Sciences, v. 39, p. 270–276.
Levy, D.A., Northcote, T.G., and Barr, R.M.
1982: Effects of estuarine log storage on juvenile salmon; University of British Columbia, Westwater Research Centre, Technical Report 26, 101 p.
Levy, D.A., Northcote, T.G., and Birch, G.J.
1979: Juvenile salmon utilization of tidal channels in the Fraser River estuary, British Columbia; University of British Columbia, Westwater Research Centre, Technical Report 23, 70 p.
Macdonald, A.L.
1984: Seasonal use of the nearshore intertidal habitats by juvenile salmon on the delta front of Fraser River estuary, British Columbia; M.Sc. thesis, University of Victoria, Victoria, British Columbia, 186 p.
Macdonald, J.S. and Chang, B.D.
1993: Seasonal use by fish of nearshore areas in an urbanized coastal inlet in southwestern British Columbia; Northwest Science, v. 67, p. 63–77.
Macdonald, J.S., Kistritz, R.U., and Farrell, M.
1990: An examination of the effects of slough habitat reclamation in the lower Fraser River, British Columbia: detrital and invertebrate flux, rearing and diets of juvenile salmon; Canadian Fisheries and Aquatic Sciences, Technical Report 1731, 71 p.
Macdonald, J.S., Levings, C.D., McAllister, C.D., Fagerlund, U.H.M., and McBride, J.R.
1988: A field experiment to test the importance of estuaries for Chinook Salmon (*Oncorhynchus tshawytscha*) survival: short term results; Canadian Journal of Fisheries and Aquatic Sciences, v. 45, p. 1366–1377.
McPhail, J.D. and Carveth, R.
1992: A foundation for conservation: the nature and origin of the freshwater fish fauna of British Columbia; Fish Museum, Department of Zoology, University of British Columbia, Vancouver, British Columbia, 39 p.
1993: Field key to the freshwater fishes of British Columbia; Fish Museum, Department of Zoology, University of British Columbia, Vancouver, British Columbia, 239 p.
Mesa, K.A.
1985: The influence of temperature, salinity and dissolved oxygen on juvenile salmon distributions in a nearshore environment; M.Sc. thesis, Department of Zoology, University of British Columbia, Vancouver, British Columbia, 136 p.
Miller, P. and Hensel, L.
1982: Roberts Bank development: a report on habitat compensation; National Harbours Board and Department of Fisheries and Oceans, West Vancouver Laboratory, 82 p.
Murray, C.D. and Rosenau, M.L.
1989: Rearing of juvenile Chinook Salmon in non-natal tributaries of the lower Fraser River, British Columbia; Transactions of the American Fisheries Society, v. 118, p. 284–289.
Nelson, T.C. and Alexander, R.F.
1995: Radio biotelemetry of the movements of sub-mature Starry Flounder (*Platichthys stellatus*) in the Fraser River estuary during March and April, 1994; *in* Studies of the Starry Flounder in the Fraser River, 1992-94, (ed.) T.C. Nelson; Fraser River Estuary Management Program, New Westminster, B.C.; Fraser River Estuary Management Program, Technical Report WQM 95-02, p. II-1–III-71.
Nelson, T.C., Alexander, R., and Levings, C.D.
1994: Ultrasonic and radio biotelemetry assessment of the distribution and movement of Starry Flounder (*Platichthys stellatus*) in the Fraser River estuary during late January to early April 1993; Fraser River Estuary Management Program, New Westminster, B.C.; Fraser River Estuary Management Program, Technical Report WQWM 93-07, 41 p.
Nishimura, D.J.H., Levings, C.D., and Whitehouse, T.R.
1995: Stomach content data from juvenile Chinook, *Oncorhynchus tshawytscha*, captured in surface trawl at Queen's Reach, lower Fraser River; March to August 1988; Canadian Fisheries and Aquatic Sciences, Data Report 961, 71 p.
Nishimura, D.J.H., Piercey, G.E., Levings, C.D., Yin, K., and McGreer, E.R.
1996: Changes in fish communities and water chemistry after cessation of municipal sewage discharge near the Iona Island foreshore, Fraser River estuary, British Columbia; Canadian Fisheries and Aquatic Sciences, Technical Report 2096, 17 p.
North, M. and Teversham, J.
1984: The vegetation of the floodplain of the Fraser, Serpentine, and Nicomekl Rivers, 1859 to 1890; Digital Conversion of Vegetation Map - Department of Fisheries and Oceans, Science Branch (with funding from Fraser River Action Plan) (Pacific and Yukon Region); Environment Canada, Canadian Wildlife Service (Pacific and Yukon Region); University of British Columbia, Department of Geography, 1997; Syesis, v. 17, p. 47–66.
Northcote, T.G.
1974: Biology of the lower Fraser River: a review; University of British Columbia Westwater Research Centre, Technical Report 3, 94 p.
Northcote, T.G. and Larkin, P.A.
1989: The Fraser River: a major salmonine production system; *in* Proceedings of the International Large River Symposium (LARS), (ed.) D.P. Dodge; Canadian Special Publication of Fisheries and Aquatic Sciences, v. 106, p. 172–204.
Northcote, T.G., Ennis, G.L., and Anderson, M.H.
1975: Periphytic and planktonic algae of the lower Fraser River in relation to water quality conditions; University of British Columbia Westwater Research Centre, Technical Report 8, 61 p.
Northcote, T.G., Johnston, N.T., and Tsumura, K.
1978: A regional comparison of species distribution, abundance, size and other characteristics of lower Fraser River fishes; University of British Columbia Westwater Research Centre, Technical Report 14, 38 p.
1979: Feeding relationships and food web structure of lower Fraser River fishes; University of British Columbia Westwater Research Centre, Technical Report 16, 73 p.

Palmer, R.N.
1972: Fraser River Chum Salmon; Fisheries and Marine Service Report; PAC/T 72-1; Vancouver, British Columbia, 284 p.

Perrin, C.J., Rempel, L.L., and Rosenav, M.L.
2003: White sturgeon spawning habitat in an unregulated large river: Fraser River, Canada; Transactions of the American Fisheries Society, v. 132, p. 154–165.

Pomeroy, W.M. and Levings, C.D.
1980: Association and feeding relationships between *Eogammarus confervicolus* (Stimpson) (Amphipoda, Gammaridae) and benthic algae on Sturgeon and Roberts Bank, Fraser River estuary; Canadian Journal of Fisheries and Aquatic Sciences, v. 37, p. 1–10.

Pomeroy, W.M., Gordon, D.K., and Levings, C.D.
1981: Experimental transplants of brackish and salt marsh species on the Fraser River estuary; Canadian Technical Report of Fisheries and Aquatic Sciences, no. 1067, 35 p.

Power, M.E.
1990: Effects of fish in river food webs; Science, v. 250, p. 811–814.

Richardson, J.S. and Healey, M.C.
1996: A healthy Fraser River? How will we know when we achieve this state?; Journal of Aquatic Ecosystem Health, v. 5, p. 107–115.

Richardson, J.S. and Levings, C.D.
1996: Chlorinated organic contaminants in benthic organisms of the lower Fraser River, British Columbia; Water Pollution Research Journal of Canada, v. 31, p. 153–162.

Richardson, J.S., Lissmore, T.J., Healey, M.C., and Northcote, T.G.
2000: Fish communities of the lower Fraser River (Canada) and a 21-year contrast; Environmental Biology of Fishes, v. 59, p. 125–140.

Rogers, I.H., Birtwell, I.K., and Kruzynski, G.M.
1990: The Pacific Eulachon (*Thaleichthys pacificus*) as a pollution indicator organism in the Fraser River estuary, Vancouver, British Columbia; The Science of the Total Environment, v. 97/98, p. 713–727.

Sambrook, R.J.
1991: Interactions between threespine stickleback (*Gasterosteus aculeatus* Linnaeus) and juvenile chinook salmon (*Oncorhynchus tshawytscha*) in an estuarine marsh; M.Sc. thesis, Department of Zoology, University of British Columbia, Vancouver, British Columbia, 82 p.

Samis, S.C.
1977: Sampling eulachon eggs in the Fraser River using a submersible pump; Fisheries and Marine Service, Technical Report PAC/T: 77-18, 7 p.

Seki, H., Otsuki, A., Fukuto, Y., Stephens, K.V., Levings, C.D., Yamagishi, H., Kotyk, M., and McAllister, C.D.
1988: Influence of wastewater discharge on the uptake kinetics of dissolved organic materials by microorganisms in the Fraser River estuary, British Columbia; Archives for Hydrobiologie, v. 112, no. 1, p. 55–65.

Semakula, S.N. and Larkin, P.A.
1968: Age, growth, food, and yield of the White Sturgeon (*Acipenser transmontanus*) of the Fraser River, British Columbia; Journal of the Fisheries Research Board, Canada, v. 25, p. 2589–2602.

Simenstad, C.A., Diether, M., Levings, C.D., and Hay, D.E.
1997: The terrestrial/marine interface; *in* Proceedings, Conference on the Environment and People of the Coastal Temperate Rain Forest, (ed.) P.K. Schoonmaker, B. van Hagen, and E.C. Wolf; Whistler, British Columbia, August 28–30 1994; Island Press, Washington, D.C., p. 149–187.

Tompkins, A. and Levings, C.D.
1991: Interspecific interactions affecting the survival of Chum Salmon fry; *in* Proceedings, 1991 Pink and Chum Workshop, Parksville, B.C.; February 27–March 1, 1991, p. 29–36.

Virgil, J.A. and McPhail, J.D.
1994: Spatio-temporal distribution of anadromous (*Trachurus*) and freshwater (*Leiurus*) Threespine Stickleback (*Gasterosteus aculeatus*); Canadian Field Naturalist, v. 108, p. 355–360.

Ward, P., Moore, K., and Kistritz, R.U.
1992: Wetlands of the Fraser Lowlands, 1989: an inventory; Canadian Wildlife Service, Pacific and Yukon Region, Technical Report Series 146, 216 p.

Whitehouse, T.R. and Levings, C.D.
1989: Surface Trawl Catch Data from the Lower Fraser River at Queens Reach During 1987 and 1988; Canadian Fisheries and Aquatic Sciences, Data Report 768, 53 p.

Whitehouse, T.R., Levings, C.D., and Macdonald, J.S.
1993: Chironomid (Diptera) insects from natural and transplanted estuarine marshes in British Columbia; *in* Proceedings, 1993 Canadian Coastal Conference, Vancouver, May 4–7, 1993; Coastal Zone Engineering Program, National Research Council Canada, Ottawa, Ontario, p. 500–524.

Wiley, K.C.
1984: Evaluation of Fraser River dredge spoil as a material to restore rearing habitat for juvenile pacific salmon; Transport Canada, January 1984, Vancouver, British Columbia, 53 p.

Williamson, H.C.
1930: Herring fishing in British Columbia; Museum and Art Notes (Vancouver), v. 5, p. 53–56.

Yoshiyama, R.M., Gerstung, E.R., Fisher, F.W., and Moyle, P.B.
1996: Historical and present distribution of Chinook Salmon in the central valley drainage of California; *in* Sierra Nevada Ecosystem Project: Final Report to Congress Vol. iii, Assessments, commissioned reports and background information; University of California, Davis Centers for Water and Wild Land Resources, p. 309–362.

Toxicological studies of fish and invertebrates in the Fraser River estuary

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Abstract: Research projects undertaken by federal and provincial governments and university programs on stress-induced changes in biota (i.e. biomarkers) in relation to industrial and municipal activities on the Fraser River estuary are reviewed. Local effects of pollution manifest in the invertebrate community as changes in species diversity or shifts to more pollution-tolerant species. Some indicator invertebrates (i.e. soft-shelled clams, neogastropod whelks, and Dungeness crabs) can be used to identify contaminants within effluent dilution zones that are bioavailable to the community. They can also give some insight on biological mode and action of pollutants at the organism level. The Fraser River estuary is also used by large numbers of fish, whose populations may be affected by environmental degradation of their habitats. Biomarkers such as detoxification enzymes, bile metabolites, and cancerous lesions have been found to be useful tools in assessing possible sublethal effects of complex mixtures of pollutants in the river that may contribute to a decline in fish populations.

Résumé : Cet article passe en revue des recherches entreprises aux niveaux fédéral et provincial, ainsi que dans les universités, sur les modifications provoquées par le stress chez les biotes — c.-à-d. les biomarqueurs — en relation avec les activités industrielles et municipales dans la région de l'estuaire du Fraser. Les effets locaux de la pollution se manifestent dans la communauté des invertébrés par des variations de la diversité des espèces ou par le remplacement de certaines espèces par d'autres plus tolérantes à la pollution. Certains invertébrés indicateurs (myes, buccins, crabes dormeurs) peuvent servir à repérer les contaminants dans les zones de dilution d'effluents qui sont biodisponibles pour la communauté. Ces invertébrés peuvent aussi aider à comprendre le mode et l'action biologiques des polluants à l'échelle de l'organisme. L'estuaire du Fraser est également fréquenté par un grand nombre de poissons, dont les populations pourraient être affectées par la dégradation environnementale de leur habitat. Des biomarqueurs, dont des enzymes de détoxification, des métabolites de la bile et des lésions cancéreuses, se sont avérés des outils utiles pour l'évaluation des effets sublétaux éventuels de mélanges complexes de polluants du fleuve qui contribuent peut-être au déclin des populations de poissons.

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INTRODUCTION

The many concerns over the degradation of our estuarine, coastal, and offshore environments by anthropogenic sources have led to an interest in the biological effects of contaminants on marine organisms. A large percentage of British Columbia's population lives within the watershed of the Fraser River, and this has led to widespread changes in aquatic and terrestrial habitats. Even though the Fraser River is not highly industrialized, its contamination by persistent organic xenobiotics (man-made organic compounds that have some effect on the biota) has nonetheless been well documented (e.g. Birtwell et al., 1988; Rogers et al., 1990). Chlorinated dioxins, furans, phenols, and guiacols in fish, water, and sediments have been traced to pulp and paper mills discharging effluent hundreds of kilometres upstream and to sawmills located in the lower reaches of the river (Carey, 1988; Carey and Hart, 1988; Servizi et al., 1988; Rogers et al., 1988, 1990; Cretney et al., 1992; B.L. Huston and C.F. Charbonneau, paper presented at Dioxin 1992, Twelfth International Symposium on chlorinated dioxins and related compounds, Tampere, Finland, 1992; D.M. Whittle, C. Mageau, R.K. Duncan, D.B. Sergeant, M.D. Nassichuk, J. Morrison, and J. Piuze, paper presented at Dioxin 1992, Twelfth International Symposium on chlorinated dioxins and related compounds, Tampere, Finland, 1992; F.A.P.C. Gobas and J.P. Pasternak, unpub. report, 1993). In addition to discharges from three major municipal waste treatment plants, the estuarine reaches of the Fraser River also receive wastes from numerous industrial locations and a multitude of 'nonpoint' sources. The industrial wastes enter the river system from the treatment of logs and broadcast pesticide use in silviculture, agriculture, and horticulture, and from 'stormwater' (Birtwell et al., 1988). While the environmental fate of this complex mixture of xenobiotics is a subject for concern, interactions of contaminants with changing physicochemical conditions characteristic of estuaries also should be considered. Only contaminant content has been well documented. The sublethal effects of these xenobiotics on organisms utilizing this habitat remain virtually unknown (Birtwell et al., 1988). In this paper we discuss issues associated with these activities, and in particular address the discharge of contaminants in relation to stress-induced changes in biota (i.e. biomarkers) from the Fraser River estuary.

Biomarkers, which are related to direct exposure to chemicals or their resultant effects, are characterized by biochemical, physiological, and histopathological changes (microscopic tissue and cell changes) in organisms (Huggett et al., 1992). Biomarkers have been used extensively in the laboratory to document and quantify both exposure to and effects of environmental pollutants that are biologically available. These changes reflect different time scales of impact. Biochemical changes are 'early warnings', whereas ecosystem or community changes are retrospective (Addison, 1996). Until recently, the assessment of toxicological effects in the aquatic environment has been done at the suborganismal and the ecosystem level of organization (Miller, 1981; Larsson et al., 1985). The predictive utility of research at these levels is limited, because impaired function or death may have occurred prior to detection of any problems. As the discipline of environmental toxicology has matured and environmental regulation has become more complex, potential biomarkers at the suborganismal levels of organization (biochemical, physiological, and histological or microscopic changes in tissues or cells) have been considered (Goldstein, 1981; Wedemeyer and McLeay, 1981). As tools to monitor biological function and health, these are quantifiable parameters that can be correlated in a dose- or time-dependent manner to the degree of dysfunction that the contaminant has produced (Mayer et al., 1992). Given the variable, synergistic nature of contaminants and receiving environments, recent approaches to biomonitoring for predicting ecosystem impacts have focused on the integration of effects by living systems (Cairns and Pratt, 1989). In addition, measurements of a suite of sublethal effects in biota can provide estimates of stress produced over an extended period of time (Root, 1990).

In this paper we focus on biomarkers of stress and parameters of biological integrity that have been examined in particular invertebrate and fish species found in the Fraser River estuary. It should be noted that many research projects have been undertaken through funding provided by the Fraser River Action Plan and the Fraser River Estuary Management programs.

INVERTEBRATE STUDIES

Local effects of pollution appear in the benthic invertebrate community as changes in species diversity or shifts in numerical proportions to more pollution-tolerant species. Some indicator species can be used to identify contaminants within effluent- dilution zones of the estuary, but these have not been monitored on a regular basis. Hence, only synoptic data are available and conclusions cannot be reached regarding changes in benthic community structure with respect to contaminant loading (Anonymous, 1992).

Soft-shell clam

Marine shellfish are used as highly sensitive monitors of aquatic environments. *Mya arenaria*, the soft-shell clam, develops leukemias (also referred to as hematopoietic neoplasia), often with fatal consequences. To date the highest prevalence of detected leukemia is in samples collected from New Bedford Harbour, Massachusetts, a site heavily contaminated with polychlorinated biphenyls (PCBs) (Harper et al., 1994). Recently *M. arenaria* were collected from beaches at Kitimat, Prince Rupert, and Crofton, British Columbia (D. Brand, unpub. data, 1997). These beaches are suspected to have sediments contaminated from industrial output (W. Cretney, pers. comm., 1997). Examination of the hemolymph (a fluid found in coelom of some invertebrates, regarded as equivalent to blood and lymph of higher forms) revealed a high prevalence of leukemia in clams collected from beaches located near an aluminum smelter and pulp mills as compared to reference sites. For instance, the high incidence of leukemia in our Kitimat clams (68%) is similar to that found in the New Bedford Harbour population (which consistently exceeded 60%) (Harper et al., 1994).

The leukemic cells express a distinct tumour-associated protein which is not detected on either normal hemocytes (blood cells in invertebrates) or on any normal tissue (Miosky et al., 1989). Specifically, a highly sensitive and specific monoclonal antibody (1E10) identifies only leukemic cells which express this protein, making the reagent extraordinarily valuable for diagnostic purposes (Smolowitz et al., 1989). Extremely high concentrations of PCBs occur in both sediments and tissues of *Mya arenaria* collected from New Bedford Harbour, and data show that the probability of developing leukemia is 7- to 8-fold higher when clams live in PCB-contaminated sites (Harper et al., 1994). This observation lends further credence to the hypothesis that industrial contaminants may be actively involved in the neoplastic (cell growth or proliferation expressed as new or added tissue, generally pathological) process. Minimal monitoring of marine animal health has been carried out due to limited funds from the Canadian government, yet it is absolutely essential to document neoplasia in marine animals that may be directly associated with bioaccumulation of industrial pollutants. Because large populations of *Mya arenaria* are located in the intertidal areas of the Fraser River estuary, monitoring of this species for leukemia has obvious merits.

Neogastropods

Tributyltin compounds (TBTX, where usually X = Cl, F, O) are among the most toxic man-made substances ever intentionally introduced (as an antifoulant) into the hydrosphere. They are also the only substances for which direct cause-effect linkages have been established for marine organisms. The two main and widely studied effects are shell malformation in oysters (Thompson et al. (1985) and references therein) and the occurrence of male sex characteristics in female neogastropod whelks, known as imposex (Smith, 1971; Gibbs et al., 1988). These organisms are extremely sensitive to tributyltin, with as little as one part in a trillion inducing imposex (Bryan et al., 1987). Imposex in its most severe manifestation can result in blockage of the oviduct and subsequent sterilization. The effects are nonreversible.

Species of neogastropod whelks have been utilized on the southern British Columbia coast as indicators of the occurrence and severity of impact from tributyltin-based marine antifoulant coatings, which are the primary source of this contaminant. Occurrence of imposex in female whelks (*Nucella* sp., *inter alia*) is determined by the presence of a penis and possibly the formation of a vas deferens (duct leading from testes to penis). The severity of impact is assessed by determination of the RPS (relative penis size; calculated from the ratio of the cube of the female penis length to the cube of the average male penis length). Recent studies (Bright and Ellis, 1990; Tester et al., 1996) have shown that there is a spatial relationship between the incidence and severity of imposex and the proximity of whelks to major harbours and shipping lanes where the release of tributyltin from large hulls and high sedimentary residues occur (Maguire et al., 1986; Garrett and Shrimpton, 1996; Stewart and Thompson, 1997). In the vicinity of Burrard Inlet (including Vancouver Harbour and the Fraser River estuary), there was an absence of individuals of any of the study species, indicating that populations had been severely impacted where they had been identified historically (D. Ellis, pers. comm., 1997). Around the southern tip of Vancouver Island, including Victoria, populations were reduced and imposex incidence was approximately 100%.

Data from three imposex surveys conducted in 1987, 1993, and 1994 indicate that the incidence and severity have decreased significantly at outlying areas around Vancouver Island (Saavedra Alvarez and Ellis, 1990; Tester and Ellis, 1995; Tester et al., 1996). These data suggest that the impact from tributyltin is lessening to some extent, although there is little indication that any major reduction will occur in areas of heavy ship traffic in the foreseeable future. Imposex should continue to serve as a sensitive indicator of temporal changes in environmental tributyltin in the Fraser River estuary. Unfortunately, there is no indication of future federal government funding to support future imposex surveys.

Dungeness crab

Studies on Dungeness crab, *Cancer magister*, sampled near the Iona Island sewage treatment plant revealed elevated concentrations of heavy metals and toxic organic compounds (Greater Vancouver Regional District, unpub. report, 1988), which subsequently led to the closure of fishing for this species. There have been numerous studies on the histopathological effects of laboratory exposure of organic or metal contaminants on the crustacean digestive gland, the hepatopancreas (e.g. Doughtie and Rao, 1984; Robinson and Dillaman, 1985; Victor, 1993), but relatively few studies on the effects of environmental exposure to contaminants on the hepatopancreas of Dungeness crab (Malins et al., 1982; Morado et al., 1988). These environmental studies, however, have shown that incidence and severity of idiopathic lesions (cell or tissue changes for which there is no known cause) of the hepatopancreas were related to the area where the Dungeness crabs were collected.

Recently, Dungeness crabs were collected from the Fraser River estuary for histopathological examination of the hepatopancreas for idiopathic lesions due to contaminant exposure (J.A.J. Thompson, D.G. Brand, and M.B. Yunker, abstract presented at Society of Environmental Toxicology and Chemistry, Second World Congress, November 5–9, 1995, Vancouver, British Columbia). The change in volume and abundance of lysosomes (organelles containing digestive enzymes of the cell) in the reserve (R-) cells is statistically different between capture sites. The Fraser River estuary population revealed a significantly greater number of lysosomes compared to the reference site populations from Sidney Island in Haro Strait. Generally, stored material within the R-cells is mobilized pre- and postmoult to sustain the crab over the nonfeeding stages of the cycle (Icely and Nott, 1992); however, these functions of the hepatopancreas also detoxify pollutants, and the response of the R-cells depends on the type of pollutant involved (Robinson and Dillaman, 1985). There is little evidence to suggest that moulting cycles vary temporally for differing crab populations (G. Jamieson, pers. comm., 1994), and because the Dungeness crabs in this study were collected during late September, moulting was unlikely (MacKay, 1942). Thus increased lysosomal numbers and size are most likely due to the involvement of contaminants (Robinson and Dillaman, 1985).

Granulomas (a localized inflammatory response in tissues, made up of white blood cells, granulocytes, and fibrin) in crustaceans were first reported in the midgut of the Dungeness crab by Sparks (1980) and were believed to be of biotic origin. Morado et al. (1988), however, observed idiopathic granulomas in virtually all organs and tissues from oil-exposed Dungeness crab. Crabs in this study also were examined for granulocytic invasion of the hepatopancreatic tubules. The Fraser River estuary samples possessed a significantly greater number of invasive granulocytes (granulomas) compared to the reference site. The toxic infusion of contaminants derived from industrial and municipal input may be involved in the induction of the severe proliferative responses. No indication of infectious agents was observed in this study. It is likely, therefore, that the granulomas were induced by abiotic, environmental sources.

The presence of nuclear and nucleolar enlargement or hypertrophy may suggest cell division impairment due to contaminant exposure (Doughtie and Rao, 1984). For crabs collected from the Fraser River estuary, nuclear and nucleolar diameters of the fibrillar F-cells were significantly greater when compared to those from the reference sites. Nuclear condensation, an indicator of cell death, was observed in the F-cells of crabs from Sand Heads in the estuary and from False Creek in Burrard Inlet.

The Dungeness crab hepatopancreas may, therefore, serve as a suitable subject for further examination of the effects of pollution because the cell types of the organ show a varied response to exposure. The present study is an example in which the prevalence and severity of certain lesions are related statistically to location of capture. It is important to point out that the data in this study are limited in time and scope; however, observations indicate that a more critical evaluation of lesions and of how they are reported may be necessary when investigating environmental disturbances of any type and their possible effects on native organisms.

FISH STUDIES

Information describing the use by juvenile salmon of the intertidal area of the inner estuary of the Fraser River has increased in recent years (e.g. Levy and Northcote, 1982; Birtwell et al., 1983, 1988), but less attention has been focused on the 'outer estuary' that lies seaward of the main land mass at high tide. Greer et al. (1980) documented the presence of 38 species of fish in these outer estuarine areas. Because the intertidal areas of the 'outer' Fraser River estuary are used by large numbers of fish, these populations may be affected by any environmental degradation of their habitats (Birtwell et al., 1983).

The alterations of fish species diversity and abundance associated with contaminant concentrations are indicators of ecosystem health; however, limited data are available for contaminants in fish from the Fraser River estuary. Fish muscle tissues and livers have been analyzed periodically over the last twenty years (Swain and Walton, 1989). Xenobiotics are accumulating in fish livers, but concentrations in muscle tissue remain within accepted standards. It should be noted there has not been a regular biomonitoring program to provide the necessary data for the assessment of long-term trends.

English sole

Bottom-feeding ground fish, in particular English sole (*Pleuronectes vetulus*), are exposed to a variety of sediment-bound contaminants by direct contact or by consumption of tainted organisms. The Fraser River estuary is a feeding ground for adult English sole and a nursery for juveniles. Changes in biomarkers that have been shown to reflect contaminant exposure (i.e. mixed function oxygenase or enzymes involved the breakdown of xenobiotics, bile metabolites, and liver histopathology) are found in English sole collected from the estuary.

The mixed function oxygenase system (i.e. ethoxyresorufin *o*-deethylase) plays a central role in the metabolism of many environmental pollutants that are lipophilic and concentrate in fatty tissues. Induction of the mixed function oxygenase activities by many xenobiotics is one of this system's major characteristics (Stegemann, 1984). Metabolically activated intermediates of aromatic hydrocarbons are known to bind to DNA (Varanasi et al., 1982) and are associated with induction of tumours (Malins et al., 1983; Varanasi et al., 1987; Krahn et al., 1988). To date, studies on the mixed function oxygenase system have revealed induction in English sole collected near the pulp mill at Crofton on the western margin of the Strait of Georgia basin when compared to fish from two reference sites, Trincomali Channel and near Bamfield, British Columbia (D.G. Brand; abstract presented at the Society of Environmental Toxicology and Chemistry Second World Congress, November 5–9, 1995, Vancouver, British Columbia; Addison and Fraser, 1996). Metabolites of polycyclic aromatic hydrocarbons (PAHs) that escape conjugation become recycled through mixed function oxygenase activity and are transformed into very reactive epoxide derivatives. It is believed that covalent binding to DNA of the epoxide derivatives is an important early event in the formation of a tumour (Gelboin, 1980).

The presence of polycyclic aromatic hydrocarbons (PAHs) in the aquatic environment is due mainly to incomplete combustion (from many sources) and to petrochemical pollution (National Research Council, 1985, p. 3, 9, 28). Uptake, biotransformation, and excretion rates of PAHs in fish are fairly high, which means that accumulation is not likely to occur, and analysis of parent (nonmetabolized) PAHs in liver or muscle tissue will reveal only very low levels (Varanasi et al., 1985; Dunn, 1991). Therefore, the biomonitoring of PAH uptake should concentrate on the determination of PAH metabolites in excreta, particularly in gall bladder bile (Krahn et al., 1984). Because these metabolites of aromatic compounds are rapidly excreted into bile for elimination, the bile can be considered a short-term indicator of contamination. Therefore, the presence of PAH metabolites in the bile is evidence of relatively recent exposure of the fish to the contaminant.

Polycyclic aromatic hydrocarbons have been identified in marine sediments associated with pulp-mill activities (W. Cretney, unpub. data, 1994). Analysis using reversed-phase high-performance liquid chromatography (HPLC; according to the methods of Krahn et al. (1988)), in which PAHs were measured as benzo[a]pyrene equivalents, revealed an increase in levels of PAH bile metabolites in English sole collected from the pulp-mill site at Crofton when compared to a reference site near Bamfield, British Columbia (D.G. Brand; abstract presented at the Society of Environmental Toxicology and Chemistry Second World Congress, November 5–9, 1995, Vancouver, British Columbia). This correlates well with previous studies on xenobiotic metabolizing enzyme levels and with preneoplastic and neoplastic liver lesion frequencies for English sole collected from these two sites.

Healey et al. (1995) recorded the incidence of gross pathological abnormalities in fish collected from the lower Fraser River. Very high percentages of all species showed evidence of pathological abnormality. For example, redside shiners from the Fraser River show greater than 90%, about 60%, and greater than 70% incidence of liver, kidney, and gill abnormalities, respectively. This compares with a much lower incidence of abnormalities in Cultus Lake and Harrison River fish. These gross pathologies suggest that the fish are suffering from environmentally induced stress; however, these abnormalities were not examined histopathologically; hence, their etiology remains unknown. Research has shown a correlation between certain xenobiotic chemicals present in sediments, seawater, or food organisms with histopathological conditions in demersal fish species (Myers et al., 1987). High tumour prevalence has been identified in the livers of wild fish from areas receiving industrial effluents (McCain et al., 1982; Mix, 1986; Myers et al., 1987; Malins et al., 1988; Brand et al., 1992). With this established association between certain histopathological conditions in fish and their exposure to xenobiotic chemicals, monitoring for neoplasia and related cell disorders has obvious merit (Goyette et al., 1988).

Histopathological analysis of liver samples from English sole, *Pleuronectes vetulus*, caught in Burrard Inlet from 1986 to 1991 revealed idiopathic liver lesions with frequencies strongly dependent on location of capture (Brand, 1987; D.G. Brand, unpub. report, 1990, 1992; Brand and Goyette, 1989). To date, results reveal cases of cellular disorders (hepatocellular hemosiderosis, variable hepatocellular vacuolation, and nonspecific necrosis), preneoplastic lesions (foci of cellular alterations), and neoplastic lesions (liver cell adenomas, hepatocellular carcinomas, and cholangiocellular carcinoma) in the livers of collected fish. A high prevalence of these preneoplastic and neoplastic lesions was found in English sole collected from Burrard Inlet, particularly from areas receiving treated storm-water and processed effluents from petroleum refineries. These areas are known to have high levels of PAHs associated with the marine sediment (Goyette and Boyd, 1989). No lesions were observed for English sole collected from the reference sites, Loughborough Inlet and Imperial Eagle Channel, British Columbia.

Research to date has shown that English sole collected from Crofton also display frequencies of preneoplastic and neoplastic lesions similar to those from Burrard Inlet (Brand et al., 1992). One histopathological difference between the two sites, however, is the condition of hemosiderosis, which was present in all the English sole from Crofton. Hemosiderosis is suggestive of an underlying metabolic disorder characterized by excessive accumulation of intracytoplasmic iron within the hepatocytes (Myers et al., 1987). The condition has been experimentally induced in English sole by intermuscular injection of Eagle Harbour sediment extracts containing high levels of aromatic hydrocarbons (Schiewe et al., 1991). When this condition is experimentally induced in rats, the probability of developing hepatocellular carcinomas with exposure to xenobiotics increases. It has been suggested that iron overload potentiates the neoplastic process with both induction and inhibition of various enzyme activities related to xenobiotics (Smith et al., 1993). Also, DNA damage and mutation brought about by iron are likely to occur by the generation of 1) hydrogen peroxide by the autoxidation of iron, and 2) hydroxyl radicals by the interaction of hydrogen peroxide with iron (Loeb et al., 1988). Further histopathological examination of English sole tissues, accompanied by measurements for products of oxidative stress such as mixed function oxygenase, excess iron, and oxidative adducts of DNA, may provide answers regarding tumour genesis.

Starry flounder

The deaths of many flatfish (primarily starry flounder, *Platichthys stellatus*) on the sand flats of Sturgeon Bank have been attributed to the discharge of sewage into the outer Fraser River estuary (Birtwell et al., 1983). Also, declining catches of flatfish since 1965 in the area adjacent to the Fraser River (K. Ketchen, pers. comm., 1983) appear to coincide with the opening of the Iona Island sewage treatment plant in 1964. Tissue analysis of Sturgeon Bank starry flounder has indicated the presence of trace levels of a series of persistent chlorinated and nonchlorinated hydrocarbons. Dichlorodiphenyltrichloroethane (DDT)-related compounds identified in the flounder most likely originated from atmospheric pathways and via agricultural runoff from areas of the Fraser River valley. Phenols and chlorinated phenols likely originated from the domestic use of such compounds as antiseptics and wood preservatives (Birtwell et al., 1983). From the close resemblance between compounds identified in the sewage and those present in the flounder, it can be concluded that the Iona Island sewage treatment plant wastewater played at least some role in the contamination of flounder on Sturgeon Bank.

Environment Canada has completed a health assessment for starry flounder collected from the estuary (B. Raymond, unpub. data, 2001). Histopathological analysis of flounder liver revealed fatty changes in the liver tissues characterized as hepatocellular steatosis and hydropic vacuolation in juvenile fish (D.G. Brand and B. Raymond, unpub. data, 2001).

Hepatocellular steatosis is a degenerative condition suggestive of metabolic disorders (Myers et al., 1987) and is also commonly associated with dietary deficiencies or toxic chemical administration. Its role in the progression of lesions towards neoplasm formation in fish is not presently understood (McCain et al., 1982). Hydropic vacuolation is another degenerative condition. It has been observed in winter flounder collected from contaminated sites in Boston Harbour, Massachusetts, and also in rock sole and starry flounder from contaminated sites in Puget Sound, Washington (Harshbarger and Clark, 1990; Stehr, 1990). This lesion was highly correlated with cholangiocytic (bile duct) neoplasms and slightly correlated with hepatocellular neoplasms (Harshbarger and Clark, 1990). The magnitude and unique nature of the cellular alterations, along with the relatively high prevalence of fish affected at contaminated sites, point to this as a specific biomarker (Hinton et al., 1992); however, the absence of laboratory studies demonstrating induction of similar changes by exposure to toxicants, and the observation of this lesion in fish collected from reference sites (M. Myers, pers. comm., 1990), warrant further investigation.

Salmonids

The Fraser River in British Columbia has long enjoyed a reputation as one of the world's major producers of Pacific salmon (*Oncorhynchus* spp.); however, since the 1950s there has been a steady decline in adult returns of chinook (*O. tshawytscha*) and coho salmon (*O. kisutch*) (Fraser et al., 1982). More recently, Starr and Schubert (1990) reported that the Harrison River fall chinook stock, which rears in the Fraser River estuary and constitutes the major contributor to both commercial and sport fishery in the Strait of Georgia, has been in a state of virtual "collapse" since 1986. In addition to overfishing, the degradation of habitat and possible sublethal effects of complex mixtures of pollutants in the river are factors which could be contributing to this decline (Kruzynski and Birtwell, 1994).

Effluent from the Iona Island sewage treatment plant was discharged intertidally in the outer estuary of the Fraser River, but now it is dispersed in the Strait of Georgia at a depth of about 100 m. The plant has been operating for over thirty years and, since then, extensive degradation of the intertidal area has occurred. This has resulted in the contamination of organisms and the often daily large-scale mortality, both direct and indirect (predation), of fishery resources, particularly in early spring and in summer months when the dilution capacity of the river was minimal (Birtwell et al., 1983). Downstream migration for juvenile salmon coincided with this period of minimal flow, which conversely resulted in maximal contaminant exposure (Birtwell et al., 1988).

Other migrating fish, including adult eulachons (*Thaleichthys pacificus*), move upstream during this period to spawn in the lower Fraser River. Hence, valuable fishery resources are being subjected to reduced-water-quality episodes during their migration (Birtwell et al., 1988). Research on juvenile chinook salmon conducted before the sewage-treatment outfall was extended into the Strait of Georgia had shown deleterious effects at low concentrations. For instance, effects included an impairment of osmoregulatory ability (water and salt control in an organism), uptake of contaminants (especially chlorinated phenols), and changes in growth rate (Kruzynski et al., 1986; Rogers et al., 1986). It is also known that, historically, the effluent is toxic to fish (the 96h LC_{50}, or concentration of effluent required to kill 50% of the test organisms within 96 hours, is about 45%; D.W. Martens and J.A. Servizi , unpub. report, 1976) and that a high oxygen demand was exerted both directly and indirectly (B.C. Research, unpub. report prepared for Greater Vancouver Sewerage and Drainage District, 1975; B.C. Research, unpub. report prepared for Greater Vancouver Sewerage and Drainage District, 1977; Birtwell et al., 1983).

Recent salmonid studies have focused on the effects of the wood preservative 'antisapstain compound' 2-(thiocyanomethylthio)benzothiazole (TCMTB), which was proposed as a replacement for pentachlorophenol in lumber storage facilities (Kruzynski and Birtwell, 1994). Storm-water leachates from treated wood running into estuarine reaches had raised concerns about the toxic effects of this compound on juvenile salmon. Under simulated flow conditions, juvenile chinook salmon (*Oncorhynchus tshawytscha*) were exposed to a sublethal concentration of TCMTB in a vertically stratified water column. In addition to the stress of salinity, they also were challenged with a marine predator (yellowtail rockfish, *Sebastes flavidus*). After five days, compared to controls, exposed chinook salmon were consumed 5.5 times more frequently.

One of the main behavioural differences between control chinook salmon and those exposed to TCMTB was the observed reduction in swimming speed leading to increased vulnerability to predators. Also, the observed gradual disruption of schooling in chinook salmon exposed to TCMTB corroborates the sensitivity of this behavioural response to toxic stress. Schooling disruption persisted for several days after transfer of the chinook salmon to the predation tank, suggesting a long-lasting effect that persisted well into the period of recovery from prior toxicant exposure (Kruzynski and Birtwell, 1994). Similar disruptions in the schooling behaviour of juvenile chinook, chum, and coho salmon have also been recorded in waters receiving acutely toxic pulp-mill effluent (Birtwell and Kruzynski, 1989). Since schooling is a well known antipredation strategy (Cushing and Harden-Jones, 1968), it is likely that even subtle aberrations of normal schooling tendency could render toxicant-exposed fish less able to evade predators (Kruzynski and Birtwell, 1994).

The predator bioassay demonstrated that prior sublethal exposure to TCMTB led to the death of salmon from predation, which raises the fundamental question of whether 'ecological death' may be an overlooked legacy of physiologically sublethal toxicant exposure. Routine laboratory studies on the toxicity of xenobiotics rarely take into account the fate of organisms after conclusion of the exposure period. Because predator avoidance represents successful integration of biochemical, physiological, and behavioural responses, the predation bioassay could be considered as an ecologically relevant technique towards understanding the significance of the multitude of complex multifactorial interactions that determine environmental risk.

CONCLUSIONS

The above examples indicate that aquatic organisms in the lower reaches of the Fraser River watershed respond to a variety of contaminants. While a more thorough examination of the extent of contamination is warranted, it is more important to determine the consequences to the health and survival of the organisms and effects on their habitat (Birtwell et al., 1988). Chemical analysis and acute toxicity responses have been found to be insufficient to assess the responses of aquatic ecosystems to various pollutants. In this context, sublethal toxicity tests may make it possible to detect incipient effects on fish and to estimate threshold concentrations; however, no single approach to the problem of monitoring biological effects can be fully satisfactory. Some methods seem more useful than others, but greatest insights are usually obtained by multidisciplinary efforts, often those in which pathology and/or physiology are allied with biochemistry, and then augmented by chemical analyses of tissue and environmental samples.

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REFERENCES

Addison, R.F.
1996: The use of "biological effects monitoring" in studies of marine pollution; Environmental Reviews, v. 4, p. 225–237.

Addison, R.F. and Fraser, T.F.
1996: Hepatic mono-oxygenase induction in benthic flatfish sampled near coastal pulp mills in British Columbia; Marine Environmental Research, v. 42, p. 273.

Anonymous
1992: State of the Environment for the Lower Fraser River Basin; A State of the Environment Report; SOE Report No. 92-1 (co-published by the B.C. Ministry of Environment), 79 p.

Birtwell, I.K. and Kruzynski, G.M.
1989: In situ and laboratory studies on the behaviour and survival of Pacific salmon (genus *Oncorhynchus*); Hydrobiologia, v. 188/189, p. 543–560.

Birtwell, I.K., Greer, G.L., Nassichuk, M.D., and Rogers, I.H.
1983: Studies of the impact of municipal sewage discharged onto an intertidal area within the Fraser River estuary, British Columbia; Canadian Technical Report of Fisheries and Aquatic Sciences, no. 1170, 55 p.

Birtwell, I.K., Levings, C.D., Macdonald, J.S., and Rogers, I.H.
1988: A review of fish habitat issues in the Fraser River system; Water Pollution Research Journal of Canada, v. 23, p. 1–30.

Brand, D.G.
1987: Histopathological evaluation of fish tissue abnormalities from Vancouver Harbour; Environment Canada, Conservation and Protection, Pacific and Yukon Region, Vancouver, British Columbia, Regional Manuscript Report 87-04, 18 p.

Brand, D.G. and Goyette, D.
1989: Further studies of the prevalence of idiopathic liver lesions in English sole, *Parophrys vetulus*, from Vancouver Harbour, British Columbia, 1987; Environment Canada, Conservation and Protection, Pacific and Yukon Region, Vancouver, British Columbia, Regional Program Report 89-02, 30 p.

Brand, D.G., Reid, R.G.B., and Harris, M.L.
1992: Prevalence of idiopathic gill and liver lesions in English and Flathead Sole collected near pulp mills of Howe Sound; Canadian Fisheries and Aquatic Sciences Technical Report, no. 1879, p. 239–250.

Bright, D.A. and Ellis, D.V.
1990: A comparative survey of imposex in the northeast Pacific gastropods (Prosobranchia) related to tributyltin contamination and the choice of a suitable bioindicator; Canadian Journal of Zoology, v. 21, p. 1915–1924.

Bryan, G.W., Gibbs, P.E., Burt, G.R., and Hummerstone, L.G.
1987: The effects of tributyltin (TBT) accumulation on adult dog-whelks, *Nucella lapillus*: long-term field and laboratory experiments; Journal of the Marine Biological Association of the UK, v. 67, p. 525–544.

Cairns, J., Jr. and Pratt, J.R.
1989: The scientific basis of bioassays; Hydrobiologia, v. 188/189, p. 5–20.

Carey, J.H.
1988: Pathways of chlorophenols in the Fraser River estuary; *in* Proceedings of the Canada–British Columbia Workshop on Water Quality Guidelines and Objectives: Focus on the Fraser; (ed.) D.D. Macdonald; November 16–17, 1988; Vancouver, British Columbia, p. 29–34.

Carey, J.H. and Hart, J.H.
1988: Sources of chlorophenolic compounds to the Fraser River estuary; Water Pollution Research Journal of Canada, v. 23, p. 55–68.

Cretney, W.J., Crewe, N.F., Macdonald, R.W., and Paton, D.W.
1992: Spatial and temporal distribution of dioxins in subtidal sediments from Howe Sound, B.C.; *in* Proceedings of the Howe Sound Environmental Science Workshop, (ed.) C.D. Levings, R.J. Turner, and B.D. Ricketts; Canadian Technical Report of Fisheries and Aquatic Sciences, no. 4879, p. 143–147.

Cushing, D.H. and Harden-Jones, F.R.
1968: Why do fish school?; Nature (London), v. 218, p. 918–920.

Doughtie, D.G. and Rao, K.R.
1984: Histopathological and ultrastructural changes in the antennal gland, midgut, hepatopancreas and gill of grass shrimp following exposure to hexavalent chromium; Journal of Invertebrate Pathology, v. 43, p. 89–108.

Dunn, B.P.
1991: Carcinogen adducts as an indicator for the public health risks of consuming carcinogen exposed fish and shellfish; Environmental Health Perspectives, v. 90, p. 111–116.

Fraser, F.J., Starr, P.J., and Fedorenko, A.Y.
1982: A review of the chinook and coho salmon of the Fraser River; Canadian Technical Report for Fisheries and Aquatic Sciences, no. 1126, 130 p.

Garrett, C.L. and Shrimpton, J.A.
1996: Chemicals in the environment, VII, Organotin compounds; Environment Canada, Environmental Protection Branch, Pacific and Yukon Region, Regional Program Report No. 95-06, 59 p.

Gelboin, H.V.
1980: Benzo[a]pyrene metabolism, activation and carcinogenesis: role and regulation of mixed-function oxidases and related enzymes; Physiological Review, v. 60, p. 1107–1166.

Gibbs, P.E., Pascoe, P.L., and Burt, G.R.
1988: Sex change in the female dog-whelk, *Nucella lapillus*, induced by tributyltin from antifouling paints; Journal of the Marine Biological Association of the UK, v. 68, p. 715–731.

Goldstein, I.F.
1981: The use of biological markers in studies of health effects of pollutants; Environmental Research, v. 25, p. 236–240.

Goyette, D. and Boyd, J.
1989: Distribution and environmental impact of selected benthic contaminants in Vancouver Harbour, British Columbia, 1985–1987; Environment Canada, Pacific and Yukon Region, Vancouver, B.C., Regional Program Report 89-02, 99 p.

Goyette, D., Brand, D.G., and Thomas, M.
1988: Prevalence of idiopathic liver lesions in English sole and epidermal abnormalities in flatfish from Vancouver Harbour, British Columbia, 1986; Environment Canada Regional Program Report 87-09, 18 p.

Greer, G.L., Levings, C.D., Harbo, R., Hillaby, B., Brown, T., and Sibert, J.
1980: Distribution of fish species on Roberts and Sturgeon Banks recorded in seine and trawl surveys; Canadian Manuscript Report for Fisheries and Aquatic Sciences, no. 1596, 51 p.

Harper, D., Flessas, D., and Reinisch, C.L.
1994: Specific reactivity of leukemia cells to polyclonal anti-PCB antibodies; Journal of Invertebrate Pathology, v. 64, p. 234–237.

Harshbarger, J.C. and Clark, J.B.
1990: Epizootiology of neoplasms in bony fish of North America; Science for the Total Environment, v. 94, p. 1–32.

Healey, M., Richardson, J., and Lissimore, T.
1995: Carbon, contaminants and fish in the Fraser estuary; *in* Proceedings of the 1995 Habitat Management Workshop; Fraser River Estuary Management Program, Technical Report H-95-1, p. 58–60.

Hinton, D.E., Baumann, P.C., Gardner, G.R., Hawkins, W.E., Hendricks, J.D., Murchelano, R.A., and Okihiro, M.S.
1992: Histopathologic biomarkers; *in* Biomarkers: Biochemical, Physiological and Histological Markers of Anthropogenic Stress, (ed.) R.J. Huggett, R.A. Kimerle, P.M. Mehrle, and H.L. Bergman; Proceedings of the Eighth Pellston Workshop, Society of Environmental Toxicology and Chemistry Special Publications Series, Lewis Publishers, Boca Raton, Florida, p. 155–209.

Huggett, R.J., Kimerle, R.A., Mehrle, P.M., Bergman, H.K., Dickson, K.L., Fava, J.A., McCarthy, J.F., Parrish, R., Dorn, P.B., McFarland, V., and Lahvis, G.
1992: Introduction; *in* Biomarkers: Biochemical, Physiological and Histological Markers of Anthropogenic Stress, (ed.) R.J. Huggett, R.A. Kimerle, P.M. Mehrle, and H.L. Bergman; Proceedings of the Eighth Pellston Workshop, Society of Environmental Toxicology and Chemistry Special Publications Series, Lewis Publishers, Boca Raton, Florida, p. 1–4.

Icely, J.D. and Nott, J.A.
1992: Digestion and absorption: digestive system and associated organs; *in* Microscopic Anatomy of Invertebrates, (ed.) F.W. Harrison and A.G. Humes; Wiley-Liss, Inc., v. 10, p. 147–201.

Krahn, M.M., Myers, M.S., Burrows, D.G., and Malins, D.C.
1984: Determination of metabolites of xenobiotics in bile of fish from polluted waterways; Xenobiotica, v. 14, p. 633–646.

Krahn, M.M., Rhodes, L.D., Myers, M.S., Moore, K.K., MacLeod, W.D., and Malins, D.C.
1986: Associations between metabolites of aromatic compounds in bile and the occurrence of hepatic lesions in English sole (*Parophrys vetulus*) from Puget Sound, Washington; Archives in Environmental Contamination and Toxicology, v. 15, p. 61–67.

Krahn, M.M., Wigren, C.A, Pearce, R.W., Moore, L.K., Bogar, R.G., MacLeod, W.D., Chan, S.L., and Brown, D.W.
1988: Standard analytical procedures of the NOAA National Analytical facility, 1988. New HPLC cleanup and revised extraction procedures for organic contaminants; NOAA Technical Memorandum NMFSF/NWC-153, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, Washington, 52 p.

Kruzynski, G.M. and Birtwell, I.K.
1994: A predation bioassay to quantify the ecological significance of sublethal responses of juvenile chinook salmon (*Oncorhynchus tshawytscha*) to the antisapstain fungicide TCMTB; Canadian Journal of Fisheries and Aquatic Sciences, v. 51, p. 1780–1790.

Kruzynski, G.M., Birtwell, I.K., and Rogers, I.H.
1986: Studies on chinook salmon (*Oncorhynchus tshawytscha*) and municipal waste from the Iona Island sewage treatment plant, Vancouver, B.C.; *in* Proceedings of the 11th Annual Aquatic Toxicity Workshop, November 13–15, 1984, Vancouver, British Columbia, (ed.) G.H. Geen and K.L. Woodward; Canadian Technical Report for Fisheries and Aquatic Sciences, no. 1480, p. 240–250.

Larsson, A., Haux, C., and Sjobeck, M.
1985: Fish physiology and metal pollution: results and experiences from laboratory and field studies; Ecotoxicology and Environmental Safety, v. 9, p. 250–282.

Levy, D.A. and Northcote. T.G.
1982: Juvenile salmon residency in a marsh area of the Fraser River estuary; Canadian Journal of Fisheries and Aquatic Sciences, v. 39, p. 270–276.

Loeb, L.A., James, E.A., Waltersdorp, A.M., and Klebanoff, S.J.
1988: Mutagenesis by the autoxidation of iron with isolated DNA; Proceedings of the National Academy of Sciences, USA, v. 85, p. 3918–3922.

MacKay, D.C.G.
1942: The Pacific edible crab, *Cancer magister*; Fisheries Research Board of Canada, Bulletin No. LXII, p. 1–32.

Maguire, R.S., Tkacz, R.J., Chau, Y.K., Bengert, G.A., and Wong, P.T.S.
1986: Occurrence of organotin compounds in water and sediment in Canada; Chemosphere, v. 15, p. 253–274.

Malins, D.C., McCain, B.B., Brown, D.W., Sparks, A.K., Hodgins, H.O., and Chan, S.-L.
1982: Chemical contaminants and abnormalities in fish and invertebrates from Puget Sound; National Oceanic and Atmospheric Administration Technical Memorandum OMPA-19, National Marine Fisheries Service, Seattle, Washington, 189 p.

Malins, D.C., McCain, B.B., Landahl, J.T., Myers, M.S., Krahn, M.M., Brown, D.W., Chan, C.L., and Roubal, W.T.
1988: Neoplastic and other diseases in fish in relation to toxic chemicals: an overview; Aquatic Toxicology, v. 11, p. 43–67.

Malins, D.C., Myers, M.S., and Roubal, W.T.
1983: Organic free radicals associated with idiopathic lesions of English sole (*Parophrys vetulus*) from Puget Sound, Washington; Archives of Environmental Contamination and Toxicology, v. 17, p. 679–685.

Mayer, F.L., Versteeg, D.J., McKee, M.J., Folmar, L.C., Graney, R.L., McCume, D.C., and Rattner, B.A.
1992: Physiological and nonspecific biomarkers; *in* Biomarkers: Biochemical, Physiological and Histological Markers of Anthropogenic Stress, (ed.) R.J. Huggett, R.A. Kimerle, P.M. Mehrle, and H.L. Bergman; Proceedings of the Eighth Pellston Workshop, Society of Environmental Toxicology and Chemistry Special Publications Series, Lewis Publishers, Boca Raton, Florida, p. 5–85.

McCain, B.B., Myers, M.S., Varanasi, U., Brown, D.W., Rhodes, L.D., Gronlund, E.D., Elliot, D.G., Palsson, W.A., Hodgins, H.D., and Malins, D.C.
1982: Pathology of two species of flatfish from urban estuaries in Puget Sound; Interagency Energy–Environment Research and Development Program Report, EPA-600/7-82-001, Environmental Protection Agency, Washington, D.C., 100 p.

Miller, D.S.
1981: Heavy metal inhibition of p-aminohippurate transport in flounder renal tissue: sites of $HgCl_2$ action; Journal of Pharmacology and Experimental Therapy, v. 219, p. 428–434.

Miosky, D.L., Smolowitz, R.M., and Reinisch, C.L.
1989: Leukemia cell specific protein of the bivalve mollusc *Mya arenaria*; Journal of Invertebrate Pathology, v. 53, p. 32–39.

Mix, M.C.
1986: Cancerous diseases in aquatic animals and their association with environmental pollutants: a critical literature review; Marine Environmental Research, v. 20, p. 1–141.

Morado, J.F., Sparks, A.K., and O'Clair, C.E.
1988: A preliminary study of idiopathic lesions in the Dungeness crab, *Cancer magister*, from Rowan Bay, Alaska; Marine Environmental Research, v. 26, p. 311–318.

Myers, M.S., Rhodes, L.D., and McCain, B.B.
1987: Pathologic anatomy and pattern of occurrence of hepatic neoplasms, putative preneoplastic lesions and other idiopathic hepatic conditions in English sole (*Parophrys vetulus*) from Puget Sound, Washington; Journal of the National Cancer Institute, v. 78, p. 333–363.

National Research Council
1985: Oil in the sea: inputs, fates and effects; National Academy Press, Washington, D.C., 601 p.

Robinson, A.G. and Dillaman, R.M.
1985: The effects of naphthalene on the ultrastructure of the hepatopancreas of the fiddler crab, *Uca minax*; Journal of Invertebrate Pathology, v. 45, p. 311–323.

Rogers, I.H., Birtwell, I.K., and Kruzynski, G.
1990: The Pacific eulachon (*Thaleichthys pacificus*) as a pollution indicator organism in the Fraser River estuary, Vancouver, British Columbia; Science for the Total Environment, v. 97/98, p. 713–727.
Rogers, I.H., Birtwell, I.K., and Kruzynski, G.M.
1986: Organic extractables in municipal wastewater; Vancouver, British Columbia; Water Pollution Research Journal of Canada, v. 21, p. 187–204.
Rogers, I.H., Servizi, J.A., and Levings, C.D.
1988: Bioconcentration of chlorophenols by juvenile chinook salmon (*Oncorhyncus tshawytscha*) overwintering in the upper Fraser River: field and laboratory tests; Water Pollution Research Journal of Canada, v. 23, p. 100–113.
Root, M.
1990: Biological monitors of pollution; Bioscience, v. 40, p. 83–86.
Saavedra Alvarez, M.M. and Ellis, D.V.
1990: Widespread neogastropod imposex in the Northeast Pacific: implications of TBT contamination surveys; Marine Pollution Bulletin, v. 21, p. 244–247.
Schiewe, M.W., Weber, D.D., Myers, M.S., Jacques, F.J., Reichert, W.L., Krone, C.A., Malins, D.C., McCain, B.B., Chan, S.-L., and Varanasi, U.
1991: Induction of foci of cellular alteration and other hepatic lesions in English sole (*Parophrys vetulus*) exposed to an extract of an urban marine sediment; Canadian Journal of Fisheries and Aquatic Sciences, v. 48, p. 1750–1760.
Servizi, J.A., Gordon, R.W., and Carey, J.H.
1988: Bioconcentration of chlorophenols by early life stages of Fraser River pink and chinook salmon (*Oncorhybcus gorbuscha, O. tshawytscha*); Water Pollution Research Journal of Canada, v. 23, p. 88–99.
Smith, A.G., Carthew, P., Francis, J.E., Ficardo, J., Cabral, P., and Manson, M.M.
1993: Enhancement by iron of hepatic neoplasia in rats caused by hexachlorobenzene; Carcinogenesis, v. 14, p. 1381–1387.
Smith, B.S.
1971: Sexuality in the American mud snail, *Nassarius obsoletus* Say; Proceedings of the Malacological Society of London, v. 39, p. 377–379.
Smolowitz, R.M., Miosky, D.L., and Reinisch, C.L.
1989: The ontogeny of leukemia cells of the sot shell clam; Journal of Invertebrate Pathology, v. 53, p. 41–52.
Sparks, A.K.
1980: Multiple granulomas in the midgut of the Dungeness crab, *Cancer magister;* Journal of Invertebrate Pathology, v. 35, p. 323–334.
Starr, P.J. and Schubert, N.D.
1990: Assessment of Harrison River chinook salmon; Canadian Manuscript Report for Fisheries and Aquatic Sciences, no. 2085, 47 p.
Stegemann, J.J.
1984: Polynuclear aromatic hydrocarbons and their metabolism in the marine environment; *in* Polycyclic Hydrocarbons and Cancer, (ed.) H.V. Gelboin, and P.O.P. Ts'o; Academic Press, Inc., New York, New York, v. 3, p. 1–60.
Stehr, C.
1990: Ultrastructure of vacuolated cells in the liver of rock sole and winter flounder living in contaminated environments; *in* Proceedings of the 12th International Congress for Electron Microscopy, Seattle, Washington, p. 522–623.
Stewart, C. and Thompson, J.A.J.
1997: Vertical distribution of butyltin residues in sediments of British Columbia harbours; Environmental Technology, v. 18, p. 1195–1202.
Swain, L.G. and Walton, D.G.
1989: Report on the 1988 fish monitoring program; Fraser River Estuary Monitoring, Fraser River Harbour Commission/B.C. Ministry of Environment, Ministry of Water, Land and Air Protection, Province of British Columbia, Victoria, British Columbia, 147 p.
Tester, M. and Ellis, D.
1995: TBT controls and the recovery of whelks from imposex; Marine Pollution Bulletin, v. 30, p. 90–91.
Tester, M., Ellis, D.V., and Thompson, J.A.J.
1996: Neogastropod imposex for monitoring recovery from marine TBT contamination; Environmental Toxicology and Chemistry, v. 15, p. 560–567.
Thompson, J.A.J., Scheffer, M.G., Pierce, R.C., Chau, Y.K., Cooney, J.J., Cullen, W.R., and Maguire, R.J.
1985: Organotin compounds in the aquatic environment: scientific criteria for assessing their effects on environmental quality; Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Publication No. 22494, Ottawa, Ontario, 284 p.
Varanasi, U., Nishimoto, M., Reichert, W.L., and Stein, J.E.
1982: Metabolism and subsequent covalent binding of benzo[a] pyrene to macromolecules in gonads and liver of rip English sole (*Parophrys vetulus*); Xenobiotica, v. 12, p. 417–425.
Varanasi, U., Reichert, W.L., Stein, J.E., Brown, D.W., and Sanborn, H.R.
1985: Bioavailability and biotransformation of aromatic hydrocarbons in benthic organisms exposed to sediment from an urban estuary; Environmental Science and Technology, v. 19, p. 836–841.
Varanasi, U., Stein, J.E., Nishimoto, M., Reichert, W.L., and Collier, T.C.
1987: Chemical carcinogenesis in feral fish: uptake, activation, and detoxication of organic xenobiotics; Environmental Health Perspectives, v. 71, p. 155–170.
Victor, B.
1993: Histopathological progression of hemic neoplasms in the tropical crab *Paratelphusa hydrodromous* (Herbst) treated with sublethal cadmium chloride; Archives of Environmental Contamination and Toxicology, v. 25, p. 48–54.
Wedemeyer, G.A. and McLeay, D.J.
1981: Methods for determining the tolerance of fishes to environmental stressors; *in* Stress and Fish, (ed.) A.D. Pickering; Academic Press, New York, New York, p. 247–275.

Evolution of estuarine governance in a metropolitan region: collaborating for sustainability in the Fraser River estuary

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Abstract: The Fraser River Estuary Management Program facilitates coordination among the activities of more than a hundred different agencies in implementing the jointly agreed upon Estuary Management Plan. The goal of the plan is to improve environmental quality in the Fraser River estuary while providing economic development opportunities and sustaining the quality of life in and around the estuary. Implementation takes place through the management processes and tools that have been created by the Fraser River Estuary Management Program for habitat classification, area designation, project review, and activity planning.

Key to strengthening the Fraser River Estuary Management Program is the inclusion of collaboration with nongovernmental stakeholders, so as to build public understanding and political commitment for achieving the sustainability goals that have been adopted in the Estuary Management Plan.

Résumé : Le programme de gestion de l'estuaire du fleuve Fraser facilite la coordination des activités de plus d'une centaine d'organismes dans la mise en œuvre d'un plan commun de gestion de l'estuaire du Fraser. Ce plan a pour but d'améliorer la qualité de l'environnement tout en offrant des perspectives de développement économique et en aidant à maintenir la qualité de la vie dans l'estuaire et la région environnante. La mise en œuvre du programme de gestion de l'estuaire du fleuve Fraser se fait au moyen des procédés et outils de gestion créés par ce programme pour la classification des habitats, la désignation des zones, l'examen des projets et la planification des activités.

Afin de consolider le programme de gestion de l'estuaire du Fraser, il est essentiel de collaborer avec les intervenants non gouvernementaux de manière à favoriser la sensibilisation du public et l'engagement politique à atteindre les objectifs de durabilité qui ont été adoptés dans le plan de gestion de l'estuaire.

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INTRODUCTION

For more than 10 000 years people have lived, worked, and played in and around the Fraser River estuary. During the vast majority of that time, what they did had no irreversible or extensive effects on the estuary, but in less than two centuries, population growth and settlement activities have transformed the estuary and delta. In the last three decades, there has been increasing concern about the impacts of this development, and varied attempts have been made to manage them. This paper describes and assesses these initiatives and focuses on the Fraser River Estuary Management Program (FREMP) (Dorcey, 1993; Fraser River Estuary Management Program, 1994). Except where otherwise noted, this paper is based on two basic sources that contain more detailed analysis and references: Dorcey (1993) and Fraser River Estuary Management Program (1994). Current and extensive information on the key programs that are mentioned in this paper can be found on the World Wide Web (*see* Appendix).

Over the nearly 20 years of FREMP's existence, there has been substantial progress in building a new collaborative system of estuarine governance. The first half of this paper sketches the slow evolution of these innovations, quoting from key documents to reveal how people defined the problem and evaluated alternative solutions at different points in building towards today's system. The second half of this paper assesses the innovative governance process that was created and its significant achievements in managing the estuary through coordinated processes for habitat classification, area designation, project review, and sectoral plans for different activities. It is concluded that building such collaborative approaches to governance will almost inevitably be slow and tortuous, but that they can be the well-spring for significant innovation, as evidenced by the management tools fashioned in the Fraser River estuary and now being copied elsewhere. At the same time, however, it is strange to conclude, in a province where there has been such strong experimentation with multistakeholder collaboration processes, that the greatest weakness has been the timidity with which nongovernmental stakeholders have been involved. It is argued that remedying this weakness in the estuarine governance system will be key in meeting the challenges of environmental, economic, and social sustainability that are in prospect for a region with one of the highest growth rates in North America.

It is important to note that in focusing the analysis in this paper on the collaborative approach to estuary governance, it is not being suggested that this is the only important issue to be considered in assessing the effectiveness of the governance process (Dorcey, 1991, 1993, 1997). While greater collaboration is a crucial and pervasive ingredient in the transformation of governance processes necessary to meet sustainability goals, it is only one of the elements that have been recognized as requiring greater emphasis. A more comprehensive evaluation (Dorcey, 1991, in press; Dorcey and McDaniels, 2001) would assess progress by putting greater emphasis on: ethics, being proactive, integrating science and politics, consensual decision-making, federation, intersectoral decision-making, integration of regulatory and economic mechanisms, and design of the total governance system.

While a full analysis of each of these considerations in the evolution of the Fraser River estuary governance system is a task for future publications, they are all at least touched upon in the current focus on collaboration.

DEVELOPMENT OF THE FRASER RIVER ESTUARY AND DELTA

From the beginning of history, estuaries such as the Fraser River estuary have preferentially attracted human settlements; in recent times, major metropolises such as Greater Vancouver increasingly bestride them. When Simon Fraser came down the river in 1808, he saw how aboriginal peoples had been living in settlements along the river and in the estuary for thousands of years (Davis and Hutton, 2004). During those millennia, the population in the Fraser River lower valley and estuary likely never exceeded 10 000 people, and the largest villages had no more than 200 people.

Only a century after Simon Fraser, any new settler would have seen that dyking and draining the wetlands for agricultural development, forestry, ports, and expanding settlements had already transformed the estuary and delta. The river had been trained to flow primarily through one large main and a smaller north arm channel, three-quarters of the wetlands had been lost, and already the total population had increased more than tenfold. Meanwhile, the aboriginal populations had been reduced to a quarter of what they had been at their zenith, and their traditional settlements were becoming lost among new waterfront developments and expanding urbanization.

Almost another century later, the new settler finds that the population has increased to two million and the water and landscapes have been radically changed. Whereas the earlier settlers likely had their first glimpses of the Fraser River as they arrived by sea from the west or rail from the east, today's settler would likely fly in above it and see beneath them a sprawling metropolis wedged in between the mountains to the north, east, and south. If their landing approach came down over the lower valley out of the east, they would see the dyked Fraser River clearly etched beneath them, and a changing landscape gradually shifting as they came closer from a dominance of rural-agricultural to urban-industrial use. Just before landing at Vancouver International Airport at the sea mouth of the estuary, they might be struck by contradictory impressions of substantial pockets of wildland still remaining amongst development; extensive agriculture apparently operating amidst urban areas; old, heavy industry existing adjacent to new, low- and high-rise residences on the waterfront; and deep-sea container shipping navigating among fleets of fishing and recreational boats, all moored together with rafts of logs and floating homes along busy waterways.

At almost any time in recent years, the new settler would not have had to be in the region long before stories in the local newspapers and on radio and television revealed that the people of greater Vancouver are facing major challenges in the Fraser River estuary. Typical items they might soon have read or heard suggest the bewildering diversity of issues and organizations involved:

- '...federal fisheries agency announces unexpectedly high returns...short openings for the commercial sockeye fishery...'
- '...provincial ministry of environment reports water quality conditions in the estuary area range from 'fair' to 'excellent'...'
- '...environmental group declares it will continue with private prosecutions of polluters even though the provincial attorney general has already refused 26 times to allow them to proceed...'
- '...homeowners informed taxes will increase by 90 percent unless the federal and provincial governments contribute more to the cost of the regional secondary sewage treatment plants...'
- '...university researchers announce studies show lead concentrations in urban runoff have declined as a result of banning lead in gasoline, but other contaminants related to transportation, including aromatic hydrocarbons, are still increasing...'
- '...aboriginal peoples submit their claim to land and water areas in the estuary to treaty negotiation process...'
- '...harbour commission argues it's essential to deepen the channel of the main arm of the estuary to maintain port's competitiveness...'
- '...local mayor says they can build more flood protection measures and need not reduce population growth in his island community...'
- '...naturalists and wildlife agencies argue the estuary's remaining wetlands are of international importance to migratory waterfowl...'
- '...spokesperson for industry warns waterfront lands need to be conserved for industrial and commercial activities in the estuary ...it would be a mistake to allow them all to be converted to residential and parks designations...'
- '...real-estate development company announces it will rebuild three times the area of wetlands lost to its new housing through a compensation project in another part of the estuary...'
- '...volunteers from environmental groups, the fishers' union, schools and companies begin a program to clean up waterfront areas...'

Thus, in two short centuries the estuary and its delta have been greatly altered by an increasing diversity and intensity of settlement and development. The prospects are for this transformation to continue apace, creating new challenges for the evolving governance system.

DESIGNING A MANAGEMENT PROGRAM

By the early 1970s, major concerns had emerged about water pollution and the loss of fish and wildlife habitats in the estuary. A proposal to expand the airport by building a new runway extending into the wetlands focused attention on those concerns as never before and led to demands for a moratorium on all development until a plan for protecting the estuary could be put into place. Although the federal and provincial governments refused to impose a moratorium, they did agree in 1977 to undertake the Fraser River Estuary Study (FRES), but it was not until after a great deal of debate about alternative governance designs that this initiative evolved into the Fraser River Estuary Management Program (FREMP) in 1985. In the following sections, this slow and often tortuous evolution is highlighted, and quotes from key documents are used to reveal the evolving perceptions of the management problem and the merits of alternative approaches to the design of the governance system. The story is complicated, but an appreciation of the details is important for understanding the difficulties and breakthroughs critical to identifying the lessons to be drawn from the 20 years of experience.

Fraser River Estuary Study, 1977–1978 (FRES I)

The agreement signed in 1977 by the federal ministers of Fisheries and of Environment and the provincial Minister of the Environment established the Fraser River Estuary Study (FRES) "...to develop a management plan which recognized the importance of the estuary both for human activities such as urban-industrial and port development, and for preservation of ecological integrity." (Fraser River Estuary Study Steering Committee, 1978, p. xiii). The study area was to include the land and water outside the dykes, including upland areas within approximately 1000 m of the dyke. Directed by the Steering Committee, made up of representatives from federal and provincial agencies, four work groups were formed to prepare reports on land use, transportation and port development, water quality, fish and wildlife habitat, and recreation (Fig. 1). A report on the constitutional and legislative framework also was prepared. The work groups were made up of personnel from agencies represented on the Steering Committee and were under the general direction of the Study Coordinator. There was no special budget for the study, and funds and personnel were contributed by the participating agencies. Their reports were drafted within 18 months.

Out of FRES, a clear picture of the nature of the estuary management problem emerged, and the Steering Committee made far-reaching recommendations on the governance system needed to meet the challenge:

> The natural system of the Fraser Estuary together with extensive use by man for industrial and port development presents a highly complex and diverse situation. This complexity is echoed institutionally - with a large number of agencies, organizations and interests involved in what happens in the estuary.
>
> The Steering Committee notes that some organizations have powerful and direct roles in estuary management. But no single agency can control the estuary. While the simple answer of a "single authority" is superficially appealing, it could not override the inherent diversity of interests and needs which exist. We are persuaded that dealing with and streamlining interjurisdictional complexity through joint consultation in developing and

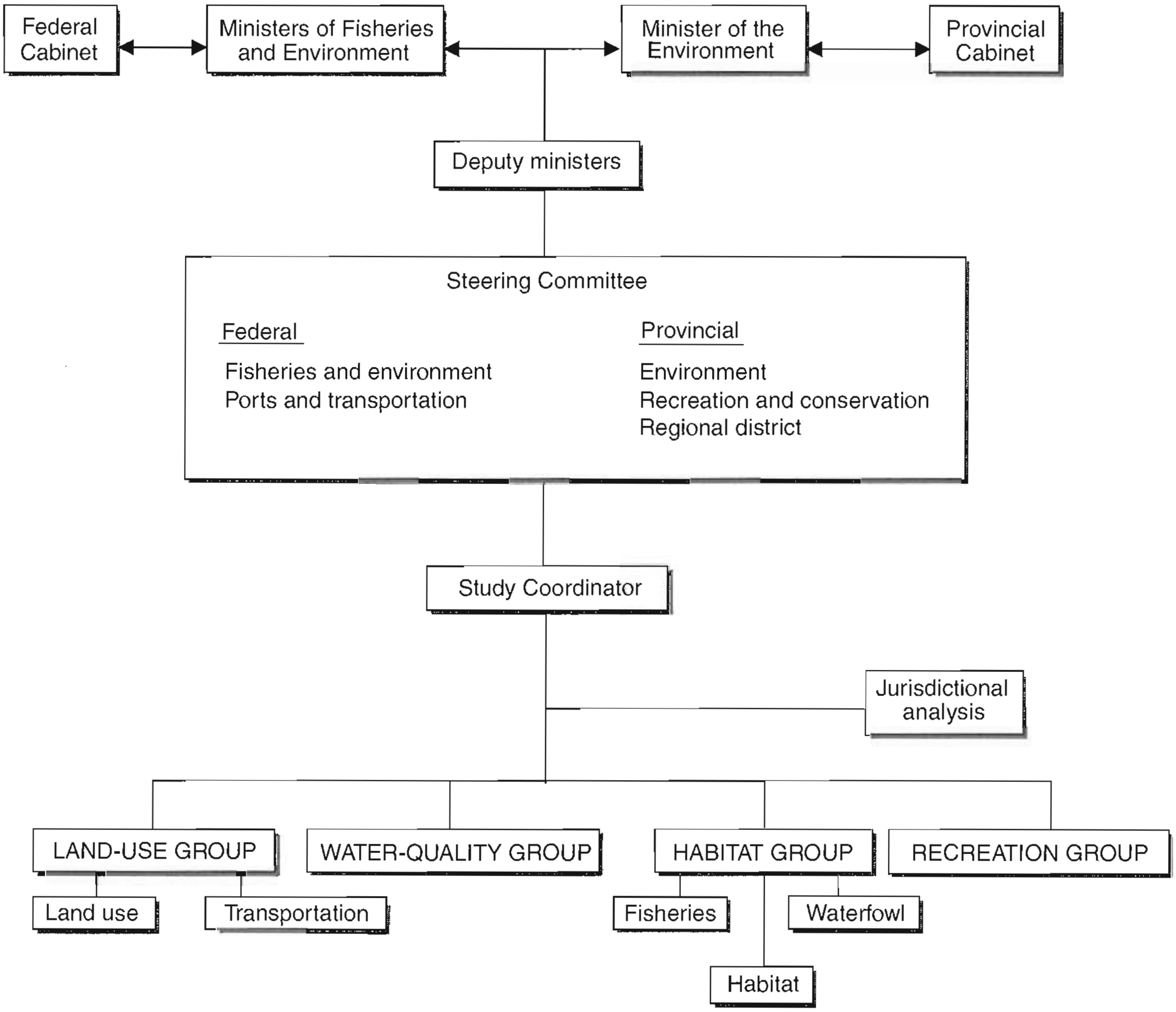

Figure 1. *The administrative framework of the Fraser River Estuary Study (FRES)* (modified from *Fraser River Estuary Study, 1978, Appendix 'D').*

agreeing on a management plan as a framework for future use is a preferred approach. We believe the goal is mutual adjustment of policies and actions in accord with agreed management principles. This means explicitly agreeing upon a "negotiated order" and "linking" the separate operational plans of different agencies in a coherent way.

We also see the need for an ultimate level of decision which would be the responsibility of the elected politicians at the various levels of government. This is because value judgements will be required to resolve some issues where objective information is not adequately available.

We offer for discussion an organizational concept comprising three interacting groups:

- a "constituency" comprising all government agencies and non-governmental groups that would meet at intervals to exchange views and understandings and to participate in task groups that may be established to resolve specific problems;
- a "policy group" comprising the key agencies with direct management powers and interests in the estuary. It will develop initiatives, explore means of reconciling conflicts, and make recommendations to the political level to which it is accountable. A well-known and capable figure outside government perhaps should be chosen to chair this group;
- an "Estuary council", a small political group bearing ultimate responsibility and accountability for formalizing policies for the estuary.

These three parts of the total "organization" are served in ways appropriate to each by a Coordinator and a small staff group or "secretariat". The Coordinator would provide the essential liaison between groups in facilitating the plan development process which as noted must be evolved by intensive consultation on the proposed policy guidelines and to achieve linkage of separate smaller plans. It also involves working towards more formal "area designations" for various development, recreation and conservation uses along the many sections of the estuary shoreline. This Coordinator and staff secretariat are essential to complete the next phase of developing a management plan for the Fraser Estuary through extensive public participation and dialogue.

As a Steering Committee, we believe an estuary management plan that collates relevant parts of the various independent "plans" of the many agencies and links them, can work and have considerable positive effect.

— Fraser River Estuary Study Steering Committee, 1978, p. xx-xxi

Fraser River Estuary Study, 1979–1982 (FRES II)

The federal-provincial phase II agreement signed in 1979 did not implement key elements of the recommended governance innovations; provincial politicians did not want a new political body, and they preferred an enhanced bureaucratic organization that would develop consensus through wide public involvement. The phase II agreement "...instructed the Study to develop and expand the Phase I proposals through further studies and evaluations and through exploration with agencies and interested public bodies" (Fraser River Estuary Study Planning Committee, 1982, p. 37). As shown in Table 1, political leadership and accountability remained with the federal and provincial ministers of the Environment. Although the ministers were designated as the Study Council, they performed the same highly removed role as in FRES I, and the council did not include other political representatives from senior and junior levels of government as had been suggested in the phase I concept of an estuary council. The study Steering Committee was renamed the Planning Committee; its agency membership doubled, and it evolved from being dominated by environmental agencies to reflecting a mix of environmental and developmental interests. Chairmanship of the committee remained with the provincial Ministry of Environment. Funding was provided to support an expanded role for a study coordinator and a small staff.

Table 1. Organization of the FRES II Study Council (*after* Fraser River Estuary Study, 1982).

STUDY COUNCIL
Honourable Steven Rogers, B.C. Minister of Environment
Honourable John Roberts, Federal Minister of Environment
PLANNING COMMITTEE
Environment Canada
Fisheries and Oceans Canada
Public Works Canada
Fraser River Harbour Commission
North Fraser Harbour Commission
Port of Vancouver
Ministry of Municipal Affairs
Ministry of Industry and Small Business Development
Ministry of Environment
Ministry of Land, Parks and Housing
Greater Vancouver Regional District
Chairman: D.R. Hehn, Ministry of Environment
Vice-Chairman: D.S. Lacate, Environment Canada

It is important to note, however, that this greatly expanded organization, which significantly enlarged representation of the diversity of agency interests, lacked the components for strong leadership that had been emphasized in the phase I report. "We believe that the next phases of the Study will require stronger and more evident leadership than we, as Steering Committee, have been able to provide in Phase I" (Fraser River Estuary Study Steering Committee, 1978, p. 107). To exert this leadership, the report had argued that not only should the council have greater political representation, but it must also be more active in interacting with the 'policy group' and the 'constituency'. Recognizing the constraints on holding frequent meetings of the politicians, it had been suggested that the Coordinator, or preferably an outsider appointed to chair the policy group, should be responsible for working with the council and providing the essential leadership.

None of these recommendations were implemented during phase II. Chairmanship of the policy group (the Planning Committee) was not assigned to a well known outsider and no longer was vested in an assistant deputy minister; instead, it was delegated to the Regional Director of the British Columbia Ministry of the Environment. The chairmanship was also shared with a federal counterpart. The appointed Coordinator was a person with less experience in such studies when compared with the Coordinator in phase I. Thus, FRES II, instead of strengthening the political leadership capability, had a more diffuse organization and assignment of bureaucratic leadership responsibility, and individuals appointed to these positions were more junior and less experienced in leading such studies than the study Coordinator in phase I. Given the diversity of interests and the complexity of the issues, the bureaucrats charged with undertaking FRES II were given an immensely difficult task by the responsible politicians.

In 1982, at the end of phase II, a 'linked management system' was proposed for the estuary. The final report analyzed three alternative approaches and recommended a hybrid. The three approaches were essentially alternative ways of organizing what had been called in phase I the 'policy group' and the 'constituency':

> **Alternative A: A committee approach**
> The Committee approach would essentially seek a voluntary consensus on an advisory management program for those government agencies involved in estuary management. Linkage would be established by agreements between key federal and provincial agencies to participate in a key agency committee made up of representatives from the estuary management level. The

committee would be a forum for discussion and voluntary agreements on areas of overlap between agency responsibilities.

Improved coordination would be facilitated in each alternative by a more effective and efficient information system and referral systems.

Alternative B: A lead agency approach
The Lead Agency approach would designate certain estuary agencies to take the lead in estuary decision-making. These agencies would make a mutual commitment to the estuary management program by means of interagency agreements or contracts. Agencies giving up job assignments to lead agencies would not be giving up their statutory authority and could step back in if need be. An example of a lead agency agreement now in place is the management agreements by which the B.C. Ministry of Lands, Parks and Housing transfers leasing management to the harbour commissions in areas where the river bed is provincially owned. The agreements designate one agency to manage rather than two.

Alternative C: An estuary council of governments
This approach would establish a council of Estuary Governments by intergovernmental agreement and executive orders. The council would be made up of senior officials of the governments involved. They would be delegated executive authority, consistent with prevailing statutes. The council as a whole would have the job of updating and adopting the management program, overseeing estuary management activity, as well as of preparing and making submissions to their Ministers for budget approval, funding and staffing. Existing agencies would continue to manage the estuary and would jointly staff the council. However, some reorganization of these agencies might be required to more clearly delineate which parts of their organization deal with the estuary.

— Fraser River Estuary Study Planning Committee, 1982, p. 41

It was concluded that "...a hybrid alternative is preferable, with the committee approach being employed for planning and representation and the lead agency approach for implementation." (Fraser River Estuary Study Planning Committee, 1982, p. 42). The perceived benefits of the proposed system were summarized as follows:

It addresses the major management challenges identified through our studies. It facilitates agreement on common goals and policies. It simplifies government administration and promotes better management of agency personnel, money and resources, while assuring accountability and improved information exchange. In addition, the proposal is simple to implement, as it involves existing powers of the Government of Canada and British Columbia. It succeeds because it affords a change in operating style and builds on the experience of those agencies that have been managers of the estuary. Finally, as a result of its streamlining aspects and encouragement of cooperation between the sixty to seventy agencies holding mandates in the estuary, it reduces regulation and cuts red tape.

It is important to note that the proposal presented in this report should not be underestimated because it suggests simple solutions. **It is not a status quo proposal.** On the contrary, it addresses an innovative and far reaching approach to "tuning-up" the processes of government decision making and resultant action while retaining flexibility. Thus, it can achieve concerted actions in the interests of both environmental and economic resources of the estuary.

— Fraser River Estuary Study Planning Committee, 1982, p. 37; emphasis in original

Thus, in contrast to FRES I, changes designed to ensure more effective political leadership were not seen to be of primary importance. As the report says, the FRES II recommendations were limited to "tuning-up" the existing system.

Fraser River Estuary Study Review, 1983–1984

Although the phase II report had been widely discussed at the draft stage and then revised, it was decided that a federal-provincial review committee should be established to obtain further comment on the proposals and design an implementation strategy (O'Riordan and Wiebe, 1984). This step was felt to be necessary because the report did not provide a clear basis for proceeding; the proposals were extremely complex, and there were doubts that it contained essential ingredients for success. The Review Committee summarized the comments they received in the following guarded terms:

Although there was general endorsement of the need for a management program, there were a number of issues which required clarification. These included the need for: broad consultation; government and industry commitment to the management process; a simplified management structure; clarification of the role of municipal and regional governments; and practical cost-effective management activities. In addition, a strong desire for meaningful action to occur as soon as possible was expressed.

— O'Riordan and Wiebe, 1984, p. 2

In response to these concerns, the Review Committee developed a revised proposal that was released in May, 1984 (Fig. 2). The proposed organization of the management system was greatly simplified and heavy emphasis was put on the need for a sparing organization at a time of severe economic restraint. At its core would be a management committee. It would have a five-member executive committee and another 27 members-at-large drawn from the key agencies, including local and regional governments and Indian bands. There would be a two-person administrative secretariat providing support to the management committee and management program. The management program would have four components: an information system, a process for coordinated project review, activity program work groups, and area planning work groups.

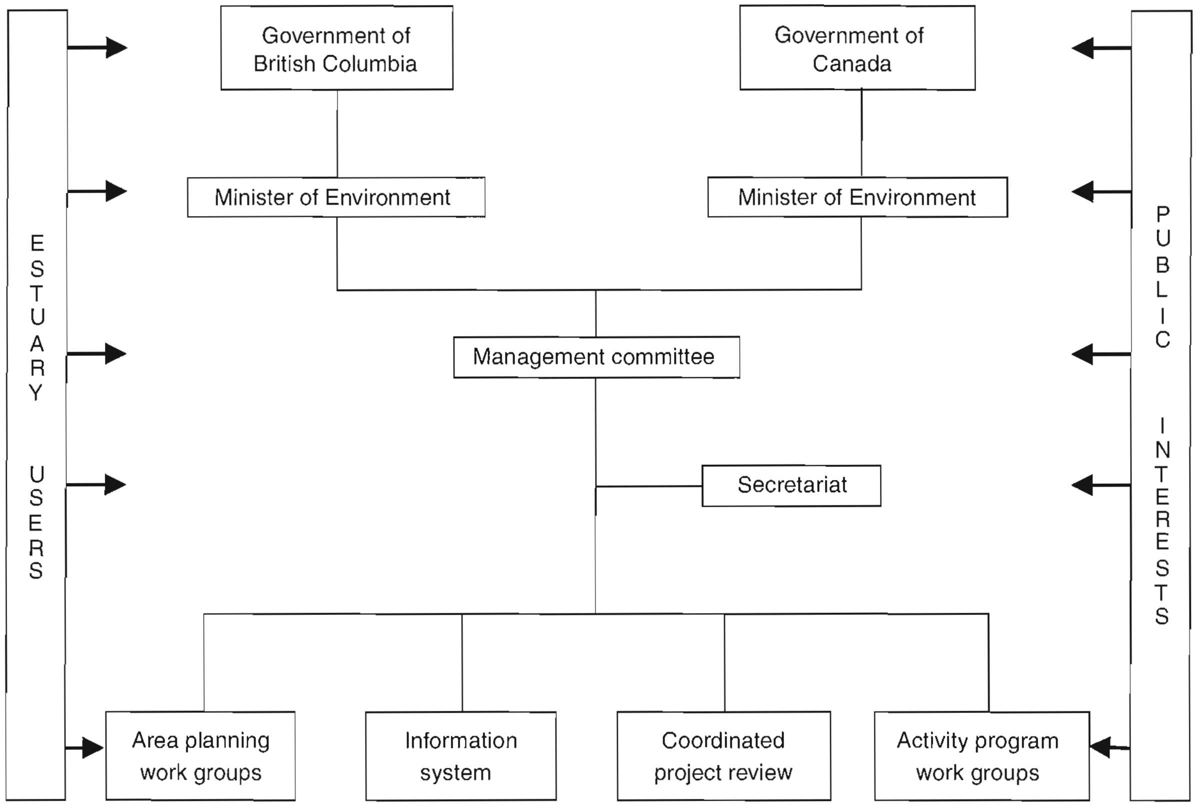

Figure 2. *The proposed organization of the management system (Fraser River Estuary Study, 1984, Fig. 1).*

Responsibility for leadership was clearly placed with the executive committee, which would consist of the federal Department of the Environment, Fisheries and Oceans Canada, the provincial Ministry of the Environment, and the two harbour commissions in the Fraser River estuary. The executive committee would in turn be accountable to the federal Minister of the Environment and the British Columbia Minister of the Environment. Representation of other agencies of government, regional districts, municipalities, and native Indian bands would be provided for by making them all members of the management committee, which would meet as a whole twice each year.

OPERATING THE MANAGEMENT PROGRAM

In late 1985, the Fraser River Estuary Management Program (FREMP) agreement was signed as had been recommended, and each of the five signatories agreed to contribute $50 000 each year for the next five years. The superordinate goal was "...[t]o provide the means for accommodating a growing population and economy, while maintaining the quality and productivity of the Fraser Estuary's natural environment." A secretariat office was opened in New Westminster to provide a contact point for the public and various secretariat services, including a central project registry. Thus, after the eight years of the Fraser River Estuary Study, a management program, FREMP, had been designed and put into operation under a five-year agreement.

In addition, key elements of FREMP had been developed and successively refined to varying degrees by work groups during the years of FRES I and II. A statement had been drafted and agreed to as a vision for the year 2002 — *A Living River by the Door*. A series of general objectives had been developed and adopted to guide management of specific sets of activities. Building upon the reports produced in FRES I, eight activity program work groups and standing committees had produced management plans for water quality, waste management, port and industrial development, recreation, habitat, emergencies, log storage, and navigation/dredging. Beyond this, progress also had been made on what were to become central components of FREMP: the 'Coordinated Project Review Process' and 'Area Designation Process', including a habitat classification scheme. Each of these components of the management program is discussed in more detail in the second half of the paper, after highlighting how FREMP has continued to evolve.

Over the last decade, FREMP has built on these foundations. At the end of the first five-year agreement in 1991, a second one, FREMP II, was signed for a further three years. The Greater Vancouver Regional District became a sixth signatory and, with a doubling of the contributions, the total budget increased to $600 000 each year. The Executive Committee was renamed the Management Committee and was reconstituted by representatives of the six signatories. The larger Management Committee of FREMP I ceased to exist, as it was felt to be unnecessary given the other opportunities for involvement in the management program. For example, a local government implementation advisory committee was concluded to be unnecessary when it was found its components could be represented on key committees, such as land-use and water-quality committees.

The major product from FREMP II was an integrated management plan for the Fraser River estuary, finalized in 1994 and entitled *A Living Working River* (Fraser River Estuary Management Program, 1994). As its title suggests, this plan continues to modify the approach initiated during FRES. The statement of vision, goals, and principles (Table 2) consolidates and elaborates earlier ideals and provides a framework for the more specific targets and actions in the plan. Six action programs that have their origins back in the reports and work groups of FRES and FREMP I are now organized under two themes: Environmental Protection, consisting of Water Quality Management and Fish and Wildlife Habitat; and Human Activities, including Navigation and Dredging, Log Management, Industrial and Urban Development, and Recreation.

Two key management tools developed earlier continue to have a central role in implementing the plan and evolving guidelines and policies for the estuary: the Project Review Process, established in 1986 to coordinate applications for use or development in the estuary, and the Area Designation Process, initiated in 1982, that identifies the primary uses for areas within the estuary (e.g. log storage, recreation, conservation, or industry), associating with them terms and conditions of use, and thus linking estuarine concerns with upland decision-making. Maps provided in the plan document detailed the status of the evolving designations, and a conflict resolution process was outlined for resolving disputes arising during implementation. Each of these management tools is discussed in more detail in the second half of this paper, which assesses the experience of building a collaborative approach to governance in the Fraser River estuary and delta.

Table 2. Vision, goals, and principles for the Estuary Management Plan (*after* Fraser River Estuary Management Program, 1994, Table 3).

Vision	Improve environmental quality in the Fraser River estuary while providing economic development opportunities and sustaining the quality of life in and around the estuary.
Goals	Conserve and enhance the environmental quality of the river and estuary to sustain healthy fish, wildlife, plants, and people.
	Respect and further the estuary's role as the social, cultural, recreational, and economic heart of the region.
	Encourage human activities and economic development that protect and enhance the environmental quality of the estuary.
Principles	**Conserve and enhance the estuary** Keep the estuary healthy. Conserve and sustain natural habitat.
	Integrated management Encourage multiple uses within the estuary. Promote integrated decision-making. Establish and maintain informed management processes.
	Fairness, equity, and accountability Promote and employ consensus-based decision making. Provide equitable access to the estuary. Establish and maintain accountable management processes. Develop active partnerships with the public in management activities.

COLLABORATIVE GOVERNANCE

The originally established Canadian governance systems could not have anticipated the challenges of estuary management that have arisen over the last two centuries. The 1867 Constitution Act allocated rights and responsibilities in ways such that all four orders of government — federal, provincial, local, and First Nations — have major roles in the management of today's uses of the estuary. In FRES I, upwards of a hundred governmental and nongovernmental organizations were identified as being involved. Today, there are over 30 governmental agencies with jurisdiction over water quality (7 agencies), waste management (6 agencies), land use (15 agencies), water use (11 agencies), and habitat protection (5 agencies) (Table 3); and this is without examining all of their subdivisions (e.g. there are 12 municipalities, each with its own collection of departments and division of responsibilities). Finding a way to overcome the fragmented and largely *ad hoc* decision-making among all these organizations was recognized during the first 18-month study in the 1970s as the fundamental problem in estuary governance.

The FRES I proposals were a perceptive and innovative response to the governance challenge. The critical need for leadership and ultimate political responsibility in decision-making were recognized and provided for with the proposal of a council. It was to be the political mechanism for making the trade-offs that would inevitably be required in governing the estuary. It would ultimately be held accountable through the electoral process. The need to represent diverse interests was accepted, and the commonly suggested idea of creating a single authority was rejected. Representation in coordination and exploration of trade-offs was provided for in an explicit process of negotiation. Accountability was secured by requiring plans to be linked within a negotiated order established by the council; as plans would be completed or revised they would be approved by the council. In turn, those responsible for implementing the plans would be accountable to the council for their performance. Finally, and perhaps of greatest significance, it was recognized that the organizational innovations must precede attempts to deal with substantive issues.

> As with other proposals, this one too is offered for review and comment, but it should have high priority because some elements of organization and the required manpower and funding must be in place before the main dialogue on policy guidelines and other substantive issues can start.
>
> —Fraser River Estuary Study Steering Committee, 1978, p. 99

Table 3. Agency jurisdiction matrix (*after* Fraser River Estuary Management Program, 1994, Fig. B-1).

AGENCIES	AREA OF JURISDICTION				
	Water quality	Waste management	Land use	Water use	Habitat protection
Federal					
Department of Fisheries and Oceans	•				•
Environment Canada	•	•			•
Fraser River Harbour Commission			•	•	
North Fraser Harbour Commission			•	•	
Public Works Canada				•	
Transport Canada			•	•	
Canadian Coast Guard				•	
Vancouver International Airport Authority			•		
Vancouver Port Corporation			•	•	
Provincial					
Ministry of Agriculture, Fisheries and Food		•	•		
Agricultural Land Commission			•	•	
Ministry of Environment, Lands and Parks					
BC Lands			•		
Environmental Protection Division	•	•	•	•	
Fish and Wildlife					•
Water Management Division	•	•	•	•	
Ministry of Health					
Health units	•	•	•		
Ministry of Small Business, Tourism and Culture					
Heritage Conservation Branch			•	•	
Ministry of Transportation and Highways			•		
Local					
Regional districts	•	•	•	•	
Municipalities	•		•	•	•
First Nations			•		•

Not surprisingly, the proposal for an 'estuary council' was not pursued. Even twenty years later, there are very few examples around the world of governance institutions for managing estuaries or watersheds that are led by people elected specifically for that purpose. For the most part, politicians and their bureaucrats perceive such innovations as threatening to take away from them more than they might gain. Instead, a more limited model of collaborative governance was adopted; ultimate authority and leadership officially resides with selected federal and provincial ministers, who only become involved on relatively few occasions. Responsibility for making decisions primarily resides with a management committee of relevant bureaucrats from participating organizations; each of the participants retains all of their original jurisdiction and, when they are unable to reach a consensus, decisions are referred for resolution to the extra-estuarine governance processes of which they are a part. In the following sections, the characteristics of this collaborative model are examined more specifically before returning in the conclusions to raise questions about the adopted model.

Goals of estuarine governance

Long before the 'Brundtland Report' (World Commission on Environment and Development, 1987) had made popular the concept and ideal of sustainable development, the vision and goal statements for the estuary reflected concerns for both the environment and the economy:

> The purpose of the study was to develop a management plan which recognized the importance of the estuary both for human activities such as urban-industrial and port development, and for preservation of ecological integrity.
>
> — Fraser River Estuary Study Steering Committee, 1978

> To provide the means for accommodating a growing population and economy while maintaining the quality and productivity of the Fraser Estuary's natural environment.
>
> — O'Riordan and Wiebe, 1984

> To improve environmental quality in the Fraser River estuary while providing economic development opportunities and sustaining the quality of life in and around the estuary.
>
> — Fraser River Estuary Management Program, 1994

While the visions and goals have remained broadly similar, there is greater comprehensiveness (Table 2) and a significantly different emphasis in the recent plan, which states explicitly that "[i]mproving environmental quality is the foremost priority, recognizing the linkages among economic needs, social and cultural heritage values, and the natural resources of the estuary."

Leadership and accountability

Leadership has been primarily focused in what was the Executive Committee of the Management Committee during the first FREMP agreement, which subsequently became the Management Committee (both hereafter referred to as "the management committee"), with its members being accountable to their respective organizations. In accordance with the goals, there has always been strong governmental agency representation of environmental interests. All of the agreements have been signed by the federal ministers of Environment and of Fisheries and Oceans, and by the provincial Minister of Environment, and each of these organizations has been a member of the management committees. Although neither federal nor provincial ministers representing economic and developmental portfolios have been signatories to the agreements, there has been strong representation of such interests since the end of FRES I through the participation of the Fraser River Harbour Commission and the North Fraser River Harbour Commission, firstly as members in the Steering Committee for FRES and then as signatories, equal financial contributors, and members of the management committees from the time of the first FREMP agreement. It was not until the second FREMP agreement in 1991 that local government, through the Greater Vancouver Regional District, formally became one of the signatories to the agreement and hence a financial contributor and member of the management committee.

More than might at first appear, this unusual hybrid mechanism that is the management committee has been an innovative means for leading collaboration among federal, provincial, and local government organizations and the harbour commissions. As the committee members have become more familiar with estuary management issues and more knowledgeable about each other's organizations and interests, and have built trust among themselves through working together, it has become an increasingly effective mechanism for collaboration. This began to happen even before the harbour commissions and the local governments became formal members of the committee. It has been reinforced by many of the same individuals being the representatives on the management committee for several years. Furthermore, it has become evident over time, as for example reflected in the 1994 management plan, that the members have greater joint interest in environmental and economic issues than might be suggested by superficially looking at their formal mandates alone.

Given the realities of demands on the time of federal and provincial ministers, local politicians, and harbour commissioners, it is not surprising that the responsibilities for leadership and accountability have fallen heavily on the management committee. How well this has worked within the confines of the adopted model of governance is a question that will be considered in the conclusions, after other key aspects of FREMP's achievements have been discussed.

Stakeholder involvement

Under the direction of the management committee, intensive use of working committees in developing and implementing the estuarine management program has provided for extensive involvement of representatives of governmental agencies, but the involvement of nongovernmental organizations and the general public has been uneven and less concerted. From the beginning of FRES and through FREMP, working committees have been used in each of the six or seven aspects of management activity (Fig. 1, 2, 3; Table 1). Over time, these committees and their various subcommittees or task groups have involved stakeholders in identifying the issues, developing possible management approaches, implementing agreements, and refining them in light of experience. Formally, these groups have been constituted predominantly of governmental agencies, with the notable addition of the harbour commissions. Although the groups have had the option under the public consultation policy adopted by FREMP of adding nongovernmental interests to their participants, this has not been done extensively; some groups have done this more than others (e.g. land use and recreation) and others not at all (e.g. waste management).

Although there was no public involvement during FRES I, there have been varied ways in which nongovernmental organizations and interests have been involved at various times during the evolution of FRES and FREMP. Public consultation exercises involving review of draft documents, workshops, and opportunities for written comments have been part of the development of the two major reports, *A Living River By the Door* (Fraser River Estuary Study Planning Committee, 1982) and *A Living Working River* (Fraser River Estuary Management Program, 1994), and the activity program reports. On various occasions, the working committees have organized their own workshops, sometimes involving a wide diversity of interests (e.g. log-handling committee) other times being more limited (e.g. the annual water-quality research workshops). During two short periods, mechanisms were established for periodic consultation with a wider diversity of interests. For a time in the early 1980s, there was an attempt to use a broadly based advisory committee involving both governmental and nongovernmental stakeholders under an independent chair, but it proved extremely difficult to obtain consensus and it was discontinued. During FREMP I, the full management committee of 27 members provided a means for involving a wider diversity of governmental stakeholders, but the full management committee was only convened twice a year, and the various working committees were primarily used to involve these stakeholders.

The establishment of the FREMP Secretariat office in New Westminster in 1985, and its later move into a building on the redeveloped waterfront, provided a point of contact for the public to obtain reports and information. Various means have been used to communicate more widely, including the

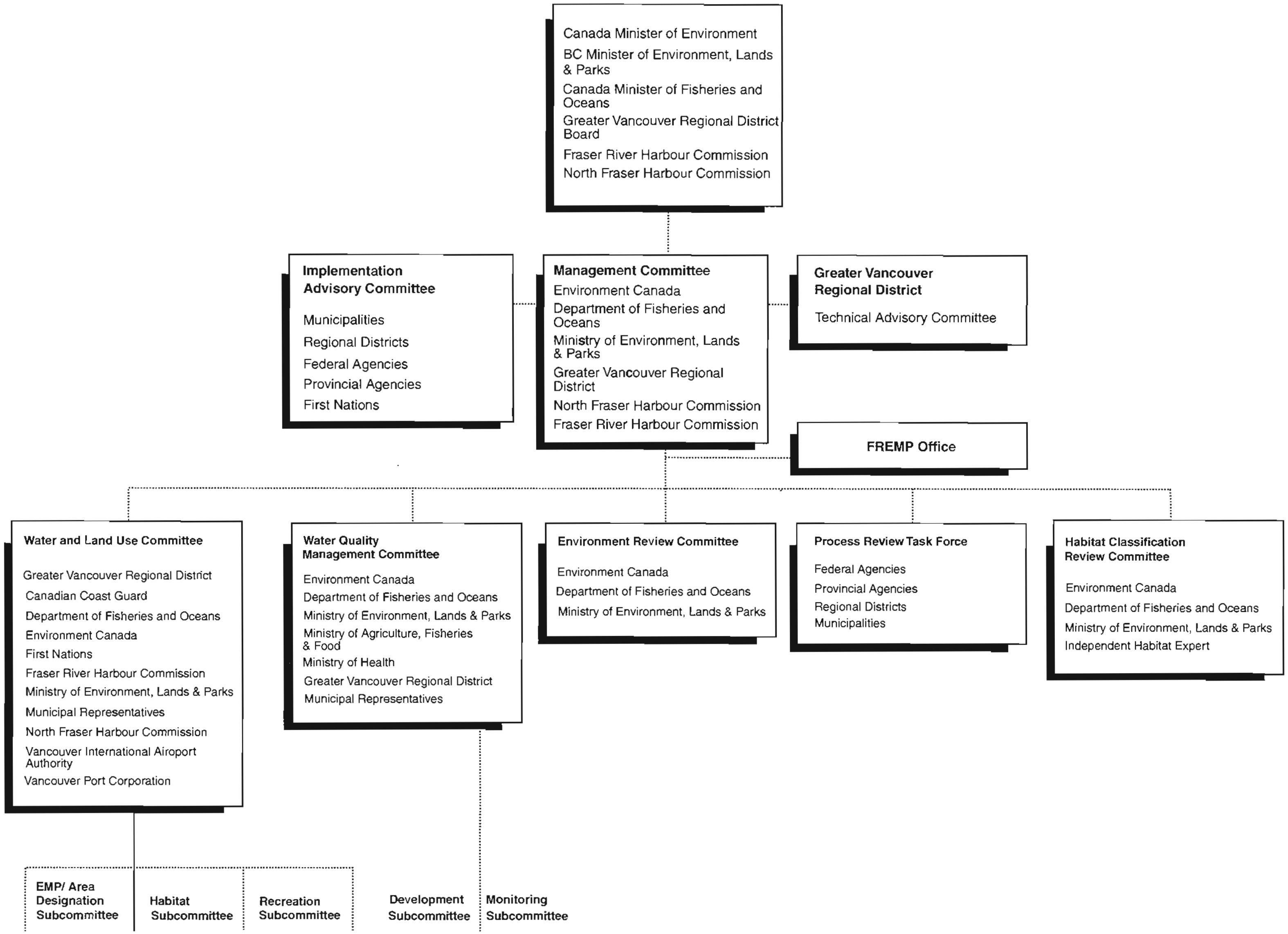

Figure 3. *Integrated management plan for the Fraser River estuary—*A Living Working River *(Fraser River Estuary Management Program, 1994, Fig. A-2).*

production of a periodic newsletter, preparation of media packages, the provision of displays for use at the annual Fraser River Festival, organization of conferences and, in the community, development of a schools program and, more recently, a site on the World Wide Web (*see* Appendix).

Overall, FRES and FREMP have been much more successful in securing direct and continuing involvement of governmental agencies, including the harbour commissions, than in involving the range of nongovernmental organizations and interests. In contrast to the multistakeholder processes that have become common in the 1990s in many other areas of governance in British Columbia and other parts of Canada, such as coastal zone management in Atlantic Canada, FREMP has remained predominantly in a conservative mould, concerned primarily with fostering the coordination of government activities. More recently, there have been some signs of movement towards a fuller partnership model of collaboration in the habitat-restoration and enhancement programs, and proposals for training citizens for clean-up tasks and reporting spills.

Collaborative management tools

Over the last decade, FRES and then FREMP have developed and refined a set of management tools that have become the ongoing means of implementing the collaborative approach to governance. The provision of funding to support a coordinator and small staff has been key in providing a secretariat that gives continuity and facilitates the involvement of a large number of part-time contributing organizations and individuals in the various work groups, committees, and processes that develop and implement policies and guidelines for management of the estuary.

Policies and guidelines

As a result of the work carried out through FRES and FREMP, and the independent but related development of new policies by some of the participating agencies, several sets of guidelines and policies for environmental protection have been implemented, including log-storage guidelines (harbour commissions), Fraser River dredging guidelines for fisheries protection (Department of Fisheries and Oceans), habitat coding and classification (FREMP), provisional water quality objectives (British Columbia Ministry of the Environment), policy for the management of fish habitat (Department of Fisheries and Oceans), official community plans (individual municipalities), and local zoning bylaws (individual municipalities).

Key FREMP tools used in the implementation of these policies and guidelines are the Project Review Process and the Area Designation Process.

Coordinated project review

The Project Review Process, established in 1986, provides lead agencies with a single window of contact with all the agencies that are potentially concerned with an application for use or development within the estuary. Proponents deal directly with the lead agency designated for the relevant area of the estuary: Fraser River Harbour Commission, North Fraser Harbour Commission (within their respective port areas), B.C. Lands (provincial crown lands), and FREMP (private lands). Prior agreements on designated uses for areas of the estuary (discussed below), specific terms and conditions of use, and common application forms enable the proponent to take requirements and expectations into account in preparing a proposal. Completed applications are forwarded to the FREMP office for referral to all agencies with regulatory authority. The office maintains a referral log, accessible by computer, that enables agencies and the public to monitor applications, and written comments may be submitted during the response period, including a request to meet with the Environmental Review Committee. This committee, consisting of representatives of Environment Canada, the Department of Fisheries and Oceans, and the British Columbia Ministry of Environment, Lands and Parks, reviews all the environmental referral responses and public comments and provides a coordinated environmental response. All responses and comments are returned to the lead agency, which then issues a decision statement reflecting all the inputs and FREMP's environmental, economic, and social objectives. Relevant leases, permits, or approval documents may accompany the decision or remain to be obtained. Anyone may submit a written request for review of the decisions of the Environmental Review Committee or lead agency (*see* discussion below in 'Conflict resolution').

The progressive refinement of the overall mechanism has made the Project Review Process increasingly predictable, effective, and efficient. In 1991, the average time from signature of the application to issuance of the decision statement was 80 days. A high proportion of applications are approved, because proposals that would not be acceptable are not likely to come forward. Growing experience and trust are leading to the development of criteria which permit lead agencies to make decisions without referral and to directly record their decision with the FREMP office. Likewise, criteria are being refined for determining when a project raises issues that merit more intensive examination through a task force or should be directed into a formal project review process of the federal or provincial governments.

Area designation

The other major FREMP tool is the Area Designation Process, which began during FRES II when a map was produced dividing the foreshore into 85 management units. It was based on available information and judgments about best use, considering natural attributes and suitability for human activities. It was developed by a task force of 15 agencies, and was reviewed by another 13 nongovernmental agencies and 9 local governments. Through a series of extended meetings, consensus was reached on 60 of the 85 units. Categories included 'conservation', 'recreation/park', 'log storage', 'small craft moorage', and 'industrial port / terminal'. The remaining 25 units were put into an 'undetermined use' category. Although the map had no formal status, it began to be widely used by management agencies and developers.

Review and refinement of these designations has been ongoing under FREMP and has included four significant adaptations:

1. A statement of intent is signed by the parties of interest to secure more formal commitment to the designations and reduce uncertainty. While this is not a legal contract, it gives the agreements much more substance.
2. Multiple-use designations are considered to reduce conflicts associated with the initial single-use designations. By designating one use as primary and another as secondary (e.g. log booming is permitted in the foreshore waters as long as it does not interfere with the conservation designation of the shoreline), it is considerably easier to reach consensus.
3. The process is eased by separate implementation with each municipality, thus having fewer parties directly involved. The process has been chaired by the FREMP Coordinator, and involves intensive meetings and review of draft agreements by other interested agencies and the public.
4. The addition of a process for reviewing designations when requested by agencies has made them more willing to make commitments. Agreement has been further eased by the adjustment of management-unit boundaries, some revision of categories, the improvement of the information base as a result of other activities, and the growing experience and familiarity of those involved.

The 1994 plan indicates that Burnaby and Richmond have area designation agreements in place and other municipalities are working on them. Generally, the area designation map is based on current uses and is not a long range plan *per se*; however, it is believed that there are good possibilities for resultant foreshore uses to be compatible with and influential on upland zoning and official community plan designations. For example, Surrey has incorporated the designations into its Official Community Plan, thus making the designations meaningful above the high-water mark and putting them into the regular cycle of update and review of its Official Community Plan. The area designation agreements are still considered useful, but are being developed more slowly because of the heavy time demands they place on contributing agencies.

Conflict resolution

A fourth key management tool is the Conflict Resolution Process laid out in the 1994 plan. Drawing on principles of consensus-based decision-making that reflect those recommended by the British Columbia Round Table on the Environment and the Economy, a voluntary process is provided for seeking resolution of conflicts arising in management. The process provides for FREMP to convene the interested parties, including nongovernmental interests where this is judged appropriate; provide for a mediator, if necessary; and engage in identifying issues and options for meeting interests within the goals and guiding principles of the Estuary Management Plan. If the parties cannot reach consensus, then the Management Committee prepares a report on the deliberations that is forwarded to the agencies with the jurisdiction and authority to make a decision. If required, the decision will ultimately be made through the political or judicial system.

Funding and resources

Under the FREMP agreements, funding commitments increased from $250 000 each year for FREMP I to $600 000 each year for FREMP II. While these funds support the direct activities of the FREMP Secretariat, it is important to recognize that the vast majority of the funding and resources that are devoted to estuary management are provided directly through the programs of the wide variety of governmental and nongovernmental organizations that are active in the estuary. The total expenditure is not known because such accounting is never done; however, without a doubt, the FREMP funds are less than 1% of the total capital and operating expenditures related to estuary management.

LESSONS AND FUTURE OUTLOOK

Arguably, estuaries such as the Fraser River estuary present the greatest governance challenges on the planet in the intensity of settlement and development they attract, the diversity of interests involved, and the uncertainties surrounding interactions of their natural and human systems. Governing such highly complex systems is still more art than science, and often only an infant art. Learning from the evolving approaches to governance in the Fraser River estuary, building on strengths, and addressing weaknesses are crucial for meeting the challenges in prospect.

Good fortune but....

Over the last two decades, good fortune has in many important ways made governance of the Fraser River estuary relatively easy. At the time of the FRES I report, it was recognized that despite the history and extent of development, in a broad sense, the supply of natural resources still considerably exceeded demands in the estuary. In particular, there were substantial areas of the estuary that had not yet been developed or committed. In addition, the enormous size of the flow through the main stem of the river meant that it was remarkably forgiving of waste discharges and runoff from upstream and the growing metropolis. Over the intervening years, there fortunately has not been a spring freshet big enough to seriously threaten the settlements and developments behind the dykes, nor have any of the seismic events been of sufficient magnitude to have any significant impacts in the delta. Economic forces, too, have been benevolent in facilitating the transition of major parts of the shoreline out of old port and industrial uses and into new residential and commercial developments. In addition, the availability of shoreland, development of new technology, and expanding import and export demands have enabled the ports to grow and flourish. At the same time, it has been possible to increase the number of parks and establish linear connections between green spaces. In many ways, the times have been good, and time has so far been on the side of the evolving governance system.

At the same time, however, growth in population, settlement, and development has been enormous. Despite what has been achieved by management efforts, the degrees of freedom for the governors have declined significantly. Information developed by the FRES and FREMP work groups and associated governance processes shows the relentlessly increasing development pressures and the environmental, economic, and social consequences and implications of these in the region, delta, and estuary (as discussed in detail in other papers). For example:

1. Since FRES started in 1977, the population in the region has almost doubled and the extent and diversity of development has more than matched this rate of growth.
2. Despite some gains from restrictions, such as on log storage, and successes in habitat restoration and banking, studies conducted in the estuary have developed a new understanding of the large amounts of wetlands lost from turn-of-the-century dyking and drainage and subsequent developments, and the threat of this to fish and waterfowl populations.
3. While there have been years when salmon stocks seemed to be rebuilding towards historical abundance levels, the last few years of drastic declines in fish returns have led to a realization of their vulnerability to the impacts of habitat loss, environmental change, and overfishing.
4. Even though the main-stem water-quality conditions appear to still be relatively good and there have been some improvements, studies in the less well flushed tributaries reveal the accumulation of contaminants and impacts of rural, urban, and industrial discharges and runoff. They also show how atmospheric transportation, precipitation, and drainage systems are moving contaminants into the estuary from activities throughout the region and even regions far away.
5. Although there has not been a major flood since 1948, there is a growing appreciation of the risk to the increasing population and development behind the dykes; it is estimated that there is a one in three chance that the highest flow on record (1894) will be exceeded in the next 60 years.
6. These risk factors have been further compounded by new understanding of the greater frequency and potentially large magnitude of earthquakes that could impact the delta.

Thus, from today's perspective, while good fortune and a degree of ignorance have made estuary governance relatively easy during much of its first 20 years of evolution, it appears the years ahead are going to be a great deal more difficult now that the excess supply has been substantially reduced, particularly with the prospects for some of the highest rates of growth in North America.

Good collaboration but...

Over the last two decades, there has been increasing collaboration among the many organizations involved in governance of the estuary. Through FRES and more recently FREMP, there has been significant progress in building an orderly management system to replace what had previously been a largely *ad hoc* decision-making process among more than a hundred organizations. The 1994 Estuary Management Plan reflects the progress in developing coordinated procedures for project review and area designation, management policies and guidelines, and standardized databases, and it lays out the next steps for their implementation and further development.

In addition, during the 1990s there also have been several other major collaborative governance initiatives that have begun to build a larger policy context and regional governance system to complement the specific focus of FREMP on the wet side of the estuarine dykes.

In 1995, the Greater Vancouver Regional District completed its growth-management planning process, with all the member municipalities agreeing to the Livable Region Strategy, built around four key and interrelated strategies: protect the green zones, build more complete communities, achieve a more compact metropolitan region, and increase transportation choice. Each of these strategies has been built into the 1994 Estuary Management Plan.

In 1991, the Burrard Inlet Environmental Action Program (BIEAP) was initiated under a five-year agreement between the same federal, provincial, and local government agencies that are involved in FREMP, plus the Vancouver Port Corporation. While its mandate was not as broad as FREMP's, the Burrard Inlet Environmental Action Program was intended to protect and improve environmental quality in Burrard Inlet. Recognizing their similar and joint interests, the parties agreed in 1996 to begin a consolidation of the two programs.

In 1991, as part of the federal government's Green Plan, the Fraser River Action Plan (FRAP) was announced as a $100 million joint program of Environment Canada and the Department of Fisheries and Oceans. Focusing on the whole of the Fraser River basin, the goal was to repair environmental damage and establish a management program for sustainable development of the basin. The Fraser River Action Plan's funds have contributed to activities advancing various components of FREMP over the last five years.

In 1992, the federal, provincial, and local governments signed a five-year agreement to establish the Fraser Basin Management Program (FBMP) and Fraser Basin Management Board (FBMB). The Fraser Basin Management Program was intended to coordinate the development of a management program for the whole basin, building on the FREMP model but with greater and more diverse stakeholder involvement. Like FREMP, it is a collaborative entity with no authority of its own, and its board and a small secretariat are supported by contributions from three signatory governments (totalling approximately $1.5 million each year). In 1997, the board was succeeded by the Fraser Basin Council, a nonprofit society consisting of 33 directors, which was launched by the governments with initial funding of $950 000.

Over the last few years, the provincial government has begun the development of the 'Georgia Basin Initiative'. Although not yet as well formulated and advanced as the other initiatives, it is designed to develop the collaborative processes that would address the growth-management issues for sustainable development of the much larger Georgia Basin and Puget Sound regions and ecosystems.

Despite the progress that has been made in developing collaboration in and around the estuary, three major problems have continuously undermined the recognition of FREMP's progress and its credibility. Firstly, despite all the work that has been done and the very large number of reports that have been produced, there has continued to be great uncertainty about the environmental and economic state of the estuary. Many reports have been produced, but many of them are highly technical and specific. Often, results of the studies have been inconclusive, in part reflecting the dynamism and variability inherent in natural and social systems, particularly those associated with estuaries. In general, there has been much more information developed about the biophysical than socio-economic systems in the estuary, and it has been more difficult to relate the socio-economic systems data to the estuary specifically. Integrative and summary reports have been relatively infrequent, and the lack of specific targets and monitoring has not helped to clearly demonstrate FREMP's achievements.

A second problem has been the general slowness in producing results. The one possible exception to this was FRES I, which was relatively productive during its short 18-month life. Since then, progress has been more drawn out, and there have been particularly slow periods between phases. The review after FRES II expressed demands for quicker action. The reports at the end of FREMP I and the management plan at the end of FREMP II show the gradual progress in evolving the governance system and the products from the various work groups, but at the same time reveal the slow advancement in key areas such as the development of a water-quality management plan and the completion of negotiations with municipalities on area designation agreements for their waterfront areas.

A third problem is the generally limited visibility of FREMP and associated lack of recognition of its achievements outside of the organizations and individuals directly involved. Several factors have contributed to this problem, including the fact that FREMP does not have high-profile people associated with it, does not spend large amounts of money, and does not have authority of its own. Furthermore, major estuary-management issues in the public eye, such as the sewage-treatment plants, fishery, and floodplain management, are largely outside of its areas of activity. The vast amount of its work has been done behind the scenes and involved relatively few stakeholders. In the earlier years, the initiative did not make the efforts at communication and education that it has done in more recent times. Unfortunately, the task of developing a clearer understanding of the role and achievements of FREMP has been made a great deal more difficult in the 1990s by the confusing proliferation of many new initiatives ('Livable Region Initiative', Fraser River Action Plan, Burrard Inlet Environmental Action Program, Fraser Basin Management Program, 'Georgia Basin Initiative').

Good governance but...

When compared with other estuarine governance systems operating around the world, the evolving system in the Fraser River estuary has received high marks, as illustrated by a review of experience in Organisation for Economic Cooperation and Development (OECD) countries (Dorcey, 1993). Furthermore, the general model piloted in the Fraser River estuary is influencing approaches not only in other parts of British Columbia but also in other parts of the world, such as the Brisbane River estuary in Queensland, Australia. It is important to appreciate how difficult estuary governance is, and that FREMP's performance needs to be compared with what has been achieved in practice elsewhere and not just with theoretical ideals. For those who are close to the Fraser River estuary and understandably preoccupied with immediate concerns, there is a tendency to lose sight of the achievements over the last two decades and of this broader perspective. The governance model that was adopted after FRES I has been progressively developed and implemented through the design and refinement of innovative procedures for coordinated decision-making on project reviews and area designations. Gradual progress has been made from the general statement of goals towards more specific objectives and targets with agreements on policies and guidelines. There is a great deal more information readily available today about the biophysical and socio-economic systems of the Fraser River estuary than was the case when FRES was getting started in 1977.

Without taking anything away from what has been achieved, there must be questions about how well the evolving governance system is equipped for the challenges in prospect with increasing and diversifying demands on the estuarine resources. The debilitating weaknesses of uncertainty about the state of the estuary, slow delivery, and lack of recognition of FREMP will continue unless their fundamental causes are mitigated. Furthermore, there is a sense that the challenges of estuarine governance are increasing faster than the capabilities to deal with them. Difficulties that the evolving governance system has encountered throughout the last two decades are likely to get worse. Chief among these are two that will exacerbate each other: decreasing governmental funding and resources, and increasing needs for collaboration among all interests in sustainability.

To meet these challenges, the governance system will have to evolve in some significantly different ways beyond what has been built so far (Dorcey, 1991). The key requirement is much greater involvement of nongovernmental stakeholders in order to build understanding and commitment and, through partnerships, generate new management resources for what is done not only by FREMP, but by all the associated initiatives in the estuary, delta, and region. This implies an accelerated shift away from the conservative attitudes on public involvement that have predominated in FREMP and towards much greater emphasis on catalyzing and facilitating the involvement of nongovernmental stakeholders, as has begun to happen in many other initiatives in British Columbia in recent years, such as those associated with land-use planning processes, watershed round tables, and stewardship initiatives (Dorcey, 1997). This can be done in ways such that governmental agencies continue to retain their ultimate decision-making authority, but move towards sharing the responsibilities for management and stewardship in the estuary. Specifically, consideration needs to be given to the ways in which nongovernmental stakeholders might become direct participants in the various committees and work groups of FREMP.

No one would claim that such new ways of doing business will be easy (Dorcey, 1991, 1997). Most would admit that the various experiments with greater involvement of nongovernmental stakeholders have had mixed success so far, as people struggle to learn how these new forms of governance can be made to work productively. Just as has been the experience of the governmental organizations that have been part of the FRES and FREMP experiments to date, it will take time to build the understanding and trust that is essential to a productive relationship. Increasingly, however, people are recognizing that there is no alternative but to begin working together in new multistakeholder processes because governments cannot do it alone. In the making is a transformation of what has been the dominant Canadian model of governance. Interestingly, it is beginning to look a lot like the collaborative estuarine governance model that was proposed and rejected at the end of FRES I!

ACKNOWLEDGMENTS

This paper was drafted in 1997. Titles for organizations and programs are correct to that date. Information on subsequent changes can be found in Dorcey (in press) and the Web sites listed in the Appendix.

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REFERENCES

Davis, H.C. and Hutton, T.A.
2004: Metropolitan Vancouver: an economic gateway to the Pacific Rim; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Dorcey, A.H.J.
1991: Towards agreement on water management: an evolving sustainable development model; *in* Perspectives on Sustainable Development in Water Management: Towards Agreement in the Fraser River Basin, (ed.) A.H.J. Dorcey; Westwater Research Centre, University of British Columbia, p. 555–586.
1993: Sustainable development of the Fraser River estuary: success amidst failure; *in* Coastal Zone Management: Selected Case Studies, OECD; Organisation for Economic Cooperation and Development (OECD), Paris, p. 25–51.
1997: Collaborating towards sustainability together: The Fraser Basin Management Board and Program; *in* Sustainable Water Management: Canadian and International Experiences, (ed.) B. Mitchell and D. Shrubsole; Canadian Water Resources Association, Cambridge, Ontario, p. 167–199.
in press: Sustainability governance: Surfing the waves of transformation; *in* Resource and Environmental Management in Canada: Addressing Conflict and Uncertainty, 3rd edition, (ed.) B. Mitchell; Oxford University Press, Toronto.

Dorcey, A.H.J. and McDaniels, T.
2001: Great expectations, mixed results: Trends in citizen involvement in Canadian environmental governance; *in* Governing the Environment: Persistent Challenges, Uncertain Innovations, (ed.) E.A. Parson; University of Toronto Press, p. 247–302.

Fraser River Estuary Management Program
1994: A Living Working River: An Estuary Management Plan for the Fraser River; Fraser River Estuary Management Program, New Westminster, British Columbia, 120 p.

Fraser River Estuary Study Planning Committee
1982: A Living River by the Door: Proposed Management Program for the Fraser River Estuary; Fraser River Estuary Study, Surrey, British Columbia, 60 p.

Fraser River Estuary Study Steering Committee
1978: Fraser River Estuary Study Summary: Proposals for the Development of an Estuary Management Plan; Victoria, British Columbia, 145 p.

O'Riordan, J. and Wiebe, J.
1984: An Implementation Strategy for the Fraser River Estuary Strategy Management Program; British Columbia Ministry of Environment, Victoria, British Columbia, 45 p.

World Commission on Environment and Development
1987: Our Common Future; Oxford University Press, Oxford, United Kingdom, 400 p.

Appendix
Online information

Current and extensive information on the key programs that are mentioned in the text can be found on the World Wide Web at the following urls (current as of press time):

Burrard Inlet Environmental Action Program
http://www.bieapfremp.org/main_bieap.html

Fraser Basin Management Board and Program
http://www.fraserbasin.bc.ca

Fraser River Estuary Management Program
http://www.bieapfremp.org/main_fremp.html

Georgia Basin Action Plan
http://www.pyr.ec.gc.ca/georgiabasin/index_e.htm

Livable Region Strategic Plan - Greater Vancouver Regional District
http://www.gvrd.bc.ca/growth/lrsp.htm

Laws, the legal system, and the conservation and protection of the Fraser River estuary

Richard Kyle Paisley[1]

Paisley, R.K., 2004: Laws, the legal system, and the conservation and protection of the Fraser River estuary; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 265–273.*

Abstract: This paper has two objectives: first, to describe the legal framework for Fraser River estuary governance, and second, to analyze the role of laws and the legal system in the conservation and protection of the natural resources of the Fraser River estuary. For illustrative purposes, this paper will focus specifically on the factors which, from a legal perspective, govern the conservation and protection of the Pacific salmon resource in the Fraser River estuary.

This paper comprises sections dealing with the constitutional framework for environmental laws in Canada, an overview of federal and provincial environmental legislation, basic common-law principles and environmental issues, First Nations and the environment, and environmental law enforcement. It concludes with thoughts for the future and the observation that further evolution in environmental law and law enforcement is required if the resources of the Fraser River estuary are going to be sustainable in the twenty-first century.

Résumé : Cet article vise deux objectifs principaux : premièrement, décrire le cadre juridique de l'intendance de l'estuaire du Fraser, et deuxièmement, analyser le rôle des lois et du système juridique dans la conservation et la protection des ressources naturelles de l'estuaire. À des fins d'illustration, l'article se penche plus particulièrement sur les facteurs qui, d'un point de vue juridique, régissent la conservation et la protection d'une ressource naturelle — le saumon du Pacifique — dans l'estuaire du Fraser.

Cet article traite des sujets suivants : le cadre constitutionnel des lois canadiennes sur l'environnement; un aperçu des lois et règlements fédéraux et provinciaux en matière d'environnement; les principes de base de la common law et les questions environnementales; les Premières nations et l'environnement; l'application des lois sur l'environnement. En conclusion, l'auteur présente des idées pour l'avenir et souligne qu'il faudra faire évoluer le droit de l'environnement et l'application de la loi pour assurer la durabilité des ressources de l'estuaire du Fraser au XXI^{e} siècle.

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INTRODUCTION

The objective of this paper is to describe the constitutional and legislative framework for Fraser River estuary governance and provide an analysis of how laws and the legal system have been involved in the conservation and protection of the Fraser River estuary.

The underlying purpose is to view the law and the legal system in the context of factors that have been influential in affecting decisions. A depiction of the law as resembling a snapshot, freezing an event in an immediate framework of time and space, is inadequate for understanding change over time. A treatment of the law solely in terms of black letter rules and doctrines, divorced from the social processes that give them life and meaning, also would be misleading. Therefore, this paper attempts to identify events in the process of interaction. The analogy is to a motion picture depicting the unfolding past and focusing on the events and relationships that influenced the shaping of the current circumstances so that these become clearer as to their meaning and significance for the future.

For illustrative purposes this paper will focus on the factors which, from a legal perspective, govern the long-term maintenance of Pacific salmon in the Fraser River estuary. The five spheres of jurisdiction for environmental laws for the Fraser river estuary are 1) federal government, 2) Province of British Columbia, 3) regional government (Greater Vancouver Regional District), 4) municipal governments, and 5) First Nation governments. There are at least three reasons for choosing to focus on Pacific salmon in order to learn about and understand the ever-evolving role of laws and the legal system in the conservation and protection of the Fraser River estuary (Dorcey, 2004). First, as natives to the Fraser River, the six species of Pacific salmon (pink, chum, sockeye, coho, chinook, and steelhead) have a complicated life cycle that is crucially dependent on the health of both the river and the associated estuary (Dorcey, 1991). They spend at least the initial part of their life cycle in fresh water, migrate through the Fraser River estuary to a marine environment, and then return through the Fraser River estuary to fresh water to reproduce. Controlling the harvest and protecting the habitats that are critical to their survival and development are essential to sustaining the Pacific salmon resource. Second, Pacific salmon contribute significantly to the regional British Columbia economy. The landed wholesale value of commercial wild salmon in the years 1987 through 1989 alone ranged from $428 million to $585 million (Paisley, 1993). Third, Pacific salmon have immense cultural, symbolic, and spiritual value over and above their commercial value, particularly to First Nations people and environmentalists.

CONSTITUTIONAL FRAMEWORK

The federal and the various provincial governments have jurisdiction over specific subject areas as set primarily by sections 91 and 92 of the *Constitution Act* (formerly the "*British North America Act*"). The term 'environment' is not mentioned in the *Constitution Act* as a specific subject area governed by either the federal or provincial governments. This is not too surprising as the term 'environment' is not readily subject to precise definition and the environment was probably not a major issue when the *British North America Act*, the predecessor to the *Constitution Act*, was enacted in 1867 (Thompson et al., 1993).

Pursuant to section 91 of the *Constitution Act*, the federal government has legislative jurisdiction over a variety of matters, including criminal law, navigation, and shipping (91(10)); sea coast and inland fisheries (91(12)); and federal lands and lands reserved for native peoples (91(24)) (Table 1). In addition, the federal government has the power to pass legislation for the "Peace, Order and Good Government of Canada". The federal government also has the benefit of the "paramountcy" provision of the Constitution. Under paramountcy a federal head of power takes precedence over, or is 'paramount' to, a provincial head of power, whenever there may be a direct conflict between a federal head of power and a provincial head of power.

Pursuant to sections 92 and 92A of the *Constitution Act*, the various provincial governments, including that of British Columbia, also have jurisdiction over a wide range of matters, including the power to legislate with respect to "property and

Table 1. Federal government overview (note: these are illustrative of some jurisdictional components).

Jurisdictional source: *Constitution Act* - Section 91	Criminal law Navigation and shipping Sea coast and inland fisheries Federal lands and lands for native peoples Declaratory power Paramountcy provisions
Key legislation	*Fisheries Act* *Canadian Environmental Protection Act* *Canada Shipping Act* *Canadian Environmental Assessment Act* *Transportation of Dangerous Goods Act* *Oceans Act*

Table 2. Provincial government overview (note: these are illustrative of some jurisdictional components).

Jurisdictional source: *Constitution Act* - Sections 92 and 92A	Property and civil right Matters of a merely local nature Hydro and hydro-electric facilities
Key legislation	*Waste Management Act* *Waste Management Amendment Act, 1993* *British Columbia Environmental Assessment Act*

civil rights" and "matters of a merely local or private nature in the provinces" (Table 2). Under these powers, the various provinces have regulated land use and most aspects of mining, manufacturing, and other business activity, including the regulation of emissions that could pollute the environment (Hogg, 1997). The individual provinces also have the power to legislate in respect of such matters as the management and sale of provincial land and timber and municipal institutions.

Regional, municipal, and First Nations governments also play an important role legally in environmental protection. Regional and municipal institutions have important powers that may impact the environment, such as the ability to regulate the construction and maintenance of sewers and drains as well as the important ability to regulate zoning and building; however, regional and municipal institutions generally have no special constitutional status and can only possess such powers as have been lawfully delegated to them by the provinces. First Nations have a particularly interesting and evolving constitutional role in environmental matters pursuant to section 35 of the *Constitution Act*, which states that "...[T]he existing aboriginal and treaty rights of the aboriginal people of Canada are hereby recognized and affirmed" (Morgan, 1996). Recently, the Supreme Court of Canada has applied section 35 to hold that, in certain circumstances, First Nations individuals have a constitutionally protected priority to fish for "food, ceremonial and social purposes". The court also has held that this priority is second only to conservation needs and ranks ahead of the rights of commercial or sport fishers (Paisley, 1993).

As a practical matter, the responsibility for conserving and managing Pacific salmon populations native to the Fraser River is shared between the federal and provincial governments. More specifically, the federal government has responsibility for the conservation and protection of all anadromous species of fish and their habitat, but since 1937, has administratively subdelegated to the province of British Columbia the responsibility for the conservation and management of freshwater fish (VanderZwaag, 1983; Paisley, 1993). There are also administrative arrangements between the federal and British Columbia governments concerning fish and fish habitat that are currently under review. In August of 1996, the Deputy Minister of the federal Department of Fisheries and Oceans and the Deputy Minister of the Office of the Premier for the Province of British Columbia entered into a Memorandum of Understanding to conduct a comprehensive, bilateral review of federal and provincial roles and responsibilities in the management of the Pacific salmon fishery. Implementation of the agreement that was subsequently negotiated between the two governments is pending, and it is not yet known what the full ramifications of either the review or the subsequent agreement will be on the conservation and protection of Pacific salmon.

In the following sections of this paper, particular attention will be paid to the following four existing legal mechanisms for the conservation and protection of fish and fish habitat and the prevention of pollution in the Fraser River estuary: 1) Canada's international legal obligations, 2) the fisheries habitat protection provisions contained in the federal *Fisheries Act*, 3) common-law actions that may allow for the recovery of damages for pollution, and 4) First Nations environmental rights.

CANADA'S INTERNATIONAL ENVIRONMENTAL LEGAL OBLIGATIONS

Canada is a party to an array of international legal obligations involving environmental matters. Many of these international legal obligations call upon the various contracting countries to pass domestic enabling legislation in order to give full force and effect to the binding international legal commitments.

Some examples of international environmental legal obligations to which Canada is a party are the Biodiversity Convention (conserving and protecting biodiversity), the Third United Nations Convention on the International Law of the Sea (among other things, conserving living marine resources and prevention and remediation of marine pollution), the Convention on International Trade of Endangered Species (prohibiting trade in endangered species), the International Migratory Birds Convention (conserving and protecting migratory birds between Canada and the United States), the Ramsar Convention (conserving and protecting wetlands), and the environmental side agreement to the North American Free Trade Agreement (providing certain procedures for resolving certain kinds of environmental disputes between Canada, the United States, and Mexico).

Entering into such international legal obligations can have immense psychological and symbolic value for the countries involved; however, the domestic legal impact of international legal obligations is really only as good as the extent to which individual countries honour their international legal obligations by enacting and enforcing domestic enabling legislation pursuant to those international legal obligations.

Regrettably, Canada has in many instances failed to enact and/or enforce the domestic enabling legislation that would give full force and effect to its international legal obligations. This problem is exacerbated by the fact that the Constitution of Canada does not provide for international treaties to automatically become the supreme law of the land, nor does the Canadian Constitution allow Parliament, through implementation of treaty obligations, to automatically alter the distribution of legislative powers within Canada. Rather, the Canadian Parliament only has the power to implement those aspects of international legal obligations that fall within the federal sphere of constitutional jurisdiction and must call upon the various provincial governments to implement those aspects of the international legal obligations that fall within the various provincial spheres of constitutional jurisdiction.

Two examples illustrate these points. First, despite being a party to the Biodiversity Convention since its inception, Canada only recently enacted the endangered species legislation called for by the convention. Second, Canada waited more than two decades before finally ratifying the Third United Nations Convention on the International Law of the Sea, which it signed back in 1982.

It follows that the impact of these and other important international laws and international legal conventions on the ability of Canada to conserve and protect the Fraser River estuary and other estuaries has been considerably diminished by Canada's inability to ratify and implement many of its important international legal obligations.

FEDERAL LEGISLATION

A number of items of federal legislation are particularly important in the context of conserving and protecting the Fraser River estuary: 1) *Fisheries Act*, 2) *Canadian Environmental Protection Act*, 3) *Canada Shipping Act*, 4) *Canadian Environmental Assessment Act*, 5) *Transportation of Dangerous Goods Act*, and 6) *Oceans Act*.

Federal Fisheries Act

Pursuant to the federal *Fisheries Act* it is an offense for anyone to carry on any work or undertaking that results in the harmful alteration, disruption, or destruction of fish habitat. It is also an offense under the *Fisheries Act* to deposit or permit the deposit of any type of "deleterious" substance in water frequented by fish. A deleterious substance is a substance which would degrade or alter the quality of water so as to render it harmful to fish or fish habitat.

In general, the *Fisheries Act* provides a comprehensive federal strategy for the protection of fish habitat and the prevention of pollution (Paisley, 1993); however, any attempt to manage fish habitat also must acknowledge provincial control over land and water resources, and any action by federal authorities to regulate or prevent land- or water-use activities cannot be seen to be usurping provincial jurisdiction over these activities unless they can be shown to be directly impinging upon fish stocks and fish habitat (Dorcey, 1991). It follows that federal and provincial enforcement activities need to be closely co-ordinated (Dorcey, 1991; Paisley, 1993). Taken literally, the federal statutory scheme makes a criminal offense of any human activity that disrupts an aquatic environment inhabited by fish. This covers activities in water or on land. In practice, these provisions set the stage for fisheries habitat management in two contexts (Webb, 1988; Paisley, 1993). First, they provide the authority by which proposed activities can be assessed by the Department of Fisheries and Oceans. In practice, development activities that have the potential to affect fisheries habitat are usually referred to the Department of Fisheries and Oceans by provincial regulatory authorities. Department of Fisheries and Oceans staff then assess whether fish habitat will be harmed and if substances deleterious to fish will be discharged. This usually sets the stage for direct negotiations between Department of Fisheries and Oceans habitat managers and developers over design modifications and habitat protection measures. Second, although the Department of Fisheries and Oceans has no official permitting capacity, it can threaten criminal prosecutions should a project proceed and fisheries habitat be damaged. In practice, this drastic action is not usually taken unless there has been wilful disregard of the law or a serious environmental incident. The need to exercise discretion as to whether to prosecute raises the sensitive question of whether prescribing criminal law sanctions is the most efficacious way of protecting fisheries habitat or ensuring environmental compliance (Webb, 1988). There are also a wide range of defenses that are available to prosecutions under the habitat protection provisions of the *Fisheries Act* (Paisley, 1993). Key among these is the "due diligence offense" whereby an accused can avoid liability if he or she can prove that all reasonable care was taken. This involves consideration of what a reasonable person would have done in the circumstances. This defense will usually be available if the accused reasonably believed in a mistaken set of facts which, if true, would render the act or omission innocent or if he took all reasonable steps to avoid the particular event. Depending on the circumstances, an accused also may be able to rely on one or more of the following defenses: abuse of process, acting under a reasonable mistake of fact, officially induced error, sabotage, or the fact that the evidence being used against him was the result of an unconstitutional search ("fruit of the poisonous tree") (Paisley, 1993).

Canadian Environmental Protection Act

The *Canadian Environmental Protection Act* (CEPA) governs activities within federal jurisdiction such as cross-border air pollution, the dumping of noxious substances into the oceans and navigable waters, and the regulation of toxic substances. Failure to comply with the *Canadian Environmental Protection Act* may result in criminal prosecution, and the maximum theoretical penalties are substantial (Thompson et al., 1993).

Canada Shipping Act

The *Canada Shipping Act* regulates the business of shipping. Any person or ship that discharges a pollutant in contravention of any regulation made pursuant to the act is liable on summary conviction to a maximum fine of $250 000.

Canadian Environmental Assessment Act

The *Canadian Environmental Assessment Act* (CEAA) is the primary piece of legislation governing environmental impact assessment in Canada at the federal level. The *Canadian Environmental Assessment Act* is supposed to provide a comprehensive regime for monitoring projects that have an environmental impact. The federal government has issued a list of types of projects that are likely to require a comprehensive environmental assessment, including: damming or diversion of rivers with an average flow greater than 100 m^3/s; creating or affecting artificial lakes, reservoirs, or wetlands greater than 300 ha; exploiting offshore resources; exploiting significant amounts of oil, natural gas, or liquefied gas; asbestos mining; constructing military bases; and constructing permanent facilities for the storage, treatment, incineration, or disposal of hazardous waste. The objective of the review process is to determine whether the project is likely to cause significant and adverse effects. If so, the project must be assessed to determine if these effects can be mitigated. If it is determined that significant adverse environmental effects cannot be mitigated or justified, there must be a recommendation that the project be rejected (Thompson et al., 1993).

Transportation of Dangerous Goods Act

The *Transportation of Dangerous Goods Act* prohibits any person from handling, offering for transport, or transporting "dangerous goods" without complying with all applicable safety regulations and rules concerning containers, packaging, and means of transportation, and displaying prescribed safety standards. Persons convicted under the act face a maximum fine of $50 000 for a first-time offense. The act also provides that if a corporation commits an offense, certain officers and directors of the corporation also may be liable.

Oceans Act

The *Oceans Act* received Royal Assent (became law) in December 1996. From an environmental perspective the most potentially significant parts of the act are those dealing with estuaries, marine protected areas, and integrated coastal zone management. The regulations and policies necessary to implement the act are still being developed.

PROVINCIAL LEGISLATION

The principal provincial environmental statute in the province of British Columbia is the *Waste Management Act* (Thompson et al., 1993). Section 3 of the act defines "waste" in a broad manner and prohibits the introduction of waste into the environment in such a manner or quantity to cause "pollution". Pollution is defined by the act as the presence in the environment of substances or contaminants that substantially alter or impair the usefulness of the environment. Pursuant to the act, a permit from the regional waste manager is required in order to deposit or discharge waste into the environment. Special approval also is required for collection and disposal of waste.

Penalties under the act may be substantial. A person with a permit to discharge waste into the environment who fails to abide by the requirements of the permit faces a maximum penalty of $1 000 000. When a person is found to have intentionally caused damage to the environment or to have shown reckless and wanton disregard for the lives or safety of persons thus creating a risk of death or harm to those persons, the maximum penalty is imprisonment up to three years and a fine of $3 000 000.

Two other particularly important pieces of British Columbia environmental legislation with potential ramifications for the Fraser River estuary are the *Waste Management Amendment Act*, 1993 and the *British Columbia Environmental Assessment Act*. The *Waste Management Amendment Act* provides for the determination of whether a site is contaminated, establishes processes for ensuring remediation, and identifies the persons potentially responsible for the cost of remediation. The act received Royal Assent (became law) in 1993 but only recently acquired the necessary Contaminated Sites Regulations to make it fully operational. The *British Columbia Environmental Assessment Act* consolidates existing environmental impact assessment processes in British Columbia and creates a project information registry as well as an Environmental Assessment Board for the review of complex and controversial projects. The act provides for a multilevel process that allows less complex or controversial projects to be approved on a more expedited basis. Regulations set out the types of reviewable projects and the thresholds for their inclusion. Generally, the following types of projects are reviewable: heavy industry, including chemicals, metals, minerals, and forest products; mines; energy; water containment and diversion; waste disposal; aquaculture and food processing; municipal responsibilities, including water, waste, and transportation; transportation, including railways, urban rail, ferry terminals, port facilities, and airports; and destination-resort projects. In addition, golf courses, tourism, and recreational projects may be reviewable projects.

BASIC COMMON-LAW PRINCIPLES

In addition to federal and provincial laws, the preservation and protection of the environment and of the living resources which depend on the environment may also proceed through the civil court system based on common-law principles (Paisley, 1993).

Action in the civil court system has at least two key features that distinguish it from the kinds of criminal prosecutions that have been noted above. First, an individual or organization bringing on a civil action based on common-law principles is usually a private party. This is in contradistinction to a criminal action where it is the government that must take the initiative. Second, the standard of proof in a civil action is the "balance of probabilities". This is in contradistinction to the situation in a criminal action where the Crown must prove its case "beyond a reasonable doubt". As a practical matter it is usually much more difficult to prove something beyond a reasonable doubt than it is to prove something on the balance of probabilities.

Among the potential civil causes of action based on common-law principles that are theoretically available to an aggrieved party in an environmental context are actions for: 1) nuisance, 2) trespass, 3) escape of dangerous substances, 4) negligence, and 5) statutory remedies (Paisley, 1993).

Nuisance

In Canada it is possible for an aggrieved party to bring a private legal action in the civil court system for a "public nuisance" if, as a result of the nuisance, the aggrieved party has suffered damage beyond that of the "average citizen".

Regrettably, the courts in Canada have yet to allow an aggrieved party, such as a commercial fisher, to recover damages for pure economic loss under a theory of public nuisance; however, this is in contradistinction to the situation in both the United States and England, which follow the modern trend to allow aggrieved parties in an appropriate case to make such a recovery (Paisley, 1993).

Trespass

The common-law offense of trespass to land involves the entering upon another's land without lawful justification or the placing of some material object on the land of another without the legal right to do so; however, the interference must be intentional and direct, making it, as a practical matter, difficult to prove. Once the act of trespass and intention are established, the quantum of damages suffered also must be proved.

Escape of dangerous substances

An eighteenth century English case is the foundation of yet another civil cause of action often used in environmental litigation. In the case of *Rylands v. Fletcher*, the defendants had constructed a water reservoir on their land to supply water to their mills. The plaintiff operated a coal mine on a property adjacent to the defendants land. The defendants were not aware that a mine shaft, connected to the plaintiff's mine, ran under the ground on which their reservoir was situated. When water in the reservoir escaped into the mine shaft and flooded the plaintiff's mine, the plaintiff sued the defendant.

In finding the defendant liable to the plaintiffs, the Court found that the defendant was "strictly liable" to the plaintiff; that is, responsible for damages their actions caused, regardless of any 'fault' on their part. A defendant may escape responsibility for an offense when they are strictly liable if they are able to supply an explanation of the incident by showing that all reasonable steps were taken to avoid the injury. Furthermore or alternatively, a defendant can try to avoid liability for a strict liability type of offense by showing that the event in question occurred because of an act of God or because of the deliberate act of a third person or pursuant to legislative authority. In Canada, the rules regarding strict liability offenses emanating from *Rylands v. Fletcher* have been applied to find a duty of care arising from the use of land in a variety of circumstances, including the storage of gasoline in drums indoors, the use of explosives, the escape of sewage, and the spraying of weeds with herbicides (Thompson et al., 1993).

Negligence

If a party suffers damages from the activities of another, they may be able to establish a cause of action for negligence. In order to succeed on a claim of negligence, an aggrieved party must show that the defendant owed him a duty of care to act or refrain from acting, the defendant acted in a particular manner, the defendant failed to meet the duty of care that he or she was under, and the aggrieved party suffered damages as a result. As a practical matter, the significant element in such actions is the nature and extent of the duty of care which one party owes to his or her neighbours. Recovery in negligence also has been considered by the courts in Canada to be generally restricted to recovery for damages consequent on physical damage. This is in contradistinction to the situation in both the United States and England, where the courts have exhibited more willingness to allow claims for pure economic loss (Paisley, 1993).

Statutory remedies

Statutory remedies are remedies that are available pursuant to particular statutes that allow an aggrieved party to recover for pollution damage in an appropriate case. An example is section 42(3) of the *Fisheries Act*, which potentially allows a licensed commercial fisher to recover economic loss following from damages caused by a deleterious substance.

FIRST NATIONS AND THE ENVIRONMENT

For many decades, First Nations fishers throughout North America have been fighting to have their aboriginal rights recognized. At this juncture, it remains to be seen whether First Nations in Canada will be able to emulate the success that their counterparts in the United States appear to have had in establishing both aboriginal fishing and aboriginal environmental rights (Blumm, 1989; Morgan, 1996).

In the Pacific northwest of the United States, disputes between native and non-native fishers have been to the Supreme Court of the United States on at least seven separate occasions between 1905 and 1976 (Blumm, 1989; Paisley, 1993). Ultimately, the Supreme Court of the United States upheld the right of certain First Nations treaty fishers to take up to 50% of the fish destined to reach their usual and accustomed fishing places. Subsequently, First Nations treaty fishers in the Pacific northwest sought judicial confirmation of both a share of government-produced hatchery fish and a right to judicially intervene to suspend activities damaging habitat upon which fish are dependent. United States aboriginal environmental law now appears to have evolved at least to the point where certain American First Nations, even those without explicit treaty rights, are able to secure judicial backing for environmental initiatives such as securing sufficient water flows to protect reserve fisheries.

In Canada, section 35 of the *Constitution Act*, enacted in 1982, states that "...[T]he existing aboriginal and treaty rights of the aboriginal people of Canada are hereby recognized and affirmed," and the Supreme Court of Canada has already relied on section 35 to hold that, in certain circumstances, certain First Nations have a constitutionally protected priority to fish for food, ceremonial, and social purposes (Paisley, 1993).

The courts also have held that the First Nations priority is second only to "conservation" needs and ranks ahead of any rights or privileges that commercial or sport fishers may have.

More recently, the courts in Canada have followed the lead of courts in other jurisdictions and begun to explore the extent to which First Nations may have additional constitutionally protected priorities to fish and other resources, including the circumstances under which First Nations aboriginal rights may be extinguished or infringed and the scope of the fiduciary duty owed to First Nations by the federal and provincial crowns (Morgan, 1996).

On the horizon may be the emergence of special First Nations "environmental rights" on the basis of the proposition that it would be inappropriate for the Canadian courts to affirm aboriginal fishing rights and then forsake those rights to uncontrolled environmental degradation (Paisley, 1993). Arguably, the Canadian courts are no more likely to decouple First Nations fishing and First Nations environmental rights than the federal Department of Fisheries and Oceans is likely to decouple conservation and protection of the fisheries from conservation and protection of fisheries habitat (Paisley, 1993). Already in British Columbia there are at least two cases, *Pasco v. CNR*, [1986] 1 C.N.L.R. 34 (C.A.) and *Saanichton Marina Ltd. v. Claxton*, (1987), 43 D.L.R. (4th) 481, which suggest that British Columbia First Nations are on the road to obtaining environmental rights to complement their emerging fishing rights (Paisley, 1993; Morgan, 1996).

The potential ramifications of developments such as these are difficult to predict, but could range from a racist backlash against First Nations to the dawn of a new age of unprecedented co-operation, born out of necessity, between First Nations, environmental groups, and development interests.

ENFORCEMENT

In describing strategies for sustainable development, the Brundtland Commission strongly advised that national governments needed to both establish clear environmental goals and enforce those environmental goals through environmental laws, regulations, incentives, and standards for industrial enterprises (Brundtland Commission, 1987). It remains to be seen whether governments throughout the world will be successful in either establishing clear environmental goals or embodying those goals in clear unambiguous statutory schemes; however, in many jurisdictions, including Canada, where we do have environmental laws, the lack of enforcement of existing environmental regulations has increasingly begun to attract attention and criticisms (Thompson et al., 1993).

Most of the various environmental statutes in Canada typically attempt to control environmentally harmful behaviour through a command and control regulatory framework and allow enforcement officials considerable discretion in how they respond to violations. Historically, the Canadian approach to the enforcement of environmental laws has been in contrast to the litigious adversarial pattern of enforcement which came to characterize the enforcement activities of entities such as the United States Environmental Protection Agency (Thompson et al., 1993). The more aggressive use of the courts in enforcing environmental laws in the United States stems from at least two factors. First, the American legal system has traditionally provided access to relatively large monetary penalties as an effective alternative to criminal sanctions in responding to noncompliance. Second, bargaining and negotiation has traditionally been more the essence of environmental regulation in Canada. Recently, the pressure on Canadian authorities to adopt a less conciliatory stance on the enforcement of environmental regulations has been increasing. Changing public attitudes towards the environment have been an important factor in this metamorphosis (Thompson et al., 1993).

Among the recent trends in environmental enforcement have been the institutionalization of the 'polluter pays' concept, increased enforcement activity, tougher sentences, and a move towards citizen enforcement actions (Thompson et al., 1993). Both the federal and provincial governments have also taken steps in recent years to expand the scope of liability in respect of environmental harms caused by companies and individuals. On the criminal side, penalties have dramatically increased for individuals, corporations, and directors, officers, and agents. On the civil side, companies and individuals can increasingly be found liable for the costs of cleanup, often long after of the event that caused the problem. At the federal level, enforcement activity under the *Canadian Environmental Protection Act* has been steadily increasing (Thompson et al., 1993). In 1989–1990, Environment Canada carried out more than 3000 inspections under the *Canadian Environmental Protection Act* across the country. This inspection and investigation effort led to 280 enforcement actions. The number of successful prosecutions pursuant to the federal *Fisheries Act*, at least until recently, also has been steadily increasing (Thompson et al., 1993). Amendments to the penalty schemes in many Canadian environmental statutes have broadened the array of sentencing tools available to sanction corporations and individuals. In addition to higher maximum fines, courts increasingly have the option of imposing jail terms, profit-stripping fines, property forfeitures, and sentencing orders. The move towards citizen enforcement actions is a phenomenon that is likely to continue in the foreseeable future. Private interest groups, of which there are an increasing number with the necessary funding and expertise, are increasingly motivated to act to preserve and protect the public interest. Both the *Canadian Environmental Protection Act* and the *Fisheries Act* have provisions that allow a successful private complainant to receive a percentage of any fine imposed. Another positive development has been increasing use of creative sentencing mechanisms that attempt to match fines to much needed work in the areas of fisheries habitat restoration and enhancement.

Despite these efforts, there continues to be a lingering perception that not enough is being done to conserve and protect resources such as Pacific salmon that are native to the Fraser River. In late 1994, the then Minister of Fisheries and Oceans, the Honourable Brian Tobin, formed the Fraser River Sockeye Public Review Board to investigate the apparent disappearance that year of more than one million sockeye salmon that were predicted to return to their spawning grounds throughout the Fraser River watershed (EB Experts, unpub. report, 1996). The board's report was released on March 7, 1995. The essence of the board's message is summarized in the Executive Summary of its report:

> "...[I]f something like the 1994 situation happens again, the door to disaster will be wide open. According to what the Board found, one more 12 hour opening could have virtually eliminated the late run of sockeye in the Adams River. Such an occurrence would have devastating consequences for the Pacific fishery, delaying stock rebuilding efforts by years and bringing dire economic consequences to the province..."
>
> —EB Experts, unpub. report, 1996

The board made 35 recommendations to the minister covering a broad range of issues. The minister accepted all of the board's recommendations, and Department of Fisheries and Oceans made explicit written responses to each recommendation describing what it would do in 1995 and beyond to implement the letter and spirit of each recommendation.

Subsequently, Department of Fisheries and Oceans commissioned an independent evaluation of its response to the review board's recommendations (EB Experts, unpub. report, 1996). Among many other things, the independent evaluation found that:

> "...[H]abitat destruction is perceived by both user groups and (DFO) C&P (Conservation and Protection) staff we interviewed to be at least as significant an enforcement challenge to the Fraser River as poaching. Both C&P field personnel and aboriginal representatives interviewed were distressed at the level of (fisheries) habitat destruction that DFO did not address in 1994 and previously. DFO is sensitive to this issue and is moving to rectify the situation in 1996 and beyond."
>
> —EB Experts, unpub. report, 1996

THE UTILIZATION OF SCIENTIFIC INFORMATION IN ENVIRONMENTAL DECISION-MAKING

In theory, science and scientists have an important influence over the way in which environmental laws are implemented and applied to the Fraser River estuary.

In practice, the model of science in environmental decision-making that has largely been relied on in establishing environmental policies in the Fraser River estuary has been an "episodic interaction" model. More specifically, scientists have usually been called upon to prepare and submit reports that have helped to shape the policy process. They have seldom been called upon to participate in the selection of policy alternatives which usually have involved compromise and bargaining for which they were deemed to be unqualified. This model of utilization of scientific information in environmental decision-making appears to be responsible for many of the problems the Fraser River estuary is currently facing.

In fundamental contradistinction to the episodic interaction model of utilization of scientific information in environmental decision-making is the desirability of a more "active adaptive" approach. The significant advantage of an active adaptive approach or model is that it would allow for action in the face of scientific uncertainties and help keep the powerful problem-solving characteristics of the scientific method continuously engaged in the service of policy development. Such a model also would be more conducive to application of a more "precautionary approach" to environmental management which would require that policy makers act with due caution in light of scientific uncertainty, taking (cost effective) measures that are possible, regardless of whether they appear environmentally essential at the time.

The general importance of interaction between political spheres and baseline and other scientific research in establishing the parameters by which effective fisheries habitat and resource management can occur cannot be overstated. The current trend to cut back on the quality and quantity of scientific research in the Fraser River estuary is disturbing and certain to further impair our ability to manage the resources of the estuary effectively.

THOUGHTS FOR THE FUTURE

Canada is a world leader in the enactment of ever more stringent environmental laws and regulations. Regrettably, much of this regulatory law is what the Brundtland Commission (1987) has described as "the effects oriented standard agenda" and this type of agenda has historically not been terribly effective in preventing environmental desecration. The reasons for this include a persistent and increasing lack of sufficiently trained legal and scientific personnel, equipment, and procedures; a seeming inability to adequately and properly utilize scientific information in environmental decision-making; government downsizing; and resistance to change on the part of existing institutions and vested interests (Brundtland Commission, 1987; Rankin, 1991).

The central message of the Brundtland Commission (1987) analysis was that the environment must be turned into a mainstream economic issue and that a subordinate role for environmental agencies is no longer adequate if sustainable development is to be anything more than ironic rhetoric (Rankin, 1991; Dorcey, 2004).

There needs to be a great deal more emphasis on compliance, enforcement, the creative utilization of scientific information in environmental decision-making, and the harnessing of market forces if the resources of the Fraser River estuary, particularly the Pacific salmon resource, are going to be sustainable in the twenty-first century. In general we already have most of the laws as well as the legal system that we need to do the job, but lack the political will and resources to do that which needs to be done; however, the current *Fisheries Act*, as it is presently applied, is largely a reactive tool whereby offenders are usually only punished after habitat loss or damage has already occurred. Among other things, there is no requirement that initiatives that may destroy fish habitat obtain permission before they can proceed. Second, the current habitat protection provisions of the *Fisheries Act* are not easily enforced. There is a real case to be made for developing strategies to both educate the public and persuade violators that what they do is morally reprehensible as well as against the law. Third, it is only recently that federal and provincial government policy changes have allowed more important responsibility for stream stewardship and fisheries habitat protection to be given over to local government and nongovernmental environmental organizations.

For all of these reasons it is difficult to be sanguine about the role of the law and the legal system in the conservation and protection of the Fraser River estuary. More environmental laws and regulations and significantly better enforcement are clearly required if the resources of the Fraser River estuary are going to be sustainable into the twenty-first century.

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REFERENCES

Blumm, M.C.
1989: Native Fishing Rights and Environmental Protection in North America and New Zealand: A Comparative Analysis of Profits a Prendre and Habitat Servitudes; Wisconsin International Law Journal, v. 8, issue 1, p. 1–50.

Brundtland Commission
1987: Our Common Future; World Commission on Environment and Development, Oxford, United Kingdom, 398 p.

Dorcey, A.H.J. (ed.)
1991: Perspectives on Sustainable Development in Water Management: Towards Agreement in the Fraser Basin; University of British Columbia, Westwater Research Centre, Vancouver, British Columbia, 592 p.

Dorcey, A.H.J.
2004: Evolution of estuarine governance in a metropolitan region: collaborating for sustainability in the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Hogg, P.W.
1997: Constitutional Law of Canada; 4th ed.; Carswell, Toronto, Ontario, 1700 p.

Morgan, N.A.
1996: The intersection of business, environmental and Aboriginal law in British Columbia; *in* Environmental Law: Business and Legal Perspectives; The Continuing Legal Education Society of British Columbia, Vancouver, British Columbia, 329 p.

Paisley, R.K.
1993: The fishing industry; *in* Environmental Law and Business in Canada, (ed.) Geoffrey Thompson, M. McConnell, and L.B. Huestis; Canada Law Book, Aurora, Ontario, p. 523–542.

Rankin, M.T.
1991: Despoiling a river: can the law help to sustain the Fraser River?; *in* Perspectives on Sustainable Development in Water Management: Towards Agreement in the Fraser River Basin, (ed.) A.H.J. Dorcey; University of British Columbia, Westwater Research Centre, Vancouver, British Columbia, p. 391–416.

Thompson, G., McConnell, M., and Huestis, L.B.
1993: Environmental Law and Business in Canada; Canada Law Book, Aurora, Ontario, 599 p.

VanderZwaag, D.
1983: Canadian Fisheries Management: A Legal and Administrative Overview; Ocean Development and International Law, v. 13, p. 171–207.

Webb, K.
1988: Pollution Control in Canada: the Regulatory Approach in the 1980s; Study Paper, Administrative Law Series, The Law Reform Commission of Canada, Ottawa, Ontario, p. 19–23.

Sustainable development for the Fraser River estuary

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Abstract: Since the Lower Mainland of British Columbia was first settled, it has been altered by development for human purposes. This, like most development now occurring in the world, has not been sustainable. This paper examines a landscape ecological model of sustainability, compares it with the current compartmentalization model of development, and proposes that adoption of the landscape ecological model and of the concept of diversity in landscape planning and development provides a basis for achieving sustainable land use.

A fundamental premise of this paper is that development is an act of ecosystem design in that it is an alteration of the structure and function of the ecosystem. Understanding this, we may use human activities as a vehicle to enhance, rather than degrade, human ecosystem function and make the region more sustainable from both a human and a natural systems perspective. Several regional case studies are examined for sustainability in relation to this model.

Résumé : Depuis l'arrivée des premiers occupants dans la vallée du bas Fraser, la région a été transformée par le développement effectué en fonction des humains. Comme dans la majeure partie du monde, ce développement n'est pas durable. L'auteur examine un modèle de durabilité fondé sur des principes d'écologie du paysage, le compare au modèle de développement actuel, qui est fondé sur des principes de compartimentation, et propose comme bases pour l'utilisation durable du territoire l'adoption du modèle fondé sur l'écologie du paysage et l'incorporation de la notion de diversité dans la planification et le développement du paysage.

Une des prémisses fondamentales de cet article est que le développement est un acte de conception de l'écosystème, du fait qu'il en modifie la structure et la fonction. La compréhension de cette prémisse nous permet d'envisager les activités humaines comme un moyen d'améliorer, plutôt que de dégrader, le fonctionnement des écosystèmes centrés sur les humains, et de rendre la région plus durable du point de vue des humains et des systèmes naturels. L'auteur examine la durabilité en relation avec ce modèle dans plusieurs études de cas de portée régionale.

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A THEORY OF SUSTAINABLE DEVELOPMENT

The Fraser River estuary has undergone extensive manipulation due to human settlement and usage. More development is inevitable. It is expected that the region will accommodate an average of 113 additional people per day for the next thirty years (Greater Vancouver Regional District, unpub. report, 1993) and that the population will exceed 3 million people by the year 2021 (Greater Vancouver Regional District, unpub. report, 1996, p. 44). This has worrisome implications not only for the ecological health of the region, but for the well-being of its residents, as crowding, living densities, traffic, and atmospheric pollution increase and per capita water supplies, opportunities for recreation, and privacy are inevitably diminished.

Development in the region has altered the original ecosystem. This area, like much of the Earth's surface, is now a human ecosystem, i.e. an ecosystem whose structure and function are derived partially from its origins and location and partially from human energy inputs (Lyle, 1985). The development process is not simply an act of using land to meet human needs, but one of ecosystem design. Fundamentally, it is an alteration of the structure and function of an ecosystem. Understanding this, we may use human activities as a vehicle to enhance, rather than degrade, human ecosystem function and to make the region more sustainable from both a human and a natural systems perspective.

Origins of sustainability

The term 'sustainable development' came into widespread usage after the 1987 publication of *Our Common Future*, the report of the World Commission on Environment and Development (World Commission on Environment and Development, 1987). Since then, the nature of sustainable development and the means of achieving it have been the subject of inquiry by researchers and theorists from a wide range of disciplines. Some authorities consider sustainable development to be continued economic expansion or "the modification of the biosphere and the application of human, financial, living and non-living resources to satisfy human needs and improve the quality of life" (International Union for Conservation of Nature and Natural Resources, 1980, World Conservation Strategy *in* Schmidheiny, 1992, p. 6). Other authors use the term sustainability to imply sustaining human activity, within resource constraints and without continuously expanding the gross national product (Beatley and Brower, 1993). They consider sustainable development to be "the expansion or realization of potentialities; the gradual bringing to a fuller, greater or better state" (Young, 1992, p. 49). The first of these views has been termed the 'expansionist' view of sustainability, while the second is known as the 'steady-state' or 'ecological' view of sustainability. These two views represent the major viewpoints in the sustainability debate (Rees, 1995). In general, there is agreement that sustainability will operate on the value of achieving human aspirations while maintaining ecological integrity (Tisdell, 1988; Forman, 1990).

A landscape ecological model for sustainability

Landscape ecology is an emerging science that examines the structure (i.e. the spatial relationships) of distinctive ecosystems, their function, and the ways they change their function and structure over time (Risser et al., 1984). Landscape ecologist Richard Forman (1990) developed a model for sustainability that ties landscape ecological theory to the assessment of sustainability. He proposed that a sustainable environment must remain stable in terms of 'foundation variables' that support sustainability (Table 1).

Because development requires alteration of the landscape, Forman (1990) proposed that foundation variables such as soil, biological diversity, and fresh water should only change very slowly. This model of sustainability is a complete model that includes the social, ecological, and economic aspects of human actions on the landscape. Recalling that development equals ecosystem design, we see that our actions on the land determine its structure and that structure determines both ecological and human function. The challenge is to find a physical arrangement of ecosystems and land use that maximizes ecological integrity and human aspirations. The landscape ecological model is explicitly an ecological or steady-state view of sustainability, since it rests on maintaining the carrying capacity of both human and natural systems.

The landscape ecological model may be used to assess the relative sustainability of the current condition and to measure relative advances toward a more sustainable condition (Mooney, 1993; P.F. Mooney, unpub. conference presentation, Council of Educators in Landscape Architecture Annual Conference, Spokane, Washington, 1996). In doing so it must be realized that sustainability is a continuum. No landscape can be said to be perfectly sustainable; rather, it is less or more sustainable when compared to a previous condition or to one or more of the landscape foundation variables.

Table 1. Foundation variables that support sustainability, according to the landscape ecological model of sustainable landscapes (Forman, 1990).

Variables underlying ecological integrity	Soil Biological productivity Biological diversity Fresh water Oceans Atmosphere
Variables underlying human aspirations	Basic human needs: food, water, health, housing Fuel Cultural cohesion and diversity

'Compartmentalization': our current planning and conservation model

Ecologist Eugene Odum (1969) examined the structure and function of human ecosystems and found that they mimic early successional ecosystems in their quality, growth, and production characteristics and that they lack the stability, protection, and quality of mature ecosystems (*see* Appendix, note 1). Odum (1969) proposed that all land be classified into the following four categories to safeguard the ecological characteristics of mature ecosystems and to maximize ecological function: 1) productive areas where succession is continually retarded by human controls to maintain high levels of productivity; 2) more natural protective or conservation areas where succession is allowed or encouraged to proceed to the mature and more stable, if not highly productive, stages; 3) compromise areas where some combination of the first two stages exists; and 4) urban-industrial or biologically nonvital areas.

The rationale behind Odum's (1969) 'compartmentalization' model is broadly accepted in today's world. It is often assumed that we can either develop a piece of land or we can conserve it. When development occurs, the maintenance or restoration of ecological function is generally not part of the development process.

The landscape ecological model suggests that we can no longer afford the luxury of biologically nonvital areas and that our productive forest and farming landscapes must not sacrifice broad measures of function for food and fibre production. While we will continue to have conservation areas, we must adopt the principle that all other sites should combine aspects of the urban-industrial, compromise and/or productive landscapes. This new category of landscape is termed 'diversity landscapes'. These landscapes are diverse in their structure and function and simultaneously incorporate the characteristics of Odum's productive, compromise, and urban-industrial landscapes. Thus defined, 'diversity landscapes' respond to both human aspirations and the maintenance or restoration of ecological function.

Achieving consensus on sustainability

In order to have effective environmental management at the global or local level, we must have accepted goals of sustainability within the population and in the professional and governmental community. Adoption of the landscape ecological model by planners, designers, and governments as a basis for achieving sustainable land use through the application of the 'diversity landscape' concept is a viable alternative to our current compartmentalization paradigm in planning and development. The demonstration project is one way of finding an acceptable form of sustainability, incrementally changing our presently unsustainable mode of inhabiting, and educating all sectors of society to a realistically alternative vision (M. Quayle and S. Reed, unpub. conference presentation, Council of Educators in Landscape Architecture Annual Conference, Spokane, Washington, 1996).

CASE STUDIES

Throughout the region, there are developments and activities that represent more sustainable development. While imperfect, these case studies illustrate trends and actions that need to be continued as the region develops. While some of the case studies are specific to the Fraser River estuary, others have been chosen from elsewhere in the region because they hold important lessons for urban development of the estuary (Fig. 1). The case studies presented here are by no means representative of the full range of action that is available in attempting to live more sustainably. Nevertheless, examination of the case studies reveals a number of principles that should guide urban development in any region.

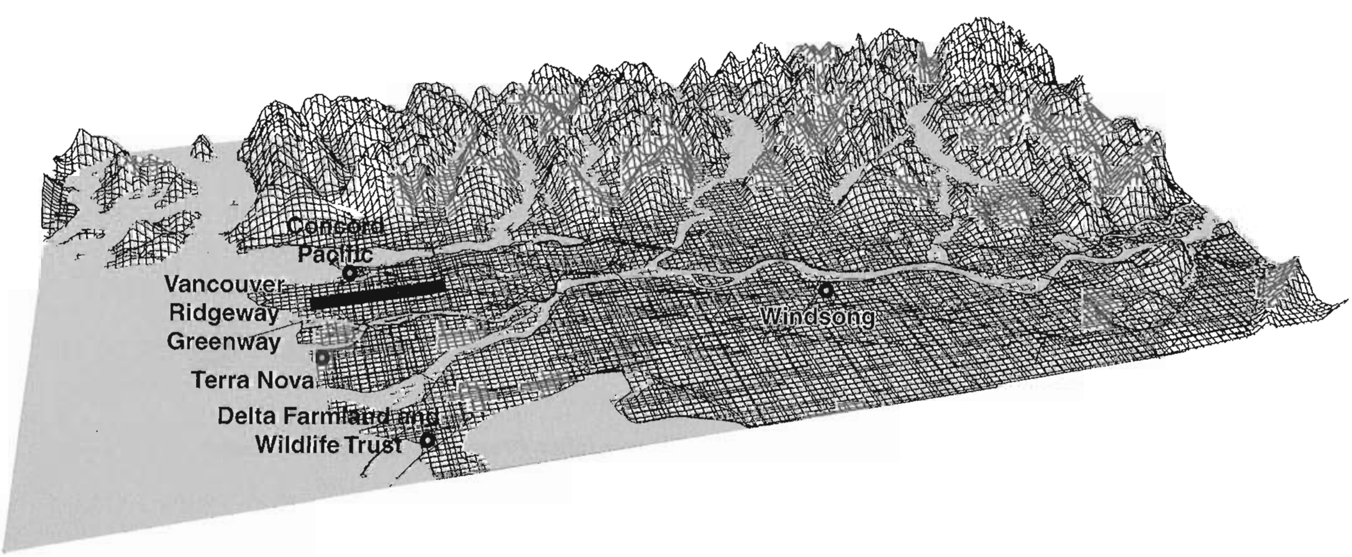

Figure 1. *Case study locations in the lower Fraser River basin and the Fraser River estuary.*

The ability to implement all of these directives will be a function of the ecological context, i.e. the extent of environmental impact, the availability of relevant biophysical data, and the societal and legislative support within the region as well as the support of the general populace. Impediments to implementation are 1) a culture of conformity and compliance; 2) fear of change and the unknown; 3) visual, social, and ecological illiteracy; and 4) the lack of a collective vision of sustainability (Quayle, 1995).

Urban-agricultural interface

The Vancouver urban-centred region is fortunate to be surrounded by high-quality agricultural land. While only 1% of the land in British Columbia is prime agricultural land, 14% of the land in the Vancouver urban-centred region has a high agricultural capability (Lands Directorate, 1985). Like most urban centres in Canada, the urban region has been developed on prime agricultural land. Across Canada, 55% of our prime

Table 2. Area included in and excluded from Agricultural Land Reserve by region, 1974–1993 (all figures are cumulative and in hectares) (*after* Provincial Agricultural Land Commission, January 1, 1994 Statistics, unpub. report, 1994).

Region	Area at designation	Inclusions	Exclusions	Area as of January 1, 1994
Lower Mainland	154 696.30	551.1	12 083.60	143 163.80
Vancouver Island	130 161.90	7899.80	24 126.30	113 935.40
Kootenay	399 109.30	832.6	11 547.50	388 394.40
Okanagan	189 838.00	1255.70	6679.90	183 581.20
Central Interior	1 525 789.50	15 207.00	40 064.20	1 568 341.00
Northern	1 904 655.80	75 489.50	4624.70	1 948 250.50
	4 721 295.30	**100 403.10**	**108 906.00**	**4 712 792.40**

Figure 2. *Area of the Agricultural Land Reserve* (after *Provincial Agricultural Land Commission, January 1, 1994 Statistics, unpub. Report, 1994).*

agricultural land is within an 80 km radius of an urban centre (Heald, 1982). With the tremendous increase in population in the region, there will be concomitant pressure to convert agricultural lands to urban use.

In British Columbia, agricultural land was protected from development in 1973 by the passing of the *Land Commission Act*, which established a province-wide Agricultural Land Reserve. Prior to that time, about 6000 ha/a were being lost to urbanization (Furuseth, 1981). Establishing the *Land Commission Act* has not protected all agricultural lands, however. Large amounts of agricultural land adjacent to the southern, urban growth areas of the Okanagan region, Vancouver Island, and Vancouver have been excluded from the Agricultural Land Reserve. These losses have been offset through subsidized forest clearing in the northern Peace River area of the province. While the amount of agricultural land in the province is close to what it was in 1979, the acreage of prime lands near our southern cities has diminished (Fig. 2, Table 2).

These lands produce a number of benefits. Within the Greater Vancouver Regional District, 80 different commodities are produced. Specializations include berries, mushrooms, dairy, poultry, flowers, greenhouse vegetables, and nursery stock. Farm receipts of $300 000 — one quarter of the province's total farm income — are produced on only 1.4% of the provincial land base (Greater Vancouver Regional District, two unpub. reports, 1993). Maintenance of agriculture on these lands results in the production of food near the urban centre, regional food security, maintenance of the rural family and community, preservation of the cultural landscape for aesthetic qualities, tourism, and recreation, and the support all of the foundation variables which underlie ecological integrity, i.e. biodiversity, bioproductivity, soils, fresh water, and oceans. Protection of these lands will become even more vital as the region develops to accommodate three million people and more.

Figure 3. *Overview of Terra Nova Public Nature Reserve site from the Richmond dyke, with Terra Nova subdivision in background.*

Agricultural lands case studies

Terra Nova and the Delta Farmland and Wildlife Trust

Terra Nova residential subdivision

Terra Nova is a 181 ha subdivision at the mouth of the Fraser River in Richmond, British Columbia. In 1988, despite strong public opposition, these prime agricultural lands were released from the Agricultural Land Reserve by the Provincial Cabinet, at the request of Richmond Municipal Council (Mooney, 1990). This exclusion is representative of how agricultural land in the Agricultural Land Reserve has been removed over the years since the act was first passed.

Subsequently, a pro-preservation council was elected in Richmond and a portion of the land was set aside for open space (Fig. 3). Now, after nearly ten years, the municipality is in the process of developing a public nature reserve on 14 ha of Crown- and municipally owned lands in Terra Nova. Public access will be restricted to a perimeter trail by a linear wetland, whereas the interior of the site will be maintained in old-field–grassland habitat with a newly created wetland. Habitat improvements will benefit raptors, herons, passerines, shorebirds and waterfowl, and terrestrial wildlife. Due to conservation and ecological restoration, this former piece of farmland, once lost to development, will provide needed habitat and recreation within the context of a typical suburban subdivision.

Delta Farmland and Wildlife Trust

A second example of sustainability in action at the rural/urban fringe is the Delta Farmland and Wildlife Trust. The Fraser River delta contains the city of Richmond, the Corporation of Delta, and the village of Ladner. In addition to having the agricultural values mentioned above, the delta supports half a million birds, and up to 1.4 million birds pass through on migration. No other site in Canada supports this number and diversity of birds. It is estimated that if the habitat values within the delta were lost, it would affect birds from 20 countries and 3 continents (Butler and Campbell, 1987).

Despite the loss of approximately 80% of the freshwater or brackish marshes and 95% of the saltwater marshes in the area since European settlement, the delta plays a role of global significance in providing habitat for birds (Butler and Campbell, 1987). These exceptional wildlife values exist within the agricultural areas of the delta. If the agricultural lands are lost to urbanization or lose their habitats, then the wildlife will be lost as well.

The Delta Farmland and Wildlife Trust (DFWT) was formed in 1993 to preserve farmland and to conserve wildlife habitat. It is now a recognized nonprofit organization. The trust has received funding from the federal Green Plan for Agriculture and from the Delta Agricultural Society. In March 1995, the Delta Farmland and Wildlife Trust was awarded $2.25 million from the fund which had been created by Transport Canada to compensate for habitat destruction resulting from the third runway expansion at Vancouver International Airport. The money is held in trust to provide farm stewardship and wildlife habitat. Projects initiated by the trust include set-asides and cover crops to improve soil structure; integrated pest management to reduce pesticide use; ditches, hedgerows, and grass margins for wildlife; and a proposed demonstration farm (Taitt, 1995).

What qualities are sustainable?

Terra Nova and the Delta Farmland and Wildlife Trust are examples of 'diversity landscapes' at different scales. The Terra Nova nature reserve will enhance public recreation and other open-space values. The Delta Farmland and Wildlife Trust will support the human benefits of economically sustainable farming, maintaining the farming community, and preserving the countryside. Both the Terra Nova wildlife area and the Delta Farmland and Wildlife Trust will increase biodiversity, increase bioproductivity, and allow soils to cleanse and recharge fresh water. In addition, the Delta Farmland and Wildlife Trust will restore health to damaged soils, maintain farming, and enhance wildlife values. These projects illustrate that wildlife values are compatible with farming, recreation, and even residential living. Both are examples of the search for the physical configuration of landscape that will yield a more sustainable human and ecological function.

Case study: Windsong cohousing community

Description

The Windsong is a 34 home cohousing community in Langley, British Columbia. Cohousing is a form of living which began in Denmark some thirty years ago. A cohousing neighbourhood design is pedestrian-oriented, with individually owned houses clustered around a common facility. Its purpose is to create, build, and sustain a supportive, multigenerational community whose members participate in a process of consensus decision-making.

Windsong is the second cohousing development in Canada, following Cardiff Place in Victoria, British Columbia, which opened in 1994. Its members envisioned a community-based sustainable development. They wanted a site with open-space potential for gardens and playfields where ecologically sensitive products and approaches could be integrated into daily living. The chosen site initially appeared ideal. It was well serviced by public transportation, schools, and recreation facilities, with 2.4 ha of sloping rural meadow and mixed forest that included a section of Yorkson Creek and its lowlands.

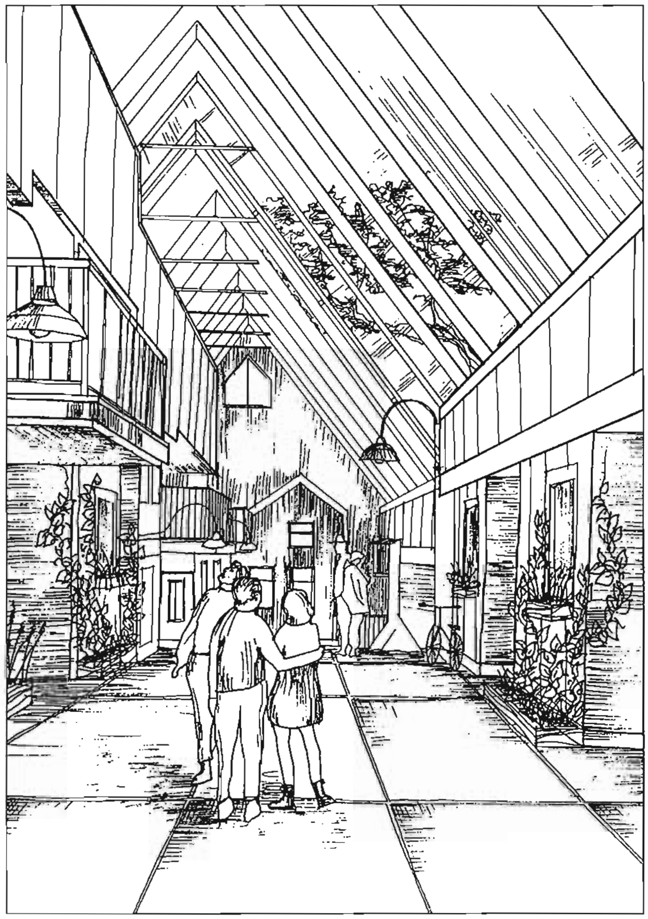

Figure 4. *Windsong Cohousing Community interior pedestrian street and atrium, looking toward common house.*

Owing to the presence of salmon in Yorkson Creek, the Ministry of Environment specified that all development was to be kept 15 m back from the creek's high-water mark. The Department of Fisheries and Oceans defined that mark to be 0.5 m back from the top of the slopes, approximately 5 m to 10 m above the level of the creek. This setback created a situation in which only 0.8 (or 1/3) of the parcel's 2.4 ha could be developed.

The resultant design provides a common house flanked by two wings of townhouse-styled units connected by a 6 m (20 foot) wide glass-covered pedestrian mall (Fig. 4) with 64 underground parking stalls. The remainder of the buildable area is to be a community landscape of garden plots and play areas. Plantings will be predominately native species such as salal, kinnikinnick, vine maple, and shore pine, chosen to minimize irrigation needs and provide for some avian habitat through plant layering. The development leaves the

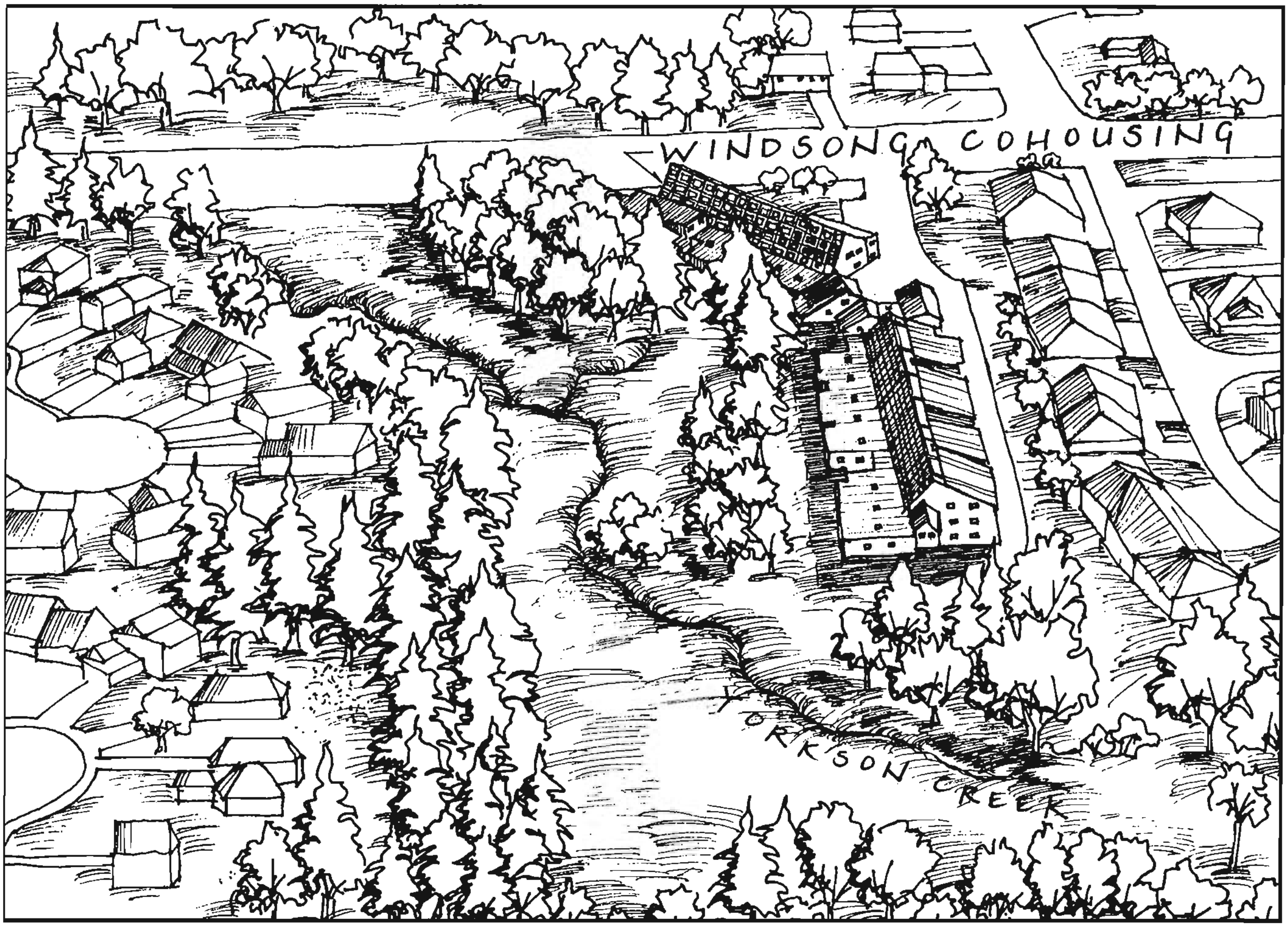

Figure 5. Overview of Windsong Cohousing Community showing clustering of building and preservation of Yorkson Creek stream corridor.

stream corridor in its predevelopment condition (Fig. 5). The project was enthusiastically received and officially opened on August 27, 1996 (D. Wright, pers. comm., 1996).

What qualities are sustainable?

Although the site design and development resulted from restricted access to Yorkson Creek, the small building footprint and the preservation of the open green space and of the fish habitat are three notable aspects of sustainability in the development. Bioproductivity, biological diversity, fresh water, and oceans are more supported by this type of development than by conventional development. The use of naturalized and native plants and the absence of an irrigation system reduce water consumption and the use of chemicals. By employing ecologically sensitive building materials, the community provides a prototype that may increase the demand for such products. The compact townhouse layout, glassed malls, and shared tools and vehicles reduce energy consumption and leave two-thirds of the site in green space.

The floor plans, especially the enclosed pedestrian street and atrium, create an inherent community integration and defensible space so that real and psychological security exists in place of elaborate gates and alarms. The common house is designed to accommodate community dining, supervised children's play, offices, and guests. All of this means that like any cohousing community the people exist in a close-knit 'village' of shared responsibilities that allows privacy and individuality, yet functions almost as an extended family. The project includes a wide range of family units, from single- and two-parent families with children of all ages to singles and seniors. This type of housing supports the acceptance of human diversity.

Case study: Concord Pacific Group Inc. Pacific Place

Description

Pacific Place is an 82.5 ha mixed residential, retail, commercial, and park development situated on the north shore of False Creek. Once the centre of Vancouver's industrial lands,

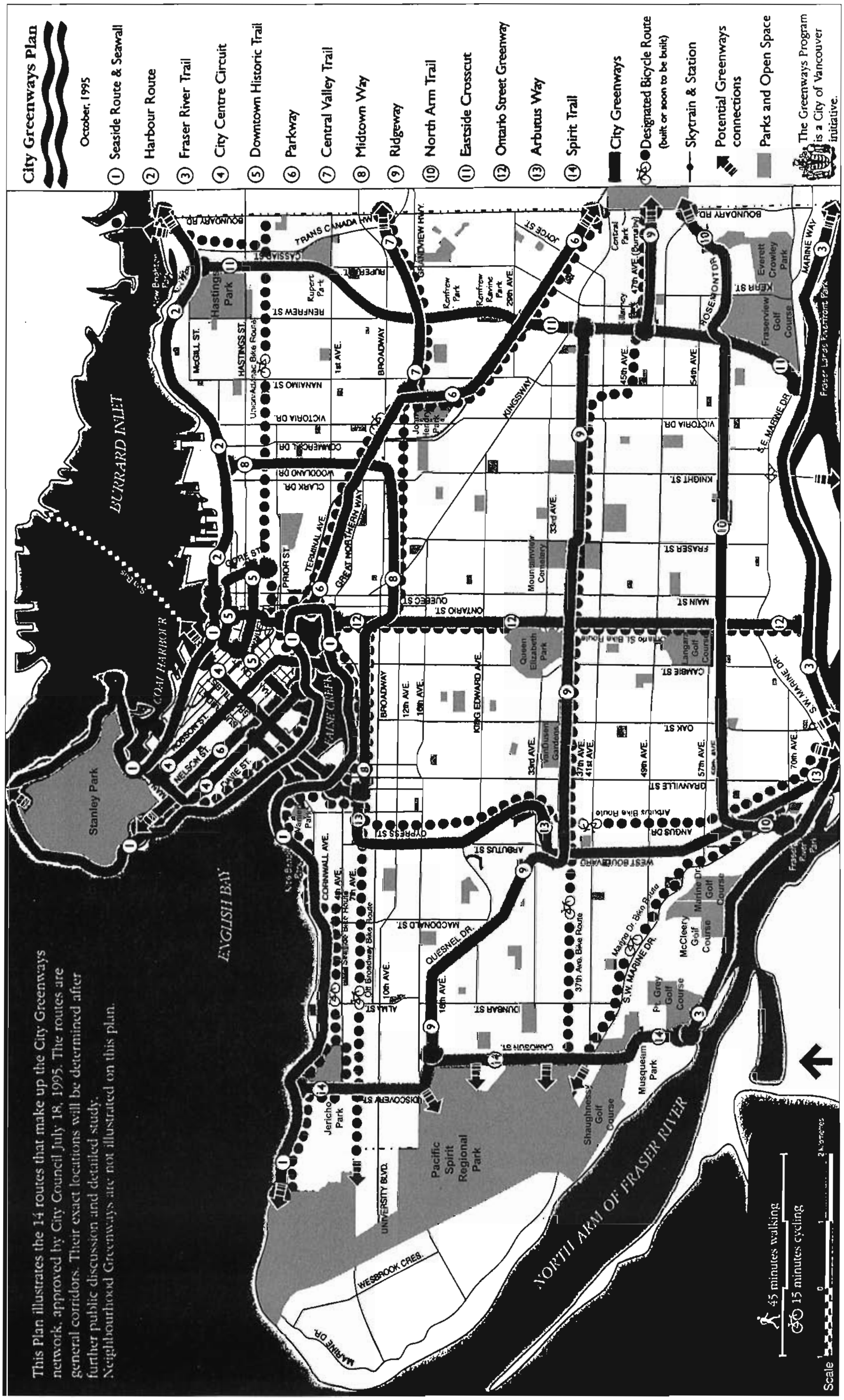

Figure 6. *City of Vancouver Greenways Plan showing waterfront access from Coal Harbour to Kitsilano Beach and the Ridgeway Greenway* (after City of Vancouver 1995 Greenways Plan).

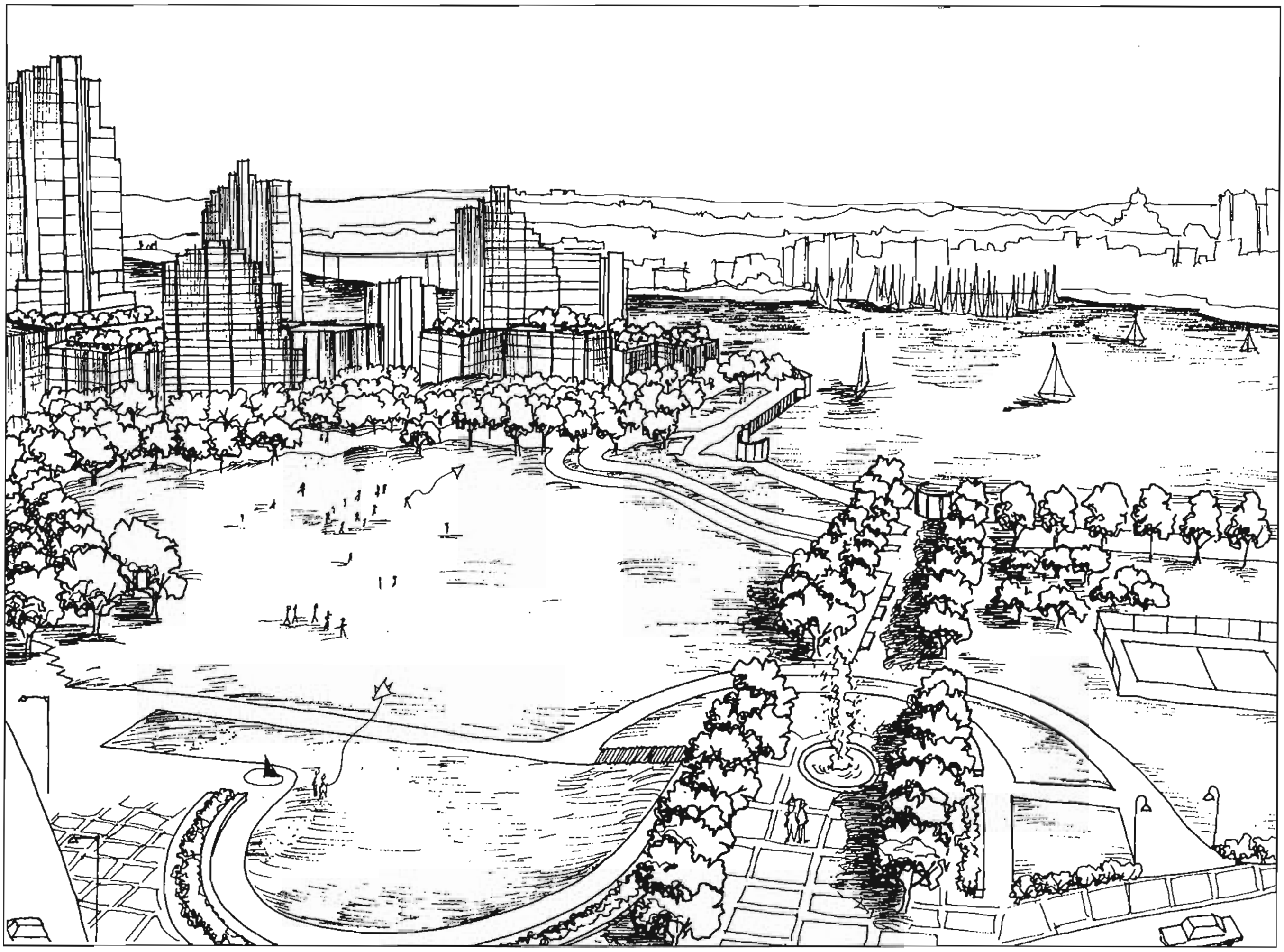

Figure 7. George Wainborn Park (with circular fountain) at the end of Richards Street. Note the extension of paving and tree avenue from outside the site, and connection to waterfront walkway.

the site was first owned by Marathon Realty and then by the British Columbia provincial government. The property was the site of the World Exposition 'Expo '86' and was subsequently sold to the Concord Pacific Group. The initial site plan focused on the urban waterfront qualities of the property itself. In what was termed the 'lagoon' scheme, a series of artificial islands were set offshore and connected by a series of bridges. The islands were to house massive condominium towers, establishing the sense of a waterfront resort on the edge of the city core. The lagoon scheme was interpreted by the city as privatizing the waterfront, while the architects realized that the structures themselves were unworkable (D. Vaughan, pers. comm., 1996).

After the rejection of the lagoon scheme, a new design objective was articulated with the goal of having Vancouver benefit from the Pacific Place development. The new plan would have to maintain the existing shoreline, allow continuous public access to the waterfront, and protect the views to the mountains from the southern uptown area.

By projecting the grid of the city streets into the plan, both view corridors and pedestrian linkages to the site would be reinforced. The site became a centre of activity for the city instead of an enclave for the residents. The resulting 'bay concept' exceeded the Parks Board requirement of 1.11 ha of parkland per 1000 people, so that total open space now accounts for 50% of the site area. The plan used the density of Vancouver's West End as a precedent that influenced how buildings were arranged on the site, and convinced the council to widen the shoreline walkway from 3 m to 9 m.

Don Vaughan, the landscape architect who developed the Pacific Place site plan, describes the development as "a great experiment" in creating human habitat. A number of simple ideas directed this concept. Firstly, the site's open space does not belong to the residents of the Pacific Place development. Rather, the southern edge of the site is a continuous public walkway and park system. This is part of Vancouver's emerald necklace, which will soon stretch from Coal Harbour to Kitsilano Beach (Fig. 6). The grid of the city streets is extended by paving material and tree avenues through the site and to the ocean-front walkway. This pattern of circulation makes it virtually impossible to get lost on the site and allows

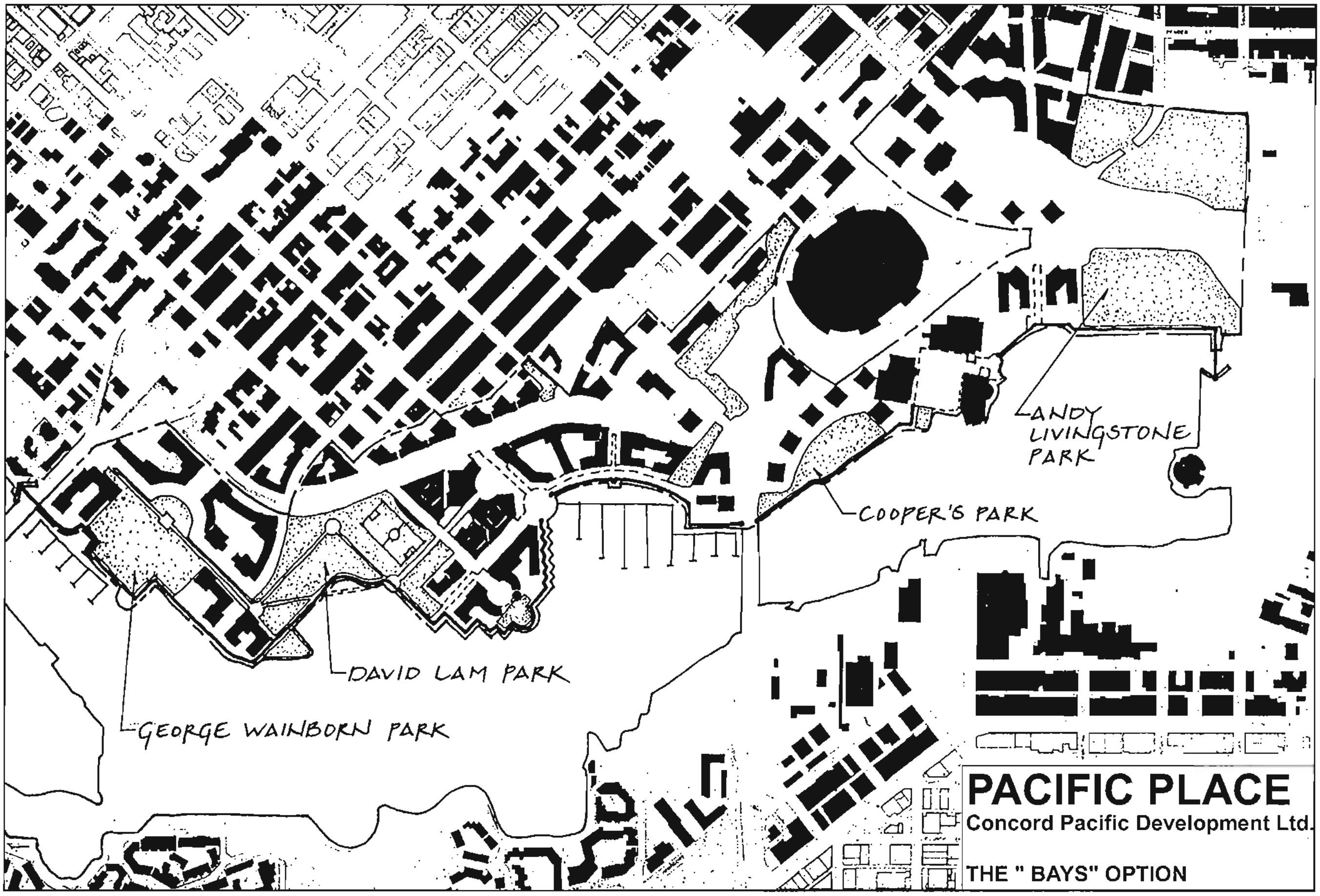

Figure 8. *Concord Pacific Developments parks and open space system.*

the user to easily form a mental picture of the site. This contributes positively to the overall recognition of the site and its sense of order without restriction of movement (Fig. 7).

There are four parks in the site (Fig. 8). At the foot of Richards Street is George Wainborn Park, a park-cum-urban plaza with a semicircular overlook to False Creek. This very urban and formal park extends the planting and paving of Pacific Boulevard into the site. In David Lam Park, the designer attempted to merge the strong image and centrality of the village green with a realization of the essence of the place, by marking the diurnal rhythms of the tides and allowing access to the water. Cooper's Park, which is located at Cambie Street bridge, was envisioned as a naturalized orchard and meadow, which contrasted its rough agrarian image with the crisp urbanity of the rest of the site. This concept was later rejected by the Vancouver Parks Board. At the eastern edge of the site, Andy Livingstone Park provides further diversity in an extensive, active sports park.

The ideas of order and diversity directed the design forms. A hierarchy of order was established through the extension of the city grid of streets through the development to the shore of False Creek via plazas and pedestrian malls and the connection of the pedestrian network to the street grid, reinforced through paving, lighting, and street trees. This was further reinforced by the continuous ribbon of the seawall for public shoreline access and movement, which employs the parks as orientation nodes and visual relief from the built-up environment. The different concepts for the four parks provide diversity of visual experience and activity. The diversity of types of movement and routes offered to users of the seawall, roads, bike lanes, plazas, and courtyards provides choice in how people move through the site and creates a diversity of experience of place. From a design perspective, this diversity is given formal expression in the intricacy of the shoreline bays and promontories and through architectural forms and materials.

What qualities are sustainable?

The site plan was derived from the open-space configuration and its underlying intention, i.e. to create a well ordered yet diverse human habitat. The large percentage of urban open space and its function as regional park provide an example of how such projects can improve human psychological aspects by providing relief from density and access to urban nature.

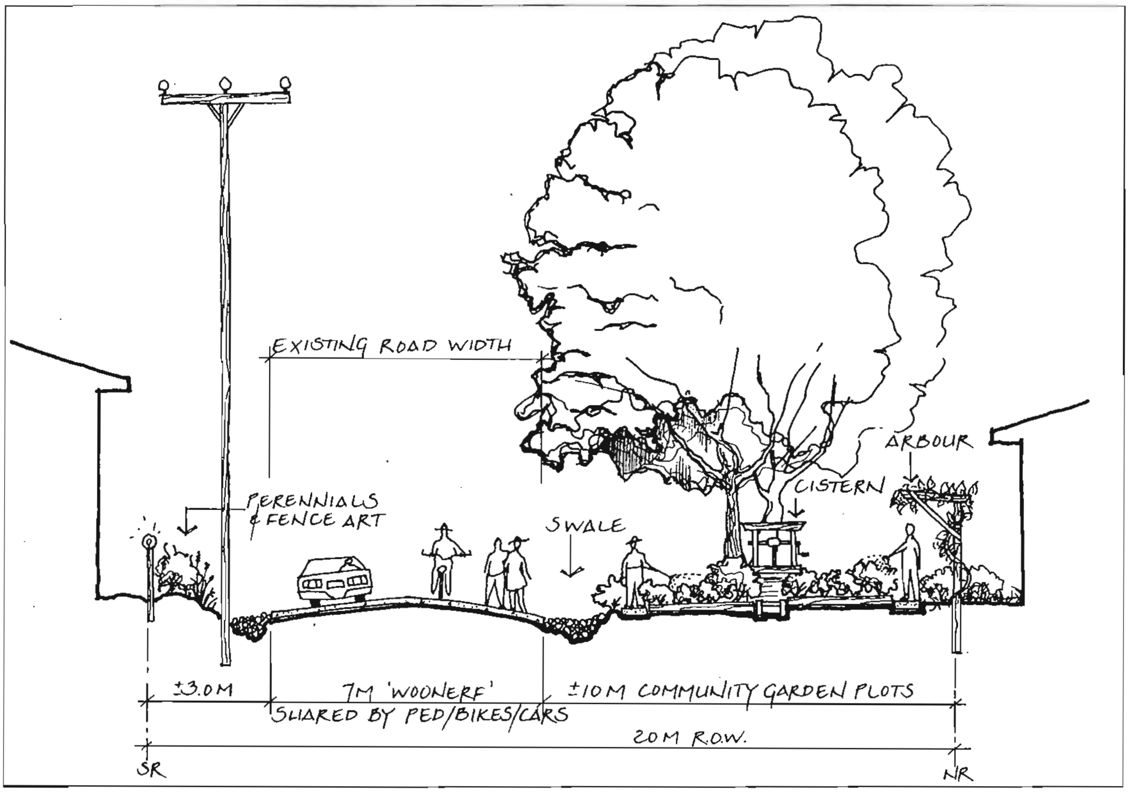

Figure 9. One of many different design sections for the Ridgeway Greenway, showing gardening to the street edge, a community garden, and a swale for storm-water cleansing. Car, bike, and pedestrians share the street, similarly to the Dutch 'Woonerf' concept.

Mental restoration and urban nature

Both scientific research and anecdotal reports strongly support the view that people of all ages and conditions benefit from contact with 'natural' environments. Researchers hypothesize that we are genetically programmed to focus on nature and that our easy and automatic cognitive processing of nature lies at the root of the restorative properties of contact with 'natural' environments (S. Kaplan, 1993; C.A. Lewis, 1996) (*see* Appendix, note 2).

In *The Experience of Nature*, published in 1989, Stephen and Rachel Kaplan examined the restorative response that results from the fascination that humans have with natural environments, and postulated their framework concept of the restorative landscape. They showed that simple observation was an important aspect of a person's involvement in nature and concluded that "The results of the various studies provide strong support that nearby nature affords a wide range of psychological and physical benefits" (Kaplan and Kaplan, 1989, p. 162).

At the present time, a wide range of benefits related to 'nearby nature' have been reported for various segments of society (Kaplan and Talbot, 1983; Ulrich, 1984; Craig, 1994; Smith and Aldous, 1994; C.A. Lewis, 1996). These benefits include life, job, and neighbourhood satisfaction. Studies have shown that people's preference for landscape increases as the amount of trees or natural elements increases (R. Kaplan, 1993), and that presence of vegetation correlates strongly with stress reduction (Cooper-Marcus and Barnes, 1995). Given that these benefits accrue most strongly from frequent contact with green environments, the value of ready access to urban nature, which is provided by projects like Concord Pacific Development, cannot be overstated.

Ecological restoration on Concord Pacific Development

Such was the state of disturbance of the site prior to Expo '86 that the project exemplifies the use of development as a means to improve ecological function. Andy Livingstone Park is built over toxic soils which have been neutralized by capping; the amount of vegetation — and, hence, biological productivity and biological diversity — is greater than before development. At the same time, had the landscape ecological model and the 'diversity landscape' been used as a basis for planning, the design of the open space might have greatly enhanced the ecological function of the site. For example, at the request of the federal Department of Fisheries and Oceans, a report was produced that showed how the shore of False Creek could be enhanced for fish habitat (P.F. Mooney and M. Healey, unpub. report, 1993). This study is now being implemented in the design of Cooper's Park (J. Philips, pers. comm., 1996). In contrast, the open space of the site was not treated similarly and was not intentionally designed to contribute to avian diversity. Thus, an important injection of function into the regional landscape mosaic was not fully realized.

Case studies: City of Vancouver greenways project

The Ridgeway Greenway city pilot project

The Ridgeway Greenway is planned on an east-west route along a ridge which forms some of the city's highest elevations. Starting at Pacific Spirit Park, the route will mostly run along 37th Avenue to Central Park in Burnaby (Fig. 6). The pilot-project portion was initiated in the fall of 1996 between Granville and Knight streets. The project will be constructed on city-owned lands and the existing public-right-of-way through a range of residential neighbourhoods and a number of major green spaces: Van Dusen Botanical Garden, Queen Elizabeth Park, Mountainview Cemetery, and a number of other smaller city parks and city-owned properties. As it will be the first city-wide greenway, the larger population requested a commuter and recreational cycling route that links major open spaces along a strong east-west connection (City of Vancouver, unpub. report, 1995). Comprehensive public-consultation and design processes have taken place. While supported by the majority of residents, the projects are also subject to public opposition and mistrust (A. Duncan, planner, City of Vancouver, pers. comm., 1996; M. Quayle and S. Reed, unpub. conference presentation, Council of Educators in Landscape Architecture Annual Conference, Spokane, Washington, 1996).

Some of the goals of the Ridgeway Greenway design are to reduce the impact of the automobile, to make the greenway greener through new and innovative plantings, and to implement environmental initiatives through drought-tolerant plantings and natural drainage. Design of the Ridgeway Greenway varies in each neighbourhood to respond to resident priorities and site conditions (Fig. 9). Ultimately, the greenway provides a safe pedestrian and bike route as an alternative to automobile transportation.

Total funds to be spent on this project are some $2.3 million. While not large in relation to transportation infrastructure funding, this amount is considered significant (A. Duncan, planner, City of Vancouver, pers. comm., 1996). The success of the pilot project will no doubt be evaluated in many respects before new capital funding is allocated in the next budget.

Garden Drive residential street redesign: a neighbourhood greenway

In addition to this first large greenway linkage, the city is undertaking a number of smaller neighbourhood-scale street renovations which are a form of greenway. These involve intensive neighbourhood consultation and incorporate both social and ecological concerns. Garden Drive Greenway in East Vancouver was undertaken as a pilot project when a group of property owners wanted to improve their street to combat drug use, prostitution, and outside traffic. As well as beautification of the area and a solution to these problems, it was a way for the residents to take back the street.

The design contains small-scale design interventions including variations in standard street treatment such as traffic-calming measures and street tree and understorey plantings. These are not as radical as the changes originally proposed by residents; this has been largely attributed to lack of local precedents and lack of confidence in City Hall implementation (M. Quayle and S. Reed, unpub. conference presentation, Council of Educators in Landscape Architecture Annual Conference, Spokane, Washington, 1996, p. 9). However, the project did result in significant changes within the city bureaucracy. A new collaboration between the engineering and planning departments was set up to facilitate the project. The community consultation process provided a medium for community building, which will be reinforced by the residents taking ownership of the project.

The performance criteria chosen by the community and developed in the project design demonstrate achievable small-scale increments toward a broad view of sustainability. These criteria include community building, contextual performance, ecological performance, economic performance, experiential performance, and functional performance. The ecological criteria, as well as corresponding responses to be built into the project, are listed in Table 3.

What qualities are sustainable?

These greenways demonstrate the need for change in attitudes both within and outside City Hall in order to facilitate change. Both projects are examples of retrofitting the city. Although at different scales, they represent creeping incremental change. It is imperative that this incremental change be part of a co-ordinated whole. The ultimate ecological function of these greenways will be realized when they are part of a larger connected network. Their human function (in terms of building community, reducing traffic and pollution, and giving mental respite) will occur immediately, but also will be increased as the network grows. The projects demonstrate the importance of pilot projects in testing practicality and acceptance of new urban forms. While requiring much planning and flexible public processes, pilot projects educate the involved public and city officials by demonstrating processes and designs.

Table 3. The ecological criteria, with corresponding responses to be built into the project (M. Quayle and S. Reed, unpub. conference presentation, Council of Educators in Landscape Architecture Annual Conference, Spokane, Washington, 1996).

Criteria	Response
Air quality	Eliminate some parking spaces
Water quality	Remove as much pavement as possible and plant areas
Wildlife habitat	Choose plants for bird and butterfly habitat
Water conservation	Plant drought-tolerant materials
Biodiversity	Encourage a potpourri of materials
Urban forest	If budget limitations develop, give priority to trees

Greenways are linear open spaces, sometimes called 'green links' (Schaefer and Schaefer, 1996). The scales of greenways range from national to neighbourhood. Their purpose is to connect human development and natural systems. Green networks assist the function of ecological processes by linking working landscapes such as forests and Agricultural Land reserves with public open spaces, or urban-built environments with ecologically sensitive lands. Stated goals can include habitat protection, erosion control, flood-hazard reduction, maintenance of water quality, historical preservation, education, nature interpretation (Searns, 1995, p. 72), and maintenance of biodiversity through the provision of connectivity for species colonization (Noss, 1983).

In the Vancouver region, the concept of greenways is not a new one. The Stanley Park Seawall and Seaside Route are greenways that were envisioned in the 1928 Bartholomew plan for Vancouver. The City of Vancouver made a commitment to greenways following the *Greenways-Public Ways* report (unpub.) in 1992. In 1995, the *Vancouver Greenways Plan* detailed a proposed plan for city and neighbourhood greenways on city-owned lands and streets (City of Vancouver, unpub. report, 1995). With continued public demand and support from the city council, a number of neighbourhood greenways have been implemented by a greenways team from the engineering and planning departments (Quayle, 1995, p. 470). Others, including the two projects reviewed here, are now being constructed.

IMPLEMENTING A SUSTAINABLE FUTURE FOR THE REGION

Having examined the physical and design context for sustainability in the case studies, conceptual approaches to more sustainable development in the region emerge.

Use development to meet human aspirations and enhance ecological function

Recognizing that most of the developable sites in the region have been impacted by previous human intervention, the design of a proposed development should enhance ecological function. This will be done by understanding landscape processes rather than designing for human use only and then mitigating the ensuing environmental damage. As a process, the generation of a sustainable design would require developing a program that includes the achievement of human benefits and a broader set of goals related to the ecosphere or ecological function. While concerned with preserving and restoring the integrity, stability, and beauty of the biotic community, the designs also must sustain cultural, social, and economic aspects of the human community.

Use landscape assessment to reduce impacts and enhance ecological function before development

As urban development occurs, buildings, roads, and paving increase the amount of pollution and surface runoff. Vegetated areas are reduced, thereby reducing bioproductivity and biological diversity. A process which considers these impacts of development and reduces impacts prior to their creation would require having a quantifiable measure of these foundation variables before we begin. Through an iterative process of calculations for the designed site, the designer can often adjust the site plan, grading, and vegetation types until the net runoff, biodiversity, and biological productivity are the same or better than before we began (P.F. Mooney, unpub. conference presentation, Council of Educators in Landscape Architecture Annual Conference, Spokane, Washington, 1996). If we can achieve this, we will have met human aspirations for development while providing a landscape structure that functions more like a 'natural' ecosystem.

For every act of development, start with the broadest range of goals

All the case studies presented fall short of the full range of sustainability options that could have been implemented. Projects seem to have either a primarily human perspective or an ecological perspective. Lacking the broad perspective of the landscape ecological model, the fullest range of goals for the project often was not considered. It must become standard practice to serve the needs of the biosphere as well as the site. This may be as simple as including goals that serve species other than ourselves.

Action by local people is necessary

As in the Garden Drive Greenways example, there will usually be resistance to change in the status quo. People are generally reluctant to accept sweeping changes to their living environments but will accept incremental change when informed and consulted. Demonstration projects provide opportunity for public involvement and are concrete examples of the reality of change brought about by implementing new urban-design policies and practices. The public consultation process used in the greenways did demonstrate the proposed changes prior to development. Unless the people directly affected by the changes are consulted, are allowed to direct the process, and are given clear representations of the reality of the proposed changes, there will be an even greater resistance to change.

The two Vancouver greenways (Ridgeway and Garden Drive), Windsong, Delta Farmland and Wildlife Trust, and Terra Nova all resulted from an interest expressed from within the local community. Even the final site plan for Pacific Place development was partially a response to negative public reaction to the original scheme. Most often this community involvement begins with a single advocate. Delta Farmland and Wildlife Trust developed, in part, from a research project of University of British Columbia professor Art Bomke. The greenways, particularly Garden Drive, happened because of the advocacy and skill of another University of British Columbia professor, Moura Quayle, Director of the Landscape Architecture Program.

Governments should facilitate, co-ordinate, and protect

It is a mistake to think that government can or should manage our environment for us. As budgets shrink and problems multiply, government will increasingly become a partner in local initiatives. The Delta Farmland and Wildlife Trust and other similar trusts are examples of this growing trend. The Delta Farmland and Wildlife Trust would not exist without government funds allocated for the type of initiatives promoted by the trust.

Pacific Place and the two Vancouver greenways (Ridgeway and Garden Drive) are directed and controlled by city government. The selection of the proposed routes, consultation with the public, and management of the design and building of the Vancouver Greenway constitute an appropriate role for government. Each neighbourhood greenway contributes to the city plan, which is part of a larger regional green zone strategy co-ordinated by the Greater Vancouver Regional District.

Government also must maintain the role of restricting unsustainable uses to protect the greater public benefit. Site restrictions placed on Windsong and Pacific Place developments did not diminish the human objectives of the developments, yet protected the larger public benefits of the open-space and fisheries values.

Look for synergy rather than conflict in your goals

Part of our 'compartmentalization' mentality tells us that ecological function is a trade-off with meeting human needs. As we have seen in several of the case studies, there often exists a synergy or mutual support for separate goals in a single action. The farming-preservation activities of the Delta Farmland and Wildlife Trust support economically and ecologically sustainable farming, sustain the farming family and the farm community, and contribute to global biodiversity.

Achieve your goals through economy of means

With limited resources and a bewildering array of potential actions, selecting the appropriate action for a site can be difficult and confusing. The best actions are those which cost the least and produce the most. Look for single actions which support both human aspirations and ecological integrity. The open space of Pacific Place, which was designed to delight and to give relief from density, also provides circulation, mental restoration, biological productivity, and improved air quality. Generally, green space allocation or development can yield the broadest range of benefits. On the human side of the model we have respite and recreation, socialization, exercise, microclimatic amelioration, food production, neighbourhood identity, and community building. On the ecological integrity side we have bioproductivity, pollution and microclimate amelioration, production of oxygen, soil stabilization, groundwater purification and recharge, and maintenance of biodiversity through wildlife habitat.

Design and build for both human and ecological diversity

Every development site should be a diversity site. There is a wide range of responses to the question 'How do we develop the region to be more sustainable?'. People and sites are diverse. From a human perspective we need to recognize the diversity of people due to culture, gender, age, lifestyle, and individual preference.

Projects like Windsong respond to the human diversity within a single site. At the same time, the project really only responds to the person or family who wants integrated community living. Projects like Concord Pacific Development respond to individuals who have a different vision of how and where they want to live. This type of project is also part of a regional sustainability solution. The project responds to human diversity by designing visual diversity into the urban fabric and by accommodating both residents and visitors from throughout the region and beyond. By maintaining a dense population in the downtown core, we will keep the area vital; allow people to work and live in an exciting city without incurring high costs in energy, traffic, and pollution; and enhance personal well-being. A more sustainable region will be extremely interesting visually because it will introduce a diverse range of open space and built form (buildings, site infrastructure, street furniture, lighting, and signs).

Determine where not to build

Landscape architect Phil Lewis has long been an advocate of the 'ecological corridor' concept, in which the setting aside of ecologically sensitive lands provides the envelope for regional or national development (P.A. Lewis, 1996). This concept is beginning to be accepted in the Vancouver region. Most municipalities now have an inventory of ecologically sensitive lands; however, the relative protection of these lands varies significantly by municipality. The Greater Vancouver Regional District board has adopted a green-zone strategy for the purposes of containing urban growth and identifying those lands which are most important to protect. These include watersheds, major parks, farmlands, wildlife habitat, and wetlands. In the development of a new regional strategic plan, these areas will be protected in perpetuity (Greater Vancouver Regional District, unpub. report, 1993). As we saw in the Terra Nova example, in order to truly protect agricultural lands near our cities, the Agricultural Land Reserve must be combined with municipal support.

The principle of deciding where not to build on the basis of ecological corridors is one that should become the norm rather than an exception. This is an example of finding a physical arrangement of ecosystems and land uses at the regional scale that maximizes ecological integrity and human aspiration.

As we move down in scale through region, city, district, neighbourhood, and the backyard, the same principle should determine where and how development occurs. The result would be a region that has vital and compact community cores set within a matrix of regional open space that retains a high level of ecological function. Within the built-up areas, the 'mosaic' of the landscape would be dappled with the green of parks, farmlands, community open space, and treed streets and yards.

While the Fraser Basin Management Program recently gave the region a rather mediocre report card on its progress toward a more sustainable future (Fraser Basin Management Program, unpub. report, 1996), the trends seen in the case studies are encouraging. There are a great number of actions taking place at all scales in the region that need to be recognized as prototypes. If done to a much greater degree and in a co-ordinated fashion, these would contribute significantly to a sustainably liveable region.

ACKNOWLEDGMENTS

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REFERENCES

Beatley, T. and Brower, D.
1993: Sustainability comes to mainstreet; Planning, v. 59, p. 16–19.

Butler, R.W. and Campbell, R.W.
1987: The birds of the Fraser River delta: populations, ecology and international significance; Canada Wildlife Service, Occasional Paper 65, 73 p.

Cooper-Marcus, C. and Barnes, M.
1995: Gardens in Healthcare Facilities: Uses, Therapeutic Benefits, and Design Recommendations; The Center for Health Design, Berkeley, California, 70 p.

Craig, K.
1994: Teaching gardening to the blind as therapy; *in* The Healing Dimensions of People-Plant Relations: Proceedings of a Research Symposium, (ed.) M. Francis, P. Lindsey and J. Stone Rice; Center for Design Research, University of California-Davis, Davis, California, p. 197–215.

Forman, R.T.T.
1990: Ecologically sustainable landscapes: The role of spatial configuration; *in* Changing Landscapes: An Ecological Perspective, (ed.) I.S. Zonneveld and R.T.T. Forman; Springer-Verlag, New York, New York, p. 261–278.

Furuseth, O.J.
1981: Planning for Agricultural Lands in British Columbia; The Environmentalist, v. 1, p. 299–309.

Heald, H.F.
1982: Canada and the world in the year 2000; Canadian Geographic, v. 102, p. 6–9.

Kaplan, R.
1993: Urban forestry and the workplace; *in* Managing Urban High-Use Recreation Settings, (ed.) P.H. Gobster; USDA General Technical Report NC-163, U.S. Forest Service, St. Paul, Minnesota, p. 41–45.

Kaplan, R. and Talbot, J.F.
1983: Psychological benefits of a wilderness experience; *in* Behavior and the Natural Environment, (ed.) I. Altman and J.E. Wohlwill; Human Behavior and the Environment, Plenum Press, New York, New York, v. 6, p. 163–203.

Kaplan, R. and Kaplan, S.
1989: The Experience of Nature: A Psychological Perspective; Cambridge University Press, Cambridge, United Kingdom, 340 p.

Kaplan, S.
1993: The role of natural environmental aesthetics in the restorative experience; *in* Managing Urban and High-Use Recreation Settings; (ed.) P.H. Gobster; USDA General Technical Report NC-163; U.S. Forest Service, St. Paul, Minnesota, p. 46–49.

Lands Directorate
1985: Vancouver Urban Centred Region; Environment Canada Lands Directorate, Lands Directorate Fact Sheet 85-5, Ottawa, Ontario, 2 p.

Lewis, C.A.
1996: Green Nature/Human Nature: The Meaning of Plants in Our Lives; University of Illinois Press, Chicago, Illinois, 148 p.

Lewis, P.H.
1996: Tomorrow By Design: A Regional Design Process for Sustainability; John Wiley and Sons, New York, New York, 258 p.

Lyle, J.T.
1985: Design for Human Ecosystems: Landscape, Land Use and Natural Resources; Van Nostrand Reinhold, New York, New York, 279 p.

Mooney, P.F.
1990: Re-examining preservation of agricultural land in B.C.; *in* Protecting Our Common Future: Conflict Resolution within the Farming Community, (ed.) R. Corbett; Rural & Small Town Research and Studies Programme, Department of Geography, Mount Allison University, Sackville, New Brunswick, p. 1–34.
1993: Structure and connectivity as measures of sustainability in agroecosystems; *in* Sustainable Landscapes: Proceedings of the Third Symposium of the Canadian Society for Landscape Ecology and Management, (ed.) J.S. Marczyk and D.B. Johnson; Polyscience, Montréal, Quebec, p. 13–25.

Noss, R.F.
1983: A regional landscape approach to maintain species diversity; BioScience, v. 33, p. 700–706.

Odum, E.P.
1969: The strategy of ecosystem development; Science, v. 164, p. 262–270.

Quayle, M.Q.
1995: Urban greenways and public ways: realizing public ideas in a fragmented world; Landscape and Urban Planning, v. 33, p. 461–475.

Rees, W.
1995: Achieving sustainability: reform or transformation? Journal of Planning Literature, v. 9, p. 343–361.

Risser, P.G., Forman, R.T.T., and Karr, J.R.
1984: Landscape Ecology – Directions and Approaches; Illinois Natural History Survey, Special Publication Number 2, Champaign, Illinois, 16 p.

Schaefer, V. and Schaefer, A.C.
1996: The Green Links Program; Wildflower, Summer, p. 13–15.

Schmidheiny, S.
1992: Changing Course: A Global Business Perspective on Development and the Environment; MIT Press, Cambridge, Massachusetts, 374 p.

Searns, R.M.
1995: The evolution of greenways as an adaptive urban landscape form; Landscape and Urban Planning, v. 33, p. 65–80.

Smith, D.V. and Aldous, D.E.
1994: The effect of therapeutic horticulture on the self-concept of the mildly intellectually disabled student; *in* The Healing Dimensions of People-Plant Relations: Proceedings of a Research Symposium, (ed.) M. Francis, P. Lindsey, and J. Stone Rice; Center for Design Research, University of California-Davis, Davis, California, p. 215–222.

Taitt, M.J.
1995: The Delta Farmland and Wildlife Trust; Marshnotes, Summer, p. 6–8.

Tisdell, C.
1988: Sustainable development: differing perspectives of ecologists and economists, and relevance to LDC's; World Development, v. 16, p. 373–384.

Ulrich, R.S.
1984: View through a window may influence recovery from surgery; Science, v. 224, p. 420–421.

World Commission on Environment and Development
1987: Our Common Future; Oxford University Press, Oxford, United Kingdom, 400 p.

Young, M.D.
1992: Sustainable investment and resource use: equity, environmental integrity and economic efficiency; United Nations Educational, Scientific, and Cultural Organization, Paris, 176 p.

Appendix

Notes to accompany paper

1. Succession is the replacement of the plant community of an area by another community with a different species composition. Succession occurring after a disturbance (such as land clearing by humans or fire) will initially be of a different species composition than that which was removed by the disturbance. Often, a series of different plant communities will occupy the site in succession before the species composition of the original growth is replaced. The earlier colonizers of a disturbed site are often characterized by fast growth rates. These species can be short-lived and are quickly replaced by longer-lived, slower-growing species. (The above is a simplification of a complex process. For a more detailed discussion of succession, *see* Spurr and Barnes, 1992, p. 395–420.)
2. Many people use the term 'natural landscape' in reference to naturalistic landscapes. Naturalistic landscapes contain elements of natural landscapes, i.e. landform, vegetation, rocks, and water. They may be designed or may have resulted from a combination of human intervention and succession. 'Natural landscape' implies a landscape in a more pristine condition. Here the terms are used interchangeably.

REFERENCES

Spurr, S.H. and Barnes, B.V.
1992: Forest Ecology; Krieger Publishing Company, Malabar, Florida, 687 p. (third edition).

Future of sustainability

Robert Woollard[1] and William Rees[2]

Woollard, R. and Rees, W., 2004: Future of sustainability; in *Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567, p. 291–300.*

Abstract: The role of science in addressing the fundamental issues confronting society is being increasingly challenged. The optimism that placed humans on the moon is being eroded by an evolving concern that science and technology are at best distractions and at worst root causes of some of the threats to our sustaining ecosystems. This bulletin represents some of the best science and thinking available addressing the issue of sustainability in the lower Fraser River basin region of British Columbia. What remains unclear is how this thinking and knowledge might be used to address the future of the basin ecosystems. Will current patterns of human activity be modified in a way that enhances the long-term health of the valley? Can we change to reduce our impacts and dependence on distant 'elsewheres'? Can the academic community contribute to such an outcome? This paper addresses the prospect for such an outcome.

Résumé : On conteste de plus en plus le rôle de la science dans la réponse aux questions fondamentales qui se posent à la société. L'optimisme qui a envoyé des humains sur la Lune s'effrite; on craint en effet que la science et la technologie ne soient au mieux que des distractions et, au pire, la cause fondamentale de certaines menaces planant sur les écosystèmes qui nous soutiennent. Ce bulletin renferme des données scientifiques et des réflexions qui se classent parmi les meilleures réponses à la question de durabilité dans la région du bassin inférieur du Fraser. Il reste à savoir comment ces idées et ces connaissances pourraient servir à assurer l'avenir des écosystèmes du bassin. Modifierons-nous les modes actuels d'activité humaine de manière à favoriser la santé de la vallée à long terme? Sommes-nous capables de réduire notre impact et notre dépendance à l'égard d'« ailleurs » éloignés? La communauté universitaire peut-elle contribuer à ce résultat? Le présent article met ces questions en perspective.

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INTRODUCTION

It is a commonplace of political rhetoric and popular history that we are at a watershed, at a fork in the road, or on the threshold of the next technological revolution. Whichever metaphor one chooses, there is a strong appeal to that narcissistic desire of each generation to see itself as pivotal to the course of human development. Given the alternative of seeing our era as one of 'banal persistence', the appeal of being self-important crisis managers is an obvious one. The homogenization of culture with attendant dissolution of regional and even national character; the rapid shift of employment patterns due to globalization, technological change, or ecological collapse; as well as the massive daily shifts of capital swirling around the globe all tend to reinforce the idea that the future is becoming unglued from the past. When you add to this heady mixture the fact that the current standard calendar places us at the beginning of a millennium, it is small wonder that the age is characterized more by apprehension than by either fear or hope. There is an appreciation that choices are ours to make and a sense of urgency about making them, but there is genuine confusion about the appropriate direction to choose.

Such platitudinous phrases as 'sustainable development', 'sustainable economic development', 'sustained development', and even 'sustainability' itself have been of marginal utility in the research literature and debate surrounding these choices. Therefore, yet another discussion about the future of sustainability and the likelihood of its achievement might be viewed by some with understandable scepticism. Nevertheless, this paper attempts to provide a practical definition of sustainability, outline some tools for its assessment and achievement, and illuminate living examples of its attainment. We also speculate on why Canada and its Organisation for Economic Co-operation and Development partners appear to be continuing in the direction of an evolutionary *cul-de-sac* incompatible with the most rudimentary concept of sustainability.

This last issue is central to our understanding of future prospects for the 'consumer society', the dominant culture at present. Despite the above-noted rhetoric, we are not in imminent danger of changing socioeconomic watersheds. The dominant economic paradigm is well entrenched and is likely to persist long after ecological limits of consumption and waste absorption are exceeded. Our cultural addiction to exponential growth ensures that these limits will be greatly exceeded before there is a broad public perception that it has occurred. Thereafter, human choice about future development will be much more severely constrained than at present.

It is against this background that we must talk about 'the future of sustainability'. Plotting any future depends upon a clear understanding not only of what choices lead towards sustainability, but why in the normal course of events we are unlikely to make those choices.

Science should not be in the business of creating illusions. If the essence of science is the unfettered search for truth, the massive academic and industrial enterprise in research and development that spans the globe should have a unifying theme or purpose. In the best of all possible worlds, this theme might be developing a better understanding of ourselves and our environment such that we can be more effective participants in the long term. It is this last phrase that moves us from the realm of simple individual (or even species) survival into the realm of sustainability. The *sine qua non* of any meaningful definition of sustainability is persistence over a time span that approximates perpetuity from the perspective of those using the term.

Thus, the challenge to science in addressing the concept of sustainability is of a very high order. Although it requires significant ingenuity, it is a relatively simple matter to devise methods of extracting fossil hydrocarbons from pools within the Earth's crust, and to burn them in engines wherein their energy can be translated into motion and used to cut down large numbers of living trees. It is an altogether different matter to understand the rate at which such human-induced transformations might be maintained indefinitely, let alone the means by which the attendant perturbations of the biosphere might be compensated.

Other papers in this bulletin provide lucid discussions of Earth systems and biological (including human) subsystems that combine in complex ways to create our regional ecosystem. This ecosystem is in turn embedded in and connected with an equally complex array of other ecosystems which collectively make up the ecosphere (Fig. 1). While increasing understanding of these many subsystems forms an enduring and essential part of our evolving understanding, a true appreciation of the principles of sustainability will require much more. Our ability to see patterns that are, if not mutable, at least predictable in this hierarchy of interacting systems will be essential if science is to serve any useful purpose in shaping a sustainable future for the human species. This is true whether the patterns exist at the subatomic, molecular, biological, social, or ecological levels. As we shall see later, some patterns may persist across many or all of these levels. While they may not lend themselves to precise predictions, it is clear that some patterns are recognizable warnings that the system is moving towards areas incompatible with its continuing existence.

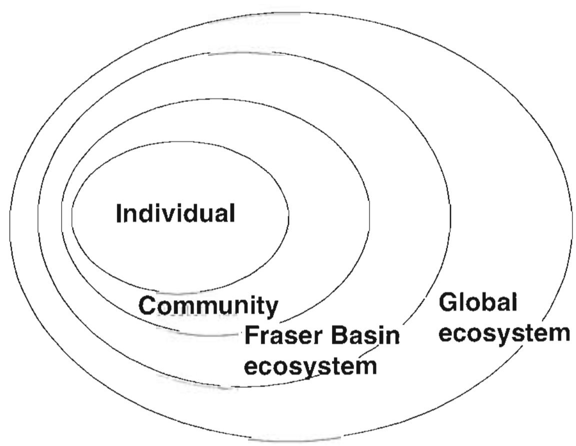

Figure 1. *Nested hierarchy of adaptive systems.*

While science can be a source of elucidation, there is danger in a limited and unidimensional view of science itself. The use of science as a reductionist, mechanistic enterprise founded upon reproducible cause and effect relationships has been remarkably successful in the anthropogenetic transformation of the planet. The global reach of transportation and communication systems, the explosion of computer technology, and the sheer size of human settlements provide ample evidence for science's transformative powers; but this creates an illusion of omnipotence in the face of new challenges to human needs. Science and technology have become the repository for human hope at a time when evidence is accumulating that technological transformation itself is threatening the integrity of the biological systems on which our long-term survival depends.

'Sustainability' is sometimes a deceptively simple concept. The World Commission on Environment and Development defines sustainable development as that which "... meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The University of British Columbia Task Force on Healthy and Sustainable Communities (Chu and Simpson, 1994; Woollard, 1994a, b; Rees, 1995; Wackernagel and Rees, 1996; Woollard et al., 1999; Woolard and Ostry, 2000) considered sustainability to be a state in which humanity lives together peacefully within the means of nature; however, translating these straightforward definitions into action is another matter altogether. To begin, neither nature's means nor the resources that future generations will require are readily quantifiable. The ways in which our current consumption patterns compromise ecological productivity are often obscured. Even a cursory review of previous papers would leave the reader in no doubt as to the difficulty of understanding the nuances of the ecosystems of the Fraser River estuary. Moreover, human behaviour and political organization add further imponderables to an already intimidating mix of factors. For all this, the measurements we do have indicate that with few exceptions the air, water, and soil of the Fraser River estuary are being degraded at a disturbing rate (Lavkulich et al., 1999). Indeed, given current trends, we must ask whether we can even conceive of a sustainable future for the lower Fraser River basin.

To answer this fundamental question we must ask several others. Can we develop adequate measures of the human impact on ecosystems such that we can determine if any particular action moves us towards or away from sustainability? Will we have to abandon our consumer lifestyles and reduce material consumption? Can we measure and evaluate the trade-offs that must be made if we dramatically reduce our material consumption? Can we dramatically reduce material consumption without giving due attention to the issues of peace, health, and equity? Has any place outside of the Fraser River estuary been more successful in consuming dramatically less while maintaining a healthy and socially cohesive population? Can any lessons from those jurisdictions be translated into positive change in the Fraser River basin?

MEASURING PROGRESS

Members of the University of British Columbia Task Force on Healthy and Sustainable Communities have developed and deployed the 'ecological footprint' concept to measure the ecological impact of collective and individual human activity (Rees, 1992, 1996, 1997; Wada, 1993; Rees and Wackernagel, 1994; Wackernagel and Rees, 1996). This analytical tool, in its full expression, is able to take many of the material- and energy-consumption and waste-management requirements of any specified human population or activity and translate that into a land surface area which represents much of the ecological impact of the activity or population. Thus, the ecological footprint of any specified population is the total area of land and water (ecosystems) required on a continuous basis to produce the resources consumed and to assimilate the wastes produced by that population wherever on Earth the land/water is located (Fig. 2).

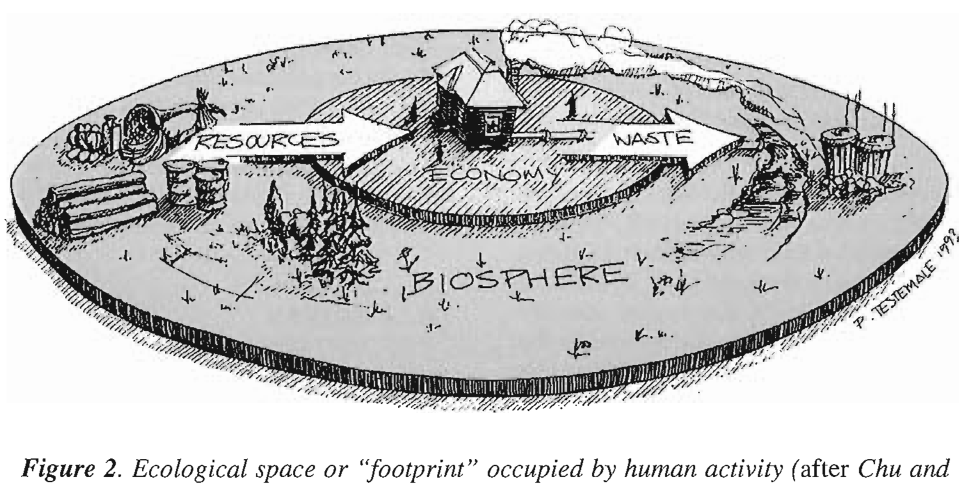

Figure 2. *Ecological space or "footprint" occupied by human activity (*after *Chu and Simpson, 1994).*

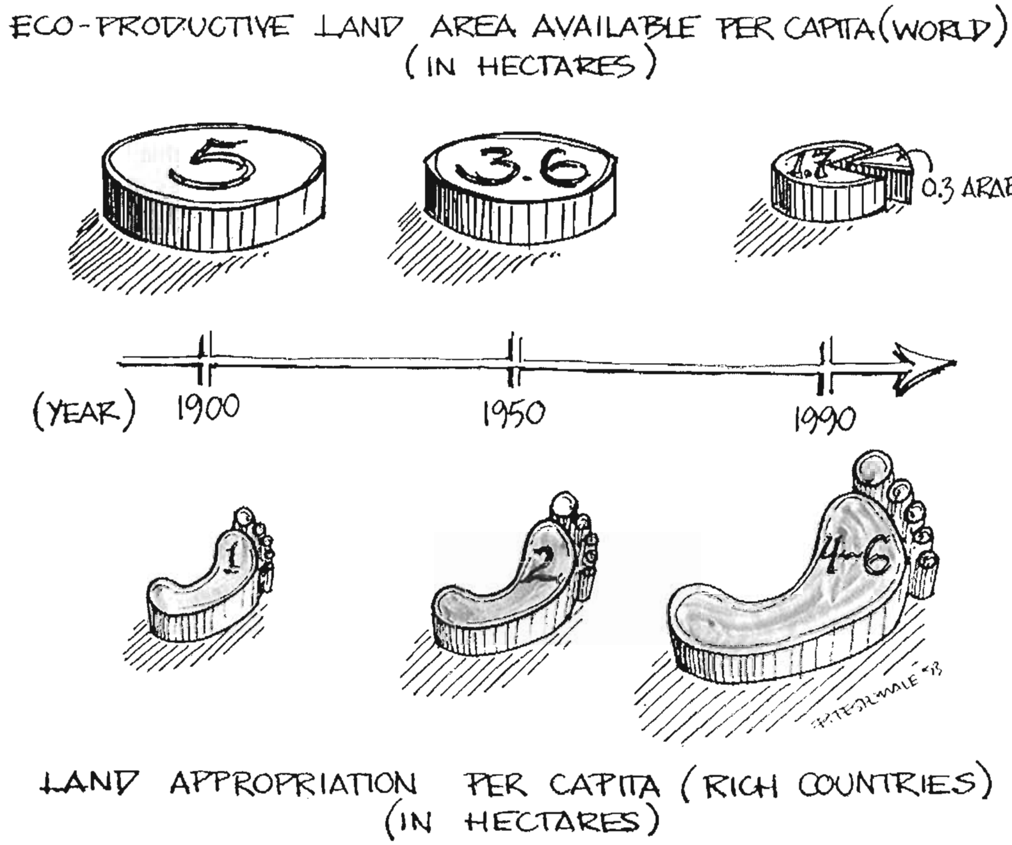

Figure 3. Ecoproductive land area available per capita in the world and land appropriation per capita (rich countries) (Chu and Simpson, 1994).

Of course, in the short term, our ecological footprint can exceed our local or regional land base. This is because we are surviving, in part, by drawing down accumulated resource stocks (fossil fuels, soils, and forests), by filling waste sinks to overflowing (contaminating our air and watersheds), and by importing various goods. Moreover, because many of the sources for current consumption are so distant (cars from Japan, coffee from Indonesia), we live blissfully ignorant of the faraway impacts. So it is that we persist in our belief that our 'environment' is just fine and that current levels of consumption are not only sustainable but can grow to even higher levels.

This is our grand cultural illusion! Ecological footprint calculations show that the citizens of lower Fraser River basin in particular are 'consuming' a land area at least 14 times larger than the geographic area of the basin itself. In material and ecological terms, the people of this region actually mostly live elsewhere. More to the point, if everyone in the world were consuming at our rate we would need at least two additional Earth-like planets to produce our material and energy and absorb our wastes. This state is obviously the antithesis of sustainability, and no amount of rehabilitation of local water or airsheds will make much difference in the global context. In order to achieve sustainability, the human population of the lower Fraser River basin, like those of high-income populations everywhere, must urgently and dramatically reduce both its consumption and its waste production.

Ecological footprinting has proved to be a powerful tool in raising public awareness and focusing concern on our current unsustainable path (Fig. 3). It also has been used to examine the potential impact of various projects and policies on the size of the community's overall ecological footprint. Unfortunately, rising awareness does not, in itself, guarantee an effective response. There are many barriers to reform (Moore, 1994; Roseland, 1997; Woollard and Ostry, 2000) within the political process when massive change is called for.

TRADE-OFFS

Any community planning to take action must address a range of explicit trade-offs, how the cost and benefits will be distributed and who will make the decisions. The University of British Columbia Task Force on Healthy and Sustainable Communities has developed the concept of 'social caring capacity (SCC)' as a way of assisting the community in addressing these issues. To a significant extent the social caring capacity reflects the 'social capital' that exists within a given community. Social capital may be seen as the relationships and social mechanisms that provide the glue holding the community together in mutual support to achieve common goals or in the face of adversity (Carr, 1999). As we shall see, such social capital and its enhancement provides a mechanism whereby significant reductions in consumption might be achieved.

Social caring capacity is founded upon the assumption that there are some cardinal issues and criteria that would define a community (virtually on any spatial scale from small village through nation to the global village, as well as nonspatially. Sustainability must be practiced at all levels for it to function at any level) capable of long-term social adaptability and hence persistence — a prime requisite of sustainability. We have explored these criteria in a number of contexts in order to establish their validity and applicability (Chu and Simpson, 1994; Woollard and Ostry, 2000). Such criteria as equity, safety, connectedness, engagement in community affairs, etc. are well grounded in the social sciences literature and numerous indicators have been tested for them. The social caring capacity concept can be used as a tool to ensure that when confronted with any particular community decision (such as a major reduction in consumption and waste production), the community must address all of the criteria simultaneously. By explicitly recognizing and enhancing its social caring capacity a community may engage in an iterative process of adapting to change, enabling it to make the successful trade-offs necessary for sustainability without disadvantaging its more vulnerable members. There is an inherent complexity in undertaking such a task; however, it provides the possibility of more effective decision-making than simply responding to the most vociferous or politically powerful group within the community. The most vociferous or politically powerful group especially may have very little appreciation of either the broad or long-term consequences of any decision involving ecological damage or its mitigation.

The above provides a brief description of tools that have been described in more detail elsewhere. They are iterated here primarily to make the point that in principle it is possible to have a more effective decision-making process that provides clarity and reflects community values.

CONSUMPTION AND CONCERN

It is not difficult to make the case that current high levels of consumer demand in the lower Fraser River basin represent attempts to purchase happiness and social stature. Unless these can be obtained in a less destructive way through the development of social capital, it is unlikely that the demand will abate. The love affair with the automobile in spite of direct and immediate knowledge of its destructive effect on air quality and human health suggests how difficult it is to shift human values and behaviour. It is not enough merely to attack consumption. We have to be able to show that redirecting our personal and public resources will enhance the quality of life in alternate, more socially constructive ways.

It also seems that our overconsumption can be mastered only if we simultaneously address the social issues in which that overconsumption is embedded (Woollard and Ostry, 2000).

Given the extent and the urgency of the task of reducing material consumption to a level consistent with long-term survival, do we have time for the niceties of equity and social harmony? Do we need Draconian measures and intense social engineering if we hope to make the trains carrying us to sustainability run on time? There is increasing evidence (M. Carr, unpub. report, 1994; Carr, 1999; Woollard and Ostry, 2000) that enhanced social capital can and has acted as a direct substitute for material consumption such that an increasingly durable society was also one that consumed less per capita. As we will discuss below, even within wealthy societies, inequitable distribution of resources has an adverse effect on the health of the population as a whole. Since declining health might reasonably be associated with a shortened persistence, it would seem that equity and social harmony in and of themselves can be seen as necessary, though not sufficient, conditions for sustainability. The lessons from Kerala, Curitiba (*see below* 'Examples of success'), and elsewhere would seem to indicate that these conditions might have the added benefit of allowing, if not actually fostering, levels of per capita consumption closer to those that might be sustainable.

EXAMPLES OF SUCCESS

If the future of sustainability in the lower Fraser River basin rests in part on the ability of its human population to dramatically reduce its consumption while increasing its social cohesiveness, can we have any confidence that such a state is possible, let alone achievable? It is clear that such a state could not be achieved in isolation from changes in the rest of the world — particularly the similar high-consumption parts of it, but can we see any hopeful signs in other places? There are numerous examples around the world of communities and populations that enjoy a health and social status comparable to those in the Fraser River basin while consuming a small fraction of our per capita amount. Moreover, international comparative statistics indicate that it is 'maldistribution' rather than absolute amount of wealth and education within nations that has the greatest adverse effect on the population's health (World Bank, 1994). Indeed, England has the dubious distinction of being the first Organization for Economic Co-operation and Development country whose health status regressed in a decade when the per capita gross domestic product (GDP) actually rose. It would appear that this is primarily on the basis of an increasing disparity between the rich and the poor within the country. Hertzman (2004) has pointed out that there are significant variations in mortality and morbidity across communities within the Fraser River valley. These appear to correlate with a number of measures of 'wealth' which might lead us to believe that any overall reduction in wealth as conventionally measured by per capita gross domestic product and income would lead to a significant deterioration in the health of the population. This may, in fact, not be the case. It is the manner in which such reductions

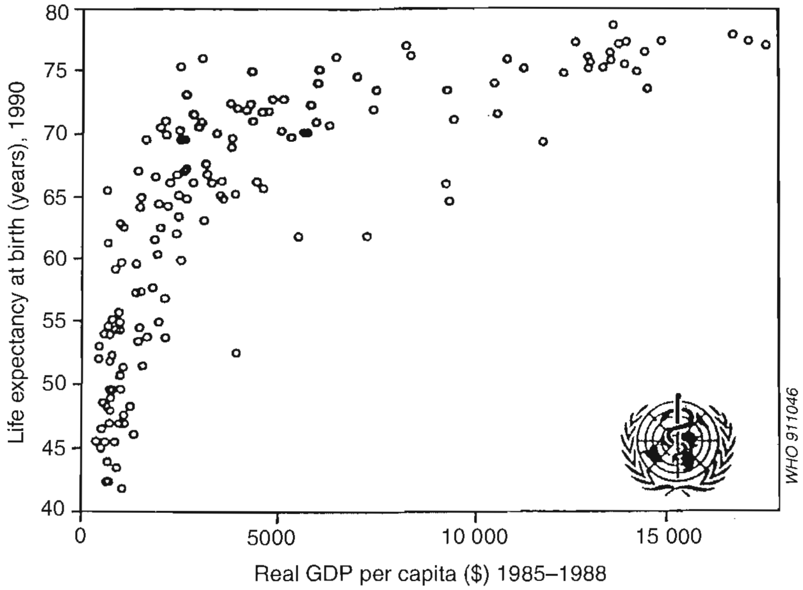

Figure 4.

Countries, per capita GDP (gross domestic product) for latest available year, plotted against life expectancy (after World Health Organization data presented by J. Roberts, World Health Organization workshop, regional office for Europe, Copenhagen, 1993; World Bank (1993)).

Table 1. Comparisons of selected countries with regard to gross national product, infant mortality, and life expectancy (*data from* Alexander, 1994).

Country	GNP per capita US dollars	Infant mortality	Life expectancy at birth
CANADA	**20 470**	**7**	77
SPAIN	11 020	8	76
SOUTH KOREA	11 020	17	71
ALGERIA	5400	17	65
KERALA	**350**	**16**	**72**
INDIA	350	92	59
MOROCCO	950	67	62

Table 2. Comparisons of selected countries with regard to female high school enrollment and fertility rates (*data from* Alexander, 1994).

Country	Female high school enrollment (%)	Fertility rates
CANADA	**105**	**1.8**
SPAIN	110	1.2
SOUTH KOREA	84	1.6
ALGERIA	43	4.2
KERALA	**93**	**1.9**
INDIA	31	3.6
MOROCCO	30	4.0

are achieved and distributed that is likely to provide the most important variable controlling the relationship between wealth and health. Several examples exist of societies with comparable health status but a per capita gross domestic product that is a mere fraction of that seen in Canada (Fig. 4).

One such example is the state of Kerala in India. For various historical and political reasons, this state, with approximately the same population as Canada concentrated in an area the size of Vancouver Island, has promoted equity, literacy, and the status of women as fundamental values guiding public policy decisions. The result is a literacy rate of over 95% including women (Table 1, 2). This is correlated with infant mortality, longevity, and fertility rates which are dramatically better than in neighbouring states and more in keeping with wealthy western countries (Alexander, 1994; McKibben, 1995). All this is achieved with a per capita income of approximately US$330 per annum (1986) — approximately one seventieth (1/70) of that in America. The phenomenon of Kerala has been extensively studied. The data provide neither simple answers nor reason for unmitigated optimism — Kerala's problems are not minor. Nonetheless, it provides some hope that the vanguard of a new low-consumption future is potentially no less pleasant than the Fraser River valley of our present time. The population can achieve a greater degree of harmony with its immediate environment while achieving much lower levels of consumption. That this has been done in a society generally beset by massive population pressures should give us even more reassurance. Given that control of human population is the *sine qua non* of sustainability, we might sum up one lesson from Kerala as: "People have fewer children in this pocket of India because life is safer, fairer, more decent. Because they have fewer children, life should be safer, fairer, more decent in the future." (McKibben, 1995)

The application of these sentiments to a more caring and sharing society in the Fraser River valley is obvious.

If necessity created virtue in Kerala, the city of Curitiba in Brazil represents an example of a city of some 500 000 people that made a series of decisions to enhance their quality of life while significantly reducing their automobile dependency (McKibben, 1995; Rabinovitch and Leitman, 1996). With less wealth (gross domestic product US$2500 per capita) and far greater social and ecological problems than currently exist in the lower Fraser River valley (Curitiba's regional population tripled to 1.5 million in 25 years), the city was able to enhance social bonds and equity while at the same time improving waste-management (garbage) and flood control, creating attractive public spaces and building a low-cost, highly effective public transportation system. The details of this achievement are beyond the scope of this paper but are explored in detail elsewhere for anyone who wishes an antidote to the despair that may result from contemplating the state of urban sustainability (McKibben, 1995; Rabinovitch and Leitman, 1996).

If we have the tools to measure progress towards sustainability and we know that people in other parts of the world have achieved a more sustainable lifestyle than ours, what is the prognosis for the Fraser River valley?

HOPE FOR THE VALLEY

There are a few hopeful signs. For example, past policies have resulted in a decrease in the soil and water burden of some heavy metals, particularly lead (Healey et al., 1999). Such positive trends, however, are the exception and serve mainly as a symbol of hope that policies to modify human behaviour and consumption patterns can have a mitigating effect. The preponderance of evidence at present suggests that two factors are likely to overwhelm such modest gains. The first is that our current consumption patterns (which have already led to a massive decline in the bioproductivity of the lower Fraser River basin) show no signs of reversing. Indeed, the formal economy sees continuing growth of consumption as necessary for sustainability!

The second factor is an anticipated major increase in the population of the Fraser River valley over the next three decades. Therefore, we must inevitably see an increase in our dependence upon ecologically productive land, water, and air from beyond the lower Fraser River basin. This imbalance and dependence is the very antithesis of long-term sustainability. Failure to address these factors makes it virtually certain that we will be further from a sustainable state 30 years from now than we are at the present. We will likely have increasingly obvious daily evidence (e.g. gridlock, soil loss, deteriorating air quality) of our unsustainable state. Such palpable evidence might be expected to foster the changes in public attitudes and behaviour required to reverse the trends; however, humans have a well demonstrated ability to deny reality, adapt to the impacts, and continue business as usual. The ineffectiveness of the *Clouds of Change* report adopted by Vancouver City Council (City of Vancouver, 1990) and then not significantly acted upon (Moore, 1994; Roseland, 1997; Woolland and Ostry, 2000) may be seen as a signal event in this regard. The major adverse health effects related to current pollution tend to peak up the valley from their sources in Vancouver. This dilutes the political impact and contributes further to inaction. Other papers in this bulletin detail these concerns.

In spite of an understandable degree of cynicism and even pessimism, we must remember that some mitigation efforts have been successful. Some (lead contamination) have succeeded because clear evidence of adverse health effects led to effective regulatory response. Others (establishment of the Agricultural Land Reserve (Mooney, 2004)) resulted from far-sighted governments that established new ground rules for development. Still others (increased fuel efficiency of automobiles) came about because of political and economic forces elsewhere which were reinforced by purchases by people within the Fraser River valley. The last example is a useful one, because its potential mitigating effect was overwhelmed by an increase in the Fraser River valley's population, a proportionally greater increase in the population of cars, an increase in the number and distance of commuter trips in the valley, and a significant decrease in fleet efficiency due to massive increase in sports utility vehicle sales and use. This is a useful symbol to underscore the fact that additional actions towards sustainability must be undertaken within the valley to reinforce larger trends elsewhere.

Given the complexity of sustainability, is there any hope that the academic and political communities can develop an effective response to the challenge of sustainability in the lower Fraser River basin? The answer has to be a cautious "yes". While political debate is often dominated by the immediate and the irrelevant, other papers in this bulletin have identified imaginative attempts to develop a more coherent policy response and regulation within the lower Fraser River basin. This bulletin, and a number of interdisciplinary activities in which many of its authors participated, demonstrate a dawning awareness in the academic community that integration across disciplines of the massive amount of work already undertaken is going to be more fruitful in addressing sustainability than is continued specialization and reductionism. Whether this shift will come soon enough is still an open question.

The epistemology of science and broader realms of knowledge also is undergoing some potentially hopeful change. The study of complex adaptive systems is shedding new light on the patterns of behaviour we might look for in such otherwise overwhelming complex systems as the lower Fraser River basin. Part of the way in which such systems adapt to changing circumstances is through a series of effective feedback loops that are capable of sensing the internal and external environment and then mounting effective responses to threats to their ongoing integrity. As noted above, for various historical, economic, and political reasons, the lower Fraser River basin has become isolated from both the causes and the consequences of its current behaviour. Thus, the necessary negative feedback has been diluted. Active efforts must be made to overcome these deficiencies.

INTEGRATION OF KNOWLEDGE

A modest step in the direction of knowledge integration is the combination of tools noted above — the ecological footprint and the social caring capacity. If used together to address particular projects (e.g. bridges, built form, etc.) and policies

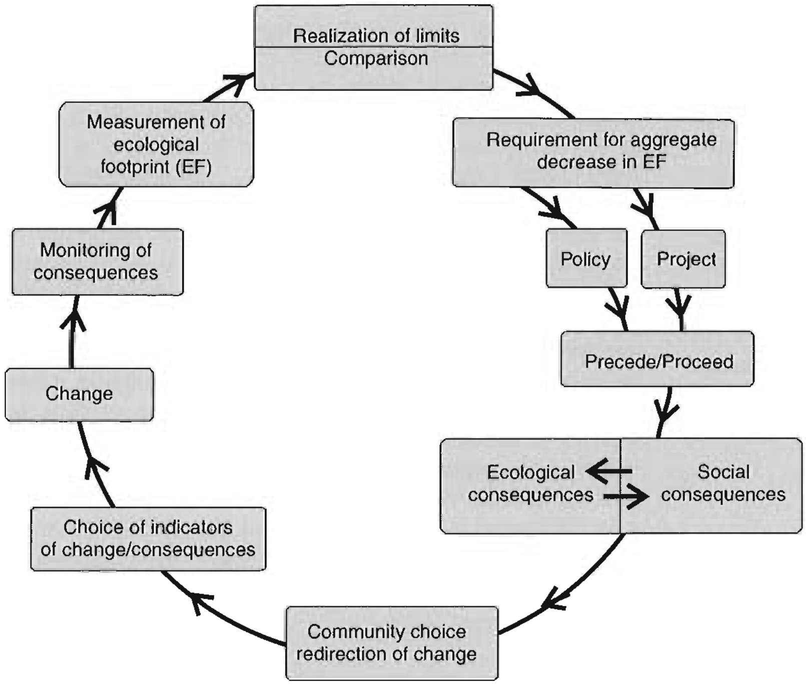

Figure 5.

Cycle of community change towards sustainability (Woollard et al., 1999).

(transportation, zoning, etc.), they are capable of focusing the discussion on the fundamental issues of sustainability as illustrated in Figure 5.

This is a deceptively simple model but one that can be applied at a number of scales from individual consumer choice through to assessment of the overall progress of the valley towards a more sustainable future. Its central assumption is that increasing social capital can substitute for decreases in consumption of material resources and energy. The concept of social capital was introduced by Hertzman (2004) and is illustrated by the examples of Kerala and Curitiba alluded to earlier in this paper. Needless to say, social capital is in turn laden with human values and emotions.

It is for this reason that any interdisciplinary contribution from the academic community must reach beyond the traditional boundaries of science to embrace the humanities. If we can accomplish this, we become capable of making a contribution towards the establishment of peace in what is often seen as a war between a technologically driven civilization and the natural systems on which it depends. To accomplish this, we must collectively go beyond mere information and knowledge such that our overall actions reflect something like wisdom. Earlier in this century, in an arguably simpler time, the British American poet T.S. Elliot raised the poignant question: "Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?" (T.S. Elliot, 1974). For that matter, where is the information we have lost in data?

While the contributions of the academic community to effective social change are modest, they are not inconsequential. This is certainly true in the realm of technology and must be increasingly so in the broader search for sustainability.

THE SEARCH FOR WISDOM

The metaphor of war for our current struggle with massive ecological degradation is tempting but dangerous. It implies a dichotomous view of absolute enlightenment and rectitude doing brave battle with the forces of darkness. Such a view is rarely helpful in advancing civilized discourse and of even less value in focusing the collective actions of humankind on the real and very urgent problems that confront us.

There is, however, a more subtle aspect of the war metaphor that may be of particular value to a scientific readership. This is the fact that wars are primarily about feelings and values although they are fought with the tools of science. While ideology and power politics are important precipitants of war, the passive or active support of populations is gained through appeal to values or threats to values. Weapons development proceeds at some distance from this clash of values. The technology exists and develops to some extent for its own sake. Boundaries are pushed by what is technically feasible with very little consideration given to what is desirable or, for that matter, what is decent. The parallel with the technologies that are currently having such adverse effects on ecosystem health (fisheries decline, global warming, ozone depletion, etc.) is an obvious one. Technology, like the tools of war, also creates the illusion of safety in the face of increasing threats.

Hand-wringing on the part of the scientific community about the misuse of technology is no longer a sufficient response. With certain notable exceptions, the scientific community has eschewed the political culture as being inherently irrational and hence beyond the pale of 'real' science. This might seem curious when one considers that it is political activity at every level from the neighbourhood to the globe that determines how the technology developed within the scientific community is actually applied; however, it is understandable if one considers that science is primarily about facts and measurement and politics about values and power, so that measurement is frustratingly difficult in the political arena. In another context, John Evans is quoted as saying, "The [political] process is frustrating, however, because what is important is difficult to measure and what is measurable is usually not important." (Des Marchais, 1996); nor is this a recent observation. Adam Smith is noted to have defined economics as "the romance of truth through measurement" — and not as a complimentary statement (Saul, 1995).

Notwithstanding these differences, the scientific and technical community must come to appreciate the urgency and importance of the difficulties that are being manifested through the political application of their considerable accomplishments. Like Albert Einstein in relation to the ultimate weapons technology, the atomic bomb, we must begin to see a collective responsibility for the application to which our measurements and developments are put.

> "Concern for man himself and his fate must always form the chief interest of all technical endeavours, concern for the great unsolved problems of the organization of labour and the distribution of goods — in order that the creations of our mind shall be a blessing and not a curse to mankind. Never forget this in the midst of your diagrams and equations." (A. Einstein, address given to California Institute of Technology, 1931)

Two decades later, he was led to say more explicitly: "The unleashed power of the atom has changed everything save our modes of thinking, and we thus drift towards unparalleled catastrophe." (Einstein, 1954)

The changes in our "modes of thinking" which Einstein envisioned are undoubtedly sweeping and must draw upon all the traditions of thought available to us. The restructuring of the sciences, the arts, the humanities, and the everyday experience of humankind must involve a thoughtful and systematic attempt to integrate across the boundaries we can no longer allow to exist between the various intellectual and moral traditions of our species. It will become increasingly important to embrace feelings and values in scientific discourse just as it is important to embrace science in political and social discourse. This is not an easy task. Even within academic institutions, with their long tradition of some measure of mutual interdisciplinary respect, attempts at long-term working relationships addressing complex societal issues are difficult (Woollard and Rees, 1999; Woollard and Ostry, 2000). The recent attempt by the three major Canadian granting agencies (Medical Research Council, Natural Science and Engineering Research Council, and Social Science and Humanities Research Council) to foster interdisciplinary research on ecosystem health has come to a close. This is at least in part because of a perception of difficulty and failure, but is symbolic of the challenge facing us. The lack of effective engagement by the humanities and to some extent the medical communities in this national exercise is a source of enduring concern.

It remains unclear whether the scientific community is yet prepared to explore a new way of thinking which embraces the humanities with their feelings and the political systems with their values. The challenge facing modern science as it seeks to address the ecological crisis is to open in that direction. If we look across that divide, we can see the humanities struggling with similar issues in confronting the fundamental questions facing humankind. The importance of integrating both thought and feeling in addressing political issues is well stated by Jon Silkin in the context of First World War poetry:

> "Even compassion must now be circumspect, for if it doesn't try to do away with, or limit, the war that causes the suffering, it's indulgence. At best compassion like this walks behind the system.
>
> Our humanity must never be outwitted by systems, and that is why we are at our most vital when our intelligence is in full and active cooperation with feeling. We shall never not be political again, and the very best way to be this .... is to think *and* feel; and if this cooperative impulsion is permeated with values we can decently share, we stand a chance, as a species, of surviving. For that, I think, is what is at stake."
>
> — Silkin, 1981

In short, the future of science in addressing the complex issues of ecological degradation and environmental threat lies in its ability to build robust cross-linkages with other intellectual traditions and the humanity in which we are all embedded. We must take practical steps to build bridges that will allow us better to understand our collective values, better to apply our knowledge-gathering and -disseminating tools, better to understand the ecological consequences of human action, and better to assist our political and social structures to have the knowledge that is necessary to take wise action. This is an intimidating charge, and it is not clear at the outset that even if we engage in it we will be successful; however, in light of the knowledge represented in this bulletin the reader holds in his/her hands, it is clear that we must embark on a serious attempt to restructure our thinking and ourselves. To do less and yet to claim compassion and concern for humankind is, in John Silkin's phrase, mere indulgence.

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REFERENCES

Alexander, W.
1994: Humans sharing in the bounty of the Earth: hopeful lessons from Kerala; International Congress on Kerala Studies, AKG Centre for Research, Thiruvanatha purum 695034, Kerala, India, 2 p.

Carr, M.
1999: Diversity against the monoculture: bioregional vision and praxis and civil society theory; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 562 p.

Chu, C. and Simpson, R.
1994: Ecological Public Health: From Vision to Practice; jointly published by Centre for Health Promotion, University of Toronto/ Griffith University and Institute of Applied Environmental Research, Nathan, Queensland, Australia, p. 111–121.

City of Vancouver
1990: Clouds of Change; City of Vancouver, Vancouver, British Columbia, 83 p.

Des Marchais, J.
1996: Apprendre à devenir Médecin; Université de Sherbrooke, Quebec, Canada, p. 325.

Einstein, A.
1954: Letter to New York Times Magazine, August 2, 1954.

Elliot, T.S.
1974: Choruses from "The Rock" in *Collected Poems, 1909–1962*; Faber and Faber, London, United Kingdom, p. 161.

Healey, M., Woollard, R., Shearer, R., and Werick, B.
1999: Seeking Sustainability on the Lower Fraser Basin, (ed.) M. Healy; Institute for Resources and Environment, Westwater Research, Vancouver, British Columbia, 348 p.

Hertzman, C.
2004: Urban environment and human health in the Lower Mainland; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Lavkulich, L.M., Hall, K.J., and Schreier, H.
1999: Land and water interactions: Present and Future; *in* Seeking Sustainability in the Lower Fraser Basin: Issues and Choices, (ed.) M. Healey; Institute for Resources and the Environment, Westwater Research, Vancouver, British Columbia, p. 170–201.

McKibben, W.
1995: Hope, Human and Wild; Little Brown & Company, Canada, Toronto, Ontario, 227 p.

Mooney, P.F.
2004: Sustainable development for the Fraser River estuary; *in* Fraser River Delta, British Columbia: Issues of an Urban Estuary, (ed.) B.J. Groulx, D.C. Mosher, J.L. Luternauer, and D.E. Bilderback; Geological Survey of Canada, Bulletin 567.

Moore, J.
1994: What's stopping sustainability? Examining the barriers to implementation of clouds of change; M.Sc. thesis, School of Community and Regional Planning, University of British Columbia, Vancouver, British Columbia, 107 p.

Rabinovitch, J. and Leitman, J.
1996: Urban planning in Curitiba; Scientific American, March 1996, p. 46–53.

Rees, W.
1992: Ecological footprints and appropriated carrying capacity: what urban economics leaves out; Environment and Urbanization, v. 5, p. 121–130.

Rees, W. (cont.)
1995: Achieving sustainability: reform or transformation?; Journal of Planning Literature, v. 9, p. 343–361.
1996: Revisiting carrying capacity: area-based indicators of sustainability; Population and Environment, v. 17, p. 195–215.
1997: Ecological footprints and the imperative of rural sustainability; Chapter 3 *in* Rural Sustainable Development in America, (ed.) I. Audirac; John Wiley and Sons, New York, New York, p. 41–77.

Rees, W. and Wackernagel, M.
1994: Ecological footprints and appropriated carrying capacity: measuring the natural capital requirement of the human economy; *in* Investing in Natural Capital — the Ecological Economics Approach to Sustainability, (ed.) A.-M. Jansson, M. Hammer, C. Folke, and R. Costanza; Island Press, Washington, D.C., p. 362–390.

Roseland, M. (ed.)
1997: Eco-city Dimensions; New Society Publishers, Gabriola Island, British Columbia and New Haven, Connecticut, p. 95–112.

Saul, J.R.
1995: The Unconscious Civilization; House of Anansi Press, Concord University, Ontario, 207 p.

Silkin, J.
1981: The Penguin Book of First World War Poetry; Penguin Books, London, United Kingdom, p. 15 (second edition).

Wackernagel, M. and Rees, W.
1996: Our Ecological Footprint: Reducing Human Impact on the Earth; New Society Publishers, Gabriola Island, British Columbia and Philadelphia, Pennsylvania, 160 p.

Wada, Y.
1993: The Appropriated Carrying Capacity of Tomato Production; M.Sc. thesis, University of British Columbia School of Community and Regional Planning, Vancouver, British Columbia, 194 p.

Woollard, R.
1994a: Tools for sustainability: iteration and implementation; *in* Ecological Public Health: From Vision to Practice, (ed.) C. Chu; Griffith University, Queensland, Australian Academic Press (Nathan, Australia) and University of Toronto Press (Toronto, Ontario), p. 111–121.
1994b: Developing Livable Choices for a Healthy and Sustainable Future; Healthcare Forum Journal, May/June, p. 30–34.

Woollard, R. and Ostry, A.
2000: Fatal Consumption: Rethinking Sustainable Development; University of British Columbia Press, Vancouver, British Columbia, 270 p.

Woollard, R. and Rees, W.
1999: Social evolution and urban systems — directions for sustainability; *in* Communities, Development and Sustainability Across Canada, (ed.) J.T. Pierce and A. Dale; University of British Columbia Press, Vancouver, British Columbia, p. 27–45.

Woollard, R., Wackernagel, M., Rees, W., Ostry, A., McIntosh, J., Manson Singer, S., Lynam, J., Hertzman, C., Green, L., Carr, M. and Boothroyd, P.
1999: The community as crucible: blending health and sustainability; *in* Seeking Sustainability in the Lower Fraser Basin: Issues and Choices, (ed.) M. Healey; Institute for Resources and Environment, Westwater Research, Vancouver, p. 263–314.

World Bank
1993: The World Development Report 1993; Oxford University Press, New York, New York, p. 34.
1994: World Development Report 1994: Infrastructure for Development; Oxford University Press, New York, New York, 264 p.

World Commission on Environment and Development
1987: Our Common Future; Oxford University Press, New York, New York, 400 p.

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