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Proceedings of the Howe Sound Environmental Science Workshop

C. D. Levings, R. B. Turner, and B. Ricketts (Editors)

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PROCEEDINGS OF THE HOWE SOUND ENVIRONMENTAL SCIENCE WORKSHOP

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ABSTRACT

Levings, C.D., R.B. Turner and B. Ricketts (Editors). 1992. Proceedings of the Howe Sound Environmental Science Workshop. Can. Tech. Rep. Fish. Aquat. Sci. 1879: 261 p.

The Howe Sound Environmental Science Workshop was held on September 30 - October 3, 1991, on Bowen Island, B.C. Scientists working in the Sound and the watershed draining into the fjord exchanged information with environmental managers. The Proceedings include 22 papers dealing with meteorology, oceanography, geology, water quality, contaminants, fish and wildlife habitat management, forestry, and marine biology. Results of current research, as well as overviews of past work in Howe Sound and the watersheds are presented. Some of the major environmental topics discussed in the papers include dioxin and metal levels in marine biota, waterbirds, and sediments in Howe Sound; vulcanism, debris torrents and other geological hazards; the status of chinook salmon (Oncorhynchus tshawytscha) populations and habitats in the Squamish River; biological effects of nutrient enrichment in the Cheakamus River; and the status of wildlife and forest habitats in the watershed.

RÉSUMÉ

Levings, C.D., R.B. Turner and B. Ricketts (Editors). 1992. Proceedings of the Howe Sound Environmental Science Workshop. Can. Tech. Rep. Fish. Aquat. Sci. 1879: 261 p.

L'atelier sur les sciences de l'environnement dans le détroit de Howe a eu lieu du 30 septembre au 3 octobre 1991, dans l'île Bowen. Des scientifiques de la Colombie-Britannique travaillant dans le détroit et le bassin hydrographique se jetant dans le fjord ont échangé de l'information avec des gestionnaires de l'environnement. Le Compte rendu comprend 22 exposés portant sur la météorologie, l'océanographie, la géologie, la qualité de l'eau, les contaminants, la gestion de l'habitat du poisson et de la faune terrestre, la foresterie et la biologie marine. Les résultats des recherches en cours, de même que des aperçus des recherches déjà menées dans le détroit de Howe et dans les bassins versants, sont présentés. Parmi les principaux sujets environnementaux abordés, mentionnons les teneurs en dioxines et en métaux dans le biote marin, les oiseaux aquatiques et les sédiments du détroit de Howe, l'activité volcanique, les glissements de terrain et autres phénomènes géologiques; la situation des populations de saumon quinnat (Oncorhynchus tshawytscha) et de leurs habitats dans la rivière Squamish; les effets biologiques de l'enrichissement en nutriments dans la rivière Cheakamus; et la situation des habitats fauniques et forestiers dans le bassin hydrographique.

INTRODUCTION

Howe Sound and its adjacent watershed, a mountainous area transected primarily by the Squamish River system that drains into a coastal fjord, is representative of southern coastal British Columbia and its environmental concerns. Within the fjord watershed boundaries are the communities of Gibsons, Horseshoe Bay, Squamish and Whistler, pulp mills at Port Mellon and Woodfibre, a major port facility and industrial area at Squamish, the Sea-to-Sky Highway transportation corridor, the abandoned Britannia Cu-Zn mine, Daisy Lake dam on the Cheakamus River, and active forest harvesting throughout the Squamish River system. Recreational use of the watershed is heavy, particularly boating and fishing on Howe Sound and all-season sports in the Whistler area. This activity is causing considerable stress on the ecosystem and there is concern about the sustainability of resources in the watershed.

In part spurred by the controversy and concern which have been engendered by such problems, a considerable amount of research in Howe Sound and its environs has been carried out or is underway. However, there has never been an opportunity for the community of researchers to collectively discuss progress and results. Given that the many problems facing Howe Sound and watershed demand investigation of an interdisciplinary nature, it was appropriate that a conference be held which brought together active researchers from a broad range of disciplines.

The Howe Sound Watershed Environmental Science Workshop, held October 1-3, 1991 on Bowen Island in Howe Sound, brought together about 70 scientists as well as representatives of environmental groups, government and industry. The focus of discussion concerned the physical and biological processes within the watershed, and the impact of human activity on the long-term health of the ecosystem. Concerns expressed at the workshop included: damage to the marine ecosystem caused by effluent from the two pulp mills and the abandoned Britannia mine; loss of critical natural habitat for juvenile salmon and other species in the Squamish River estuary because of industrial development; the sharp decline of some salmon stocks in the Squamish River; algal growth in the Cheakamus River due to sewage effluent discharge from Whistler municipality; sediment erosion from old logging roads and the potential damage to salmon spawning habitat in streams; and loss of mature forest habitat due to logging in the lower valleys of the Squamish and Mamquam river systems. The discussions following papers and during a final plenary session were recorded and have been published through Environment Canada in a companion volume *Howe Sound Watershed, Environmental Science Workshop and Public Meetings -Summary of Proceedings*[1]. The proceedings volume also contains summaries of discussions during a series of public meetings which were held in the watershed communities of Whistler, Gibsons, Squamish, West Vancouver, as well as Vancouver. Each public meeting consisted of an information fair during the day followed by a scientific panel discussion in the evening. The public meetings were preceded by a series of presentations made by Tim Turner, an educational consultant on contract to Environment Canada, to watershed school and public groups during the winter and spring of 1991. This series of presentations has led to new environmental education initiatives within watershed schools and the community.

A strong commitment was expressed by participants of the Science Workshop to develop stronger links with other disciplines through meetings, a scientific newsletter and coordinated scientific research and technical monitoring. A Howe Sound Watershed Science Advisory Committee has been formed to promote these objectives. It is hoped that this Committee will improve the history of limited coordination of research and monitoring efforts among the many government agencies and other technical groups that have operated within the watershed.

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[1] Copies of these volumes are available from Bob Turner, Geological Survey of Canada, 100 W. Pender Street, Vancouver, B.C. V6B 1R8

ACKNOWLEDGEMENTS

The Howe Sound Environmental Science Workshop could not have been conducted without the generous financial support of a number of Federal, Provincial, and non-governmental agencies: Canadian Departments - Energy, Mines and Resources: Geological Survey of Canada; Environment: Atmospheric Environment Service, Conservation and Protection, and Canadian Parks Service; Fisheries and Oceans; British Columbia Ministry of Environment; B.C. Water and Waste Association; Canadian Geographic Society; Canadian Geological Foundation; Canadian Society of Zoologists; Chemical Institute of Canada, Environmental Division; Vancouver Aquarium. Thanks are due to the following members of the Steering Committee for their valuable advice in setting up the Workshop: Chris Pharo, Environment Canada; Brian Clarke, British Columbia Ministry of Environment, Lands and Parks; Walter Cretney, Fisheries and Oceans; Tom Pedersen, Department of Oceanography, University of British Columbia and John Rich, West Coast Environmental Law Society. A number of colleagues assisted in the editing process by reading papers and providing comments. We would also like to thank the following individuals for their hard work and expert assistance: Ms. Tracey Feeney for logistic support during the Workshop; Ms. Chris Craft for word processing; and Ms. Betsy Gordon for her excellent advice on formatting and her production editing of the manuscript.

THE WEATHER AND CLIMATES OF HOWE SOUND

by

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INTRODUCTION

If the earth were smooth and its surface homogeneous, climate would vary by latitude only. It is apparent Howe Sound (and the earth), is neither flat (it is enclosed by steep mountains), nor of homogeneous surface type (having both land of varying surface roughness, and water). Consequently it displays a variety of climates. Howe Sound is a steep walled channel oriented perpendicular to, and dissecting, a substantial topographic barrier (the Coast Mountains). As such, it (as well as other fjords along the coast) links the elevated interior plateau of Central British Columbia with the coast (see Fig. 1). These topographic factors result in fascinating local modifications to regional climate and weather. In order to illustrate this, and build a picture of the weather and climates of Howe Sound, some of the topographic modifications of the main synoptic weather types of British Columbia defined by Suckling (1977) will be examined. This will be done for typical summer and winter patterns emphasizing conceptual understanding of some of the more interesting topographic enhancements which are depicted schematically in Figure 2.

SUMMER

Figure 3, from Suckling (1977), shows a typical summer surface weather pattern. A ridge of high pressure oriented across the coast with generally light pressure gradients is associated with clear skies and light winds. These conditions are ideal for the establishment of a (daytime) seabreeze/(nighttime) landbreeze circulation.

Seabreezes occur along any coastline during the day under sunny conditions with light synoptic winds as a result of the different thermal characteristics of land and water: water, due to its large heat capacity, has relatively small diurnal temperature fluctuations. In contrast, land has a relatively large fluctuation in temperature, warming during the day and cooling at night. This results in hydrostatic expansion of the air column over land during the day causing low pressure over land near the surface and high pressure over land at elevation. The air near the ground then moves from the relatively high pressure over water to low pressure over land, rises up over the land and then flows at elevation from land to water where it subsides, completing the circulation.

In Howe Sound the same process occurs; however, two topographic factors act to enhance the seabreeze circulation. Howe Sound is part of a low level path to the Interior Plateau where daytime temperatures can be very high, resulting in very low surface pressure which draws surface air from the Coast, through the fjord to the Interior. This seabreeze circulation is on a scale that is much larger than typical. As low level air is drawn up valley, the constriction of Howe Sound causes the air to converge and increase in speed resulting in an enhanced seabreeze, with speeds that can easily double the typical 5-10 m/s maximum seabreeze found on flat coastlines. The seabreeze circulation in Howe Sound is schematically illustrated in Figure 4.

At night the land surface cools due to longwave radiative losses more than the ocean surface so that the air column over land contracts relative to that over water. This results in a relatively high pressure near the surface and low pressure at elevation over land creating a landbreeze circulation depicted in Figure 5. The speed of the landbreeze is less than that of the seabreeze, but is enhanced in Howe Sound by the katabatic drainage of air down the slopes and sides of valleys which concentrates along major valley axes. This katabatic flow, which is a nocturnal calm wind feature over most of the slopes, is a more or less constant feature on the glaciers which cover the highest terrain to the north of Howe Sound.

WINTER

Two typical winter synoptic patterns in which the Howe Sound topography results in distinct local weather conditions are shown in Figures 6 and 7 (Suckling, 1977). The first (Fig. 6), depicting a large area of low pressure at the surface in the northeast Pacific, is a pattern typically associated with a frontal system possibly containing moist tropical air which could bring copious amounts of precipitation. The second, which usually occurs less frequently, (Fig. 7) is often associated with "Squamish Winds".

PRECIPITATION

The synoptic pattern depicted in Figure 6 is associated with winter precipitation over the B.C. coast. The topographic configuration of Howe Sound results in two mechanisms which locally enhance precipitation amount. These result in the patterns shown by the contoured annual totals depicted in Figure 8 from Schaefer and Nikleva (1973).

The most important topographic enhancement is the "upslope" effect, whereby moist air, forced to rise over steep terrain, cools, thus forcing condensation and droplet formation resulting in clouds and precipitation. Forced ascent of air can also "trigger" convection by releasing latent and potential instability in the air. The "upslope" effect is dramatically illustrated by the five-fold increase in annual precipitation amount (Fig. 8) as one moves from sealevel to the mountain tops.

The second topographic enhancement of precipitation in Howe Sound, like the "upslope effect" also increases precipitation by forcing ascent in the moist air. As for the case of seabreeze enhancement, it is a result of confluence of Howe Sound causing convergence of air and consequent upward motion as the air flows to the North. This is illustrated in Figure 8 by the increase in precipitation amount from south to north up the axis of Howe Sound.

SQUAMISH WIND

The most singular meteorological phenomenon encountered in Howe Sound (as well as the other fjords of British Columbia and Alaska) is the locally named "Squamish Wind". These winds occur in Howe Sound mainly in winter when an intense anticyclone building over Alaska and the Yukon Territory moves southward. The coastal mountains act as a partial barrier, separating the cold, dense air associated with the anticyclone from the warmer, less dense maritime air mass. This density difference results in a strong cross coastal pressure gradient, and often very strong winds through gaps (such as Howe Sound) in the mountains. Figure 9 is a schematic representation of a Squamish Wind flow showing dense low level air moving down a pressure gradient through the fjord dissecting the Coast Mountains.

Figure 10 is a representation of the wind frequency by speed and direction at the Pam Rocks buoy (see Fig. 1 for location) from October 1987 until April 1988. Several things are apparent from this diagram:

1. channelling in Howe Sound due to the mountains on either side of the channel confine the winds to two predominant directions -- either up or down channel, and

2. the predominant wind direction at this location is northerly, with strong winds having a large frequency, an indication of Squamish Winds.

One of the consequences of a high frequency of northerly winds in the winter, is a decreased incidence of persistent fall/winter fog compared to the neighbouring Lower Mainland as the fog is displaced by the dry outflowing air. While Squamish Winds represent a topographic enhancement of the regional wind, there are many situations when, for example, the wind and waves are much less severe in Howe Sound than in surrounding open areas due to topographic sheltering. This occurs when the synoptic configuration is such that the predominant regional wind direction is across (rather than along) the axis of Howe Sound.

A field study of the Squamish Winds in Howe Sound was undertaken in the period October 1987 to April 1988, using meteorological stations shown in Figure 1. Subsequently, a 3-dimensional mesoscale numerical model (Colorado State University Regional Atmospheric Modeling System - CSU RAMS) was applied to a Squamish Wind event that occurred during the field study period. Some of the numerical modelling results will be shown.

The case presented here, from January 30 to February 2, 1988, was of moderate intensity. Figure 11 is the surface weathermap just before the onset of Squamish Winds in Howe Sound. It shows an Arctic airmass associated with the high pressure centre of central B.C. separated from maritime air by an Arctic front which, at map time, is passing through Howe Sound.

Figure 12 is a vector representation of the modelled winds on January 31 at 16:00 PST showing a well developed Squamish Wind. The flow is down the Cheakamus and Squamish river valleys, and out of the main channel. Notice the increase in speed down the channel, and also the difference in direction and speed of the winds over the high terrain on either side of the Sound compared to the winds near sea level in Howe Sound.

Vertical cross sections of down channel wind component and potential temperature are shown in Figure 13. The cross section is oriented along the main channel (east side) of Howe Sound. The winds below 1 - 2 km are clearly distinct from the winds above this elevation. This is also illustrated by a near neutral layer (shown by the near constant potential temperature in Figure 13b below about 1.5 km elevation which is surmounted by a layer of increased stability (shown by a rapid increase in potential temperature). Since the potential temperature contours are isentropes, the flow in the plane of the vertical cross section parallels them. In the southern part of Howe Sound (near coordinates -140 to -165 in Figure 13) there is a layer of descending air which corresponds to a region of maximum surface winds. This layer then increases its thickness (near coordinate -165 in Figure 13) and the surface winds decrease. This is analogous to the transition from subcritical to supercritical flow in hydraulic theory. The increase in thickness of the Squamish Wind, and decrease in velocity is analogous to a hydraulic jump.

The Squamish Winds are a strongly forced (by both synoptic conditions and topography) meso-scale phenomenon with considerable spatial variability, the small scale details of which appear to be analogous to hydraulic flow of water in a channel.

CONCLUSIONS

The topography of Howe Sound results in some fascinating local modifications to regional weather, making its climate distinct from that of neighbouring areas. Some of these modifications, which are summarized in Figure 2, have been discussed. These include enhanced sea and land breezes during the summer, enhanced precipitation over higher terrain, and Squamish Winds during the winter.

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Suckling, P.W. 1977. Solar radiation in British Columbia. University of British Columbia, Ph.D. Thesis.

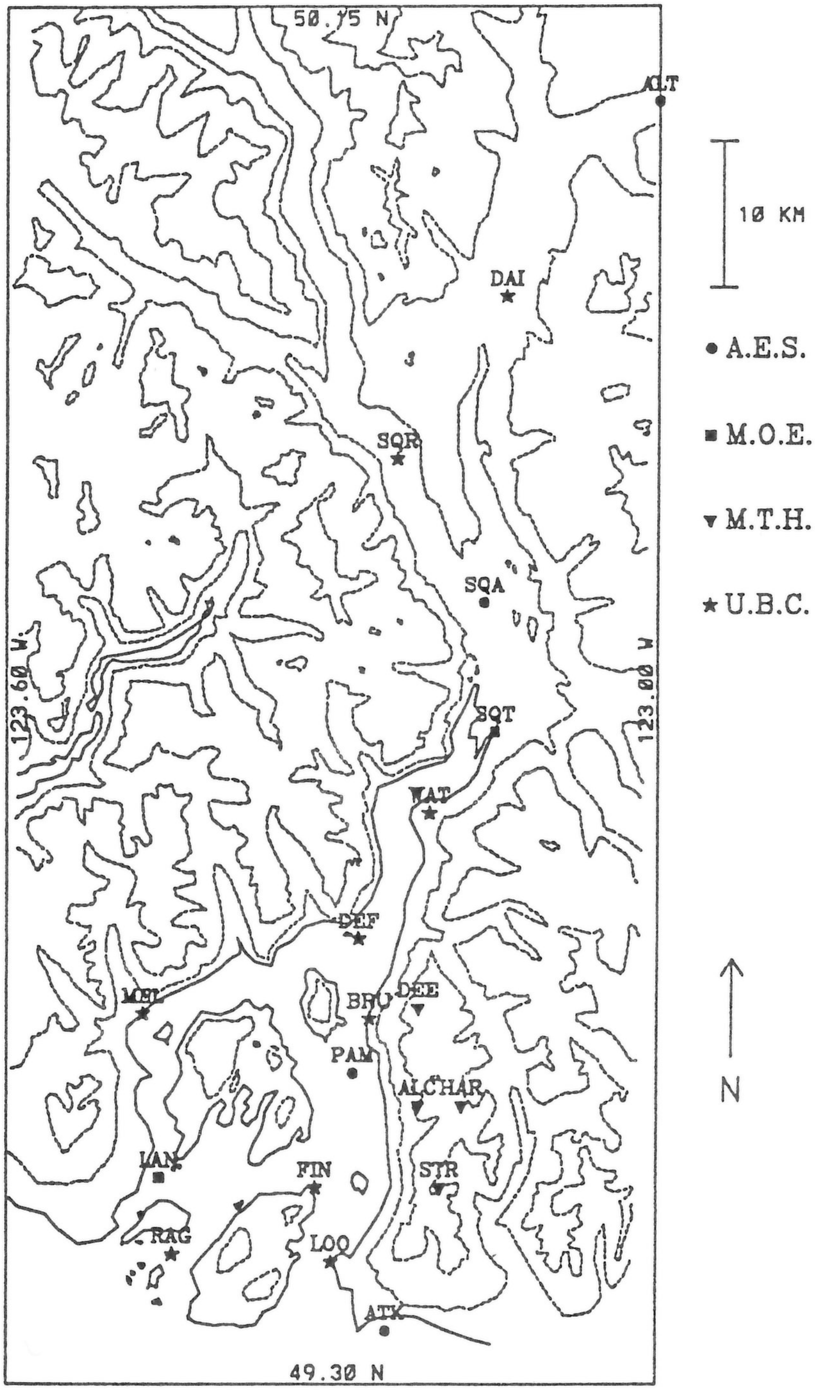

Figure 1. Map of Howe Sound showing topography and locations of meteorological stations used in a study of Squamish winds. Contours are at 300, 900, and 1,800 m.

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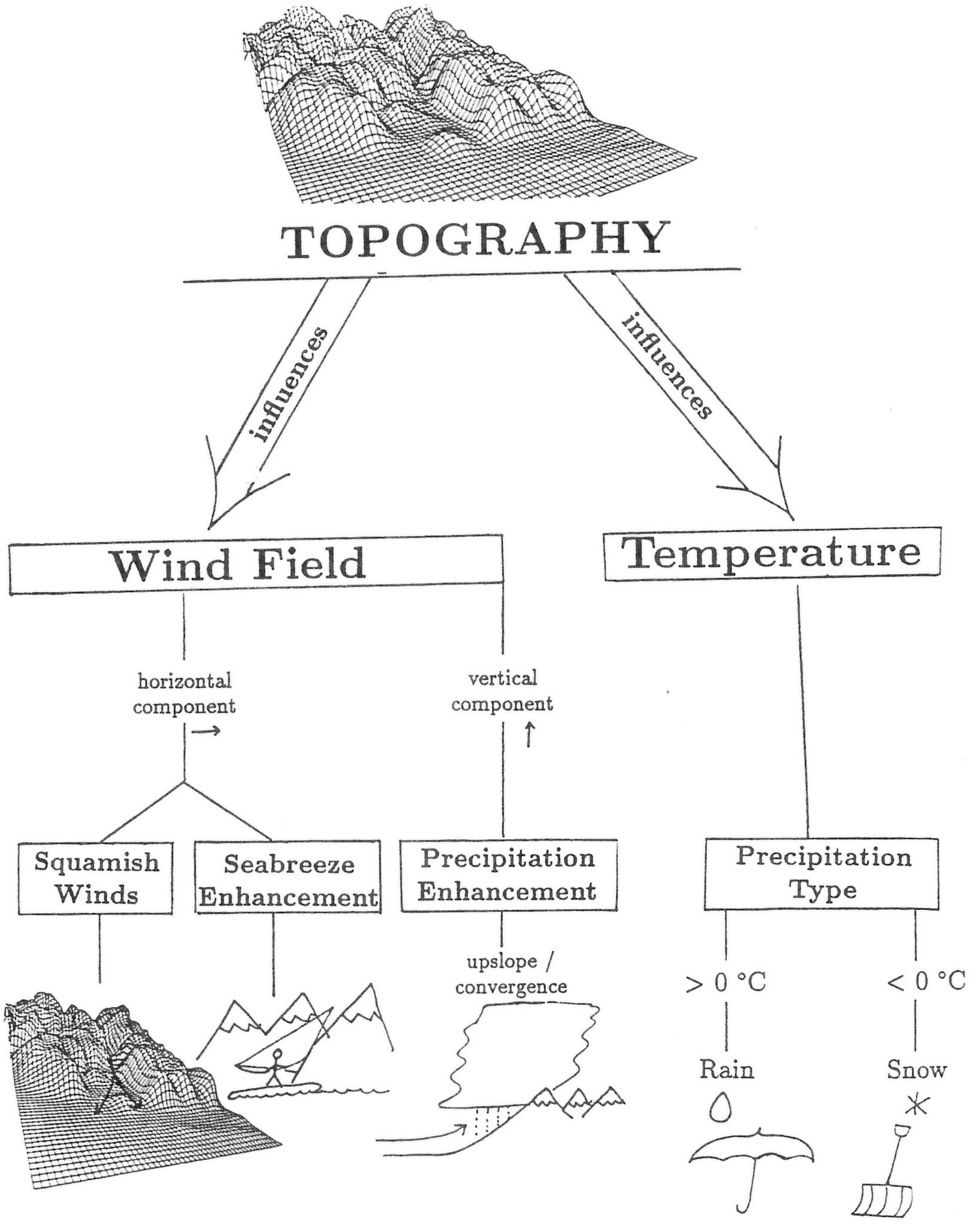

Figure 2. Schematic diagram illustrating some of the more interesting topographic modifications to regional weather patterns in Howe Sound.

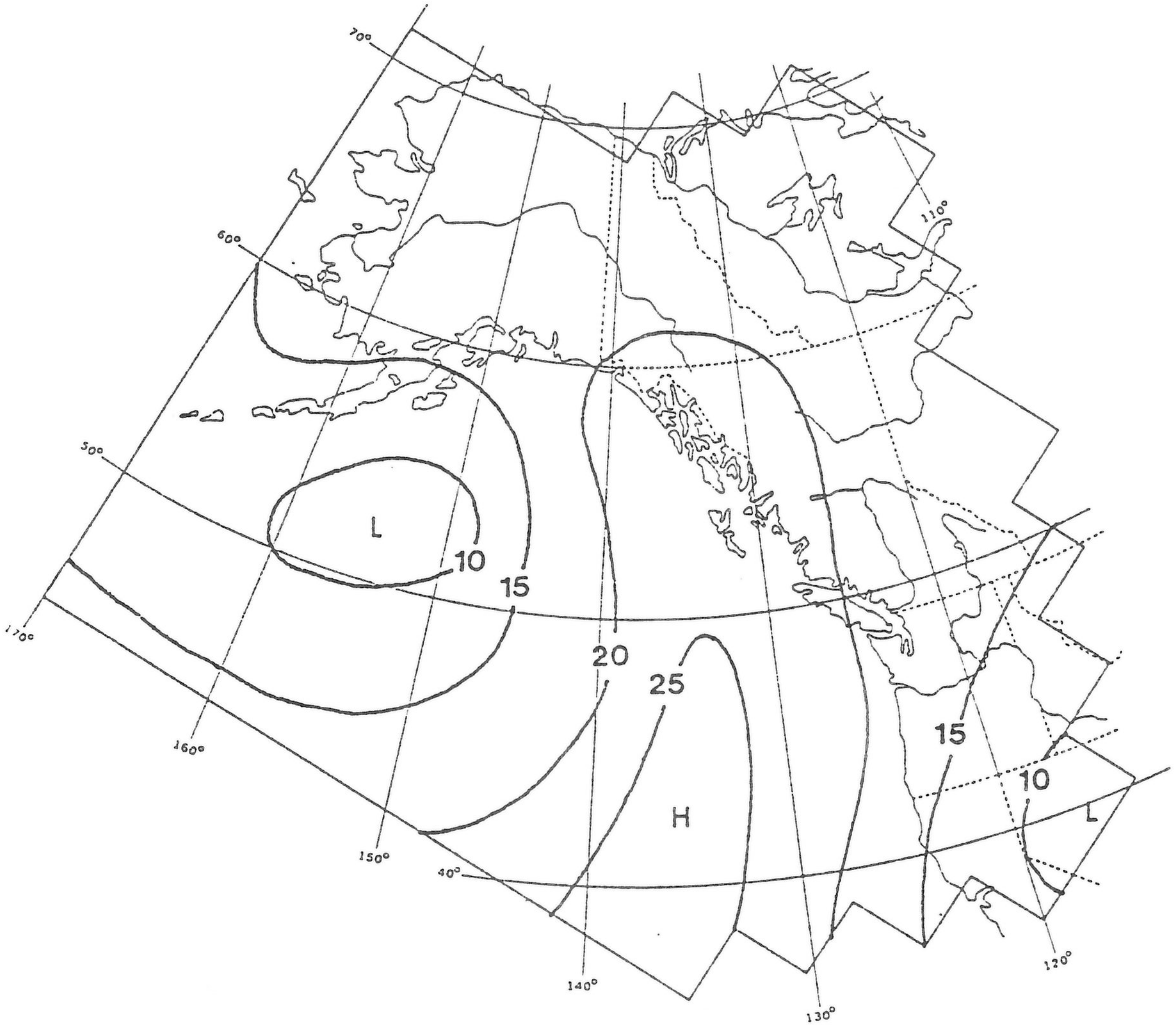

Figure 3. 100 Kpa weather map from July 23, 1968 illustrating Ridge synoptic type, from Suckling (1977). This is a typical summer fair weather pattern allowing seabreeze development.

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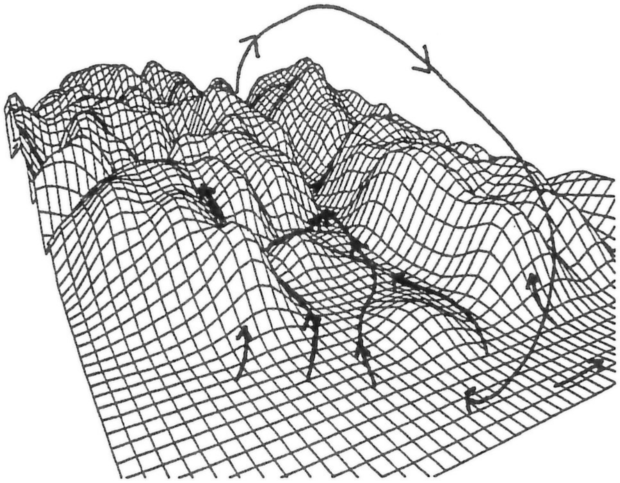

Figure 4. Schematic depiction of seabreeze circulation in Howe Sound. View is from the southsouthwest looking up Howe Sound. Vertical exaggeration of the topography is 10.

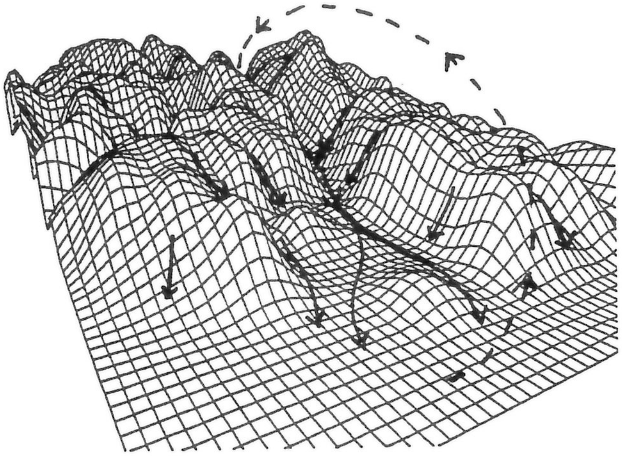

Figure 5. Schematic depiction of landbreeze circulation in Howe Sound. View is from the southsouthwest looking up Howe Sound. Vertical exaggeration of topography is 10.

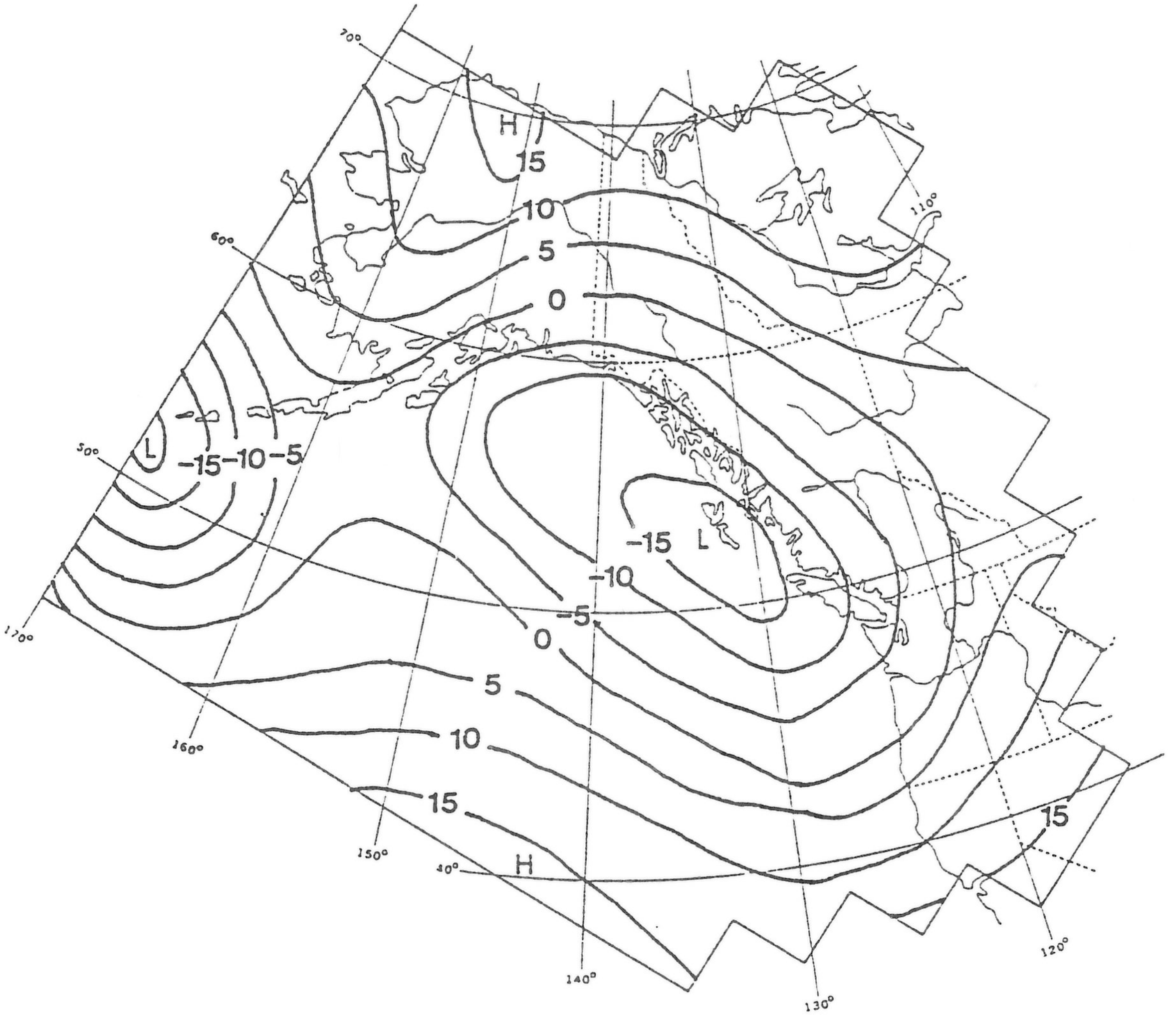

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Figure 6. 100 kPa weather map from December 29, 1970 illustrating Ocean Low synoptic type, from Suckling (1977). This is a typical winter weather pattern bringing precipitation to B.C.

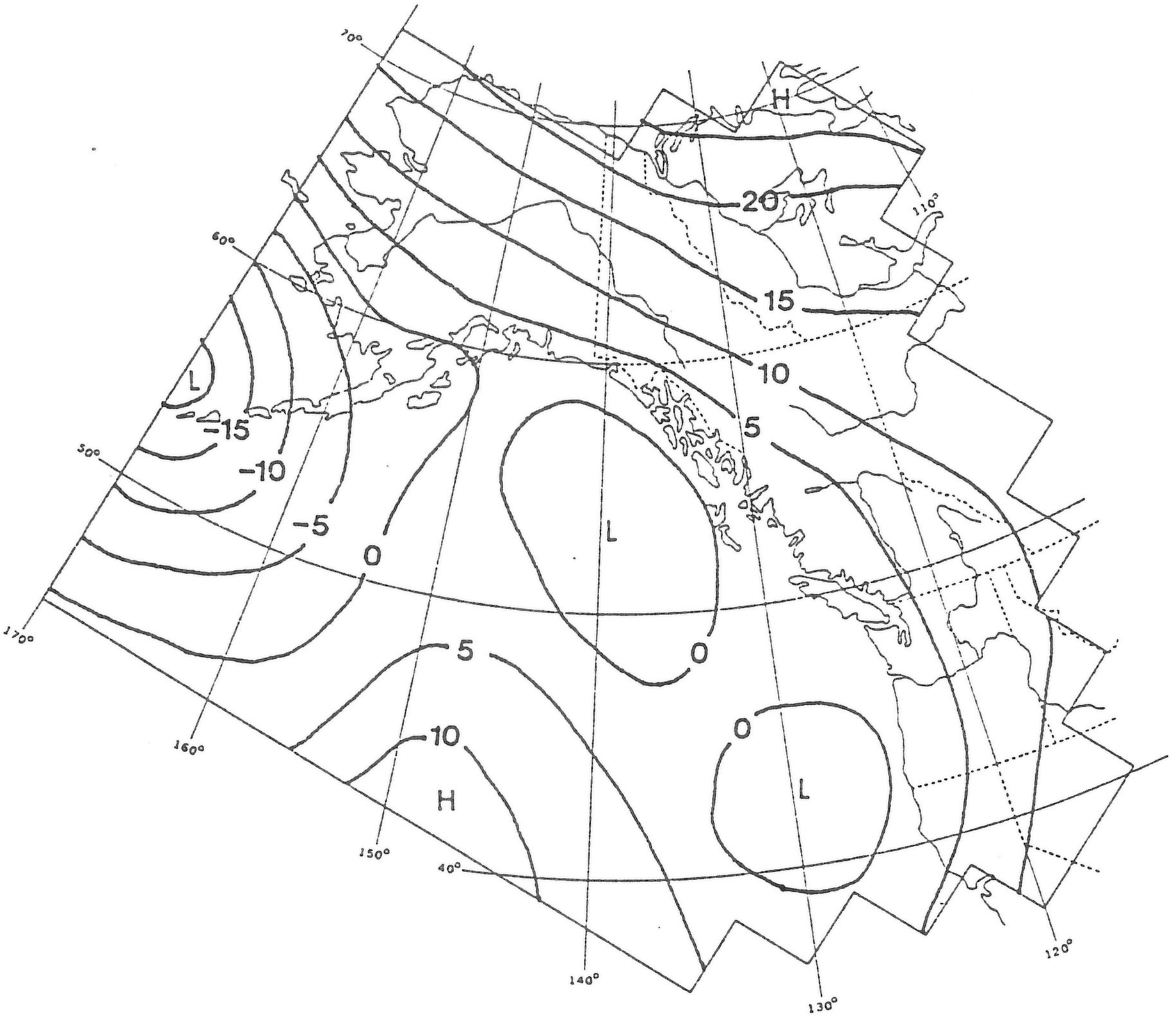

Figure 7. 100 pKa weather map from January 30, 1966 illustrating Trough synoptic type, from Suckling (1977). This is a typical winter weather pattern which could develop into a "Squamish Wind" situation.

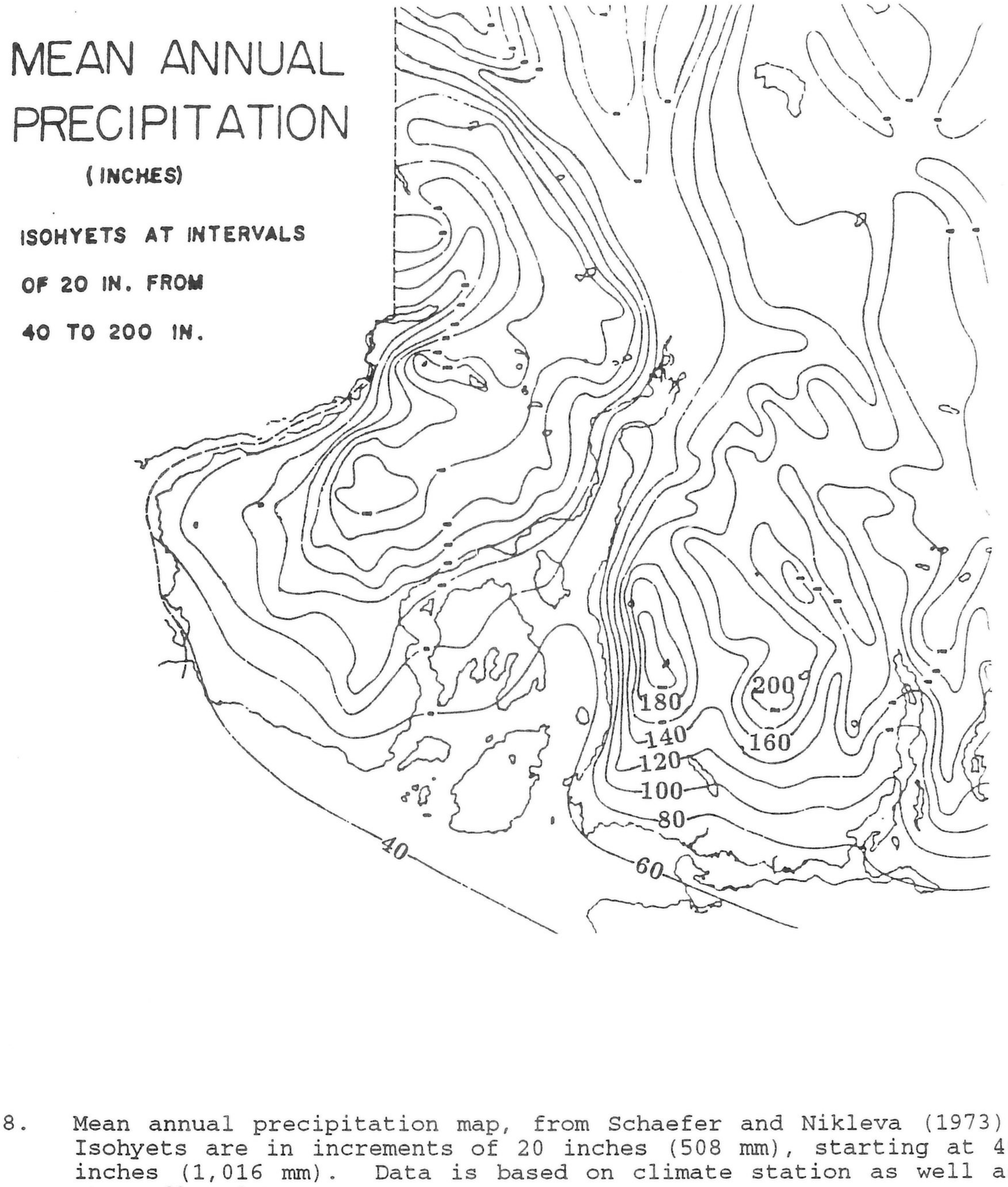

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Figure 8. Mean annual precipitation map, from Schaefer and Nikleva (1973). Isohyets are in increments of 20 inches (508 mm), starting at 40 inches (1,016 mm). Data is based on climate station as well as streamflow data.

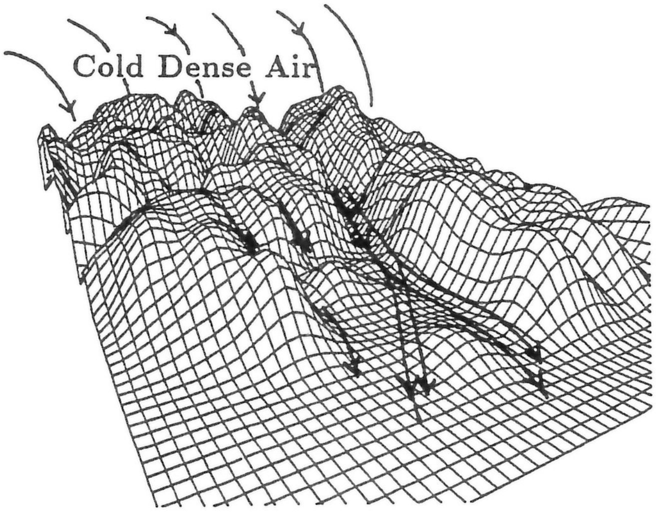


Figure 9. Schematic depiction of Squamish Wind flow in Howe Sound. View is from the southsouthwest looking up Howe Sound. Vertical exaggeration of the topography is 10.

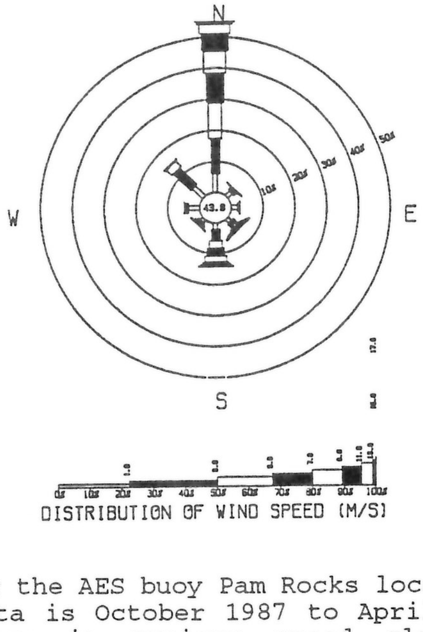
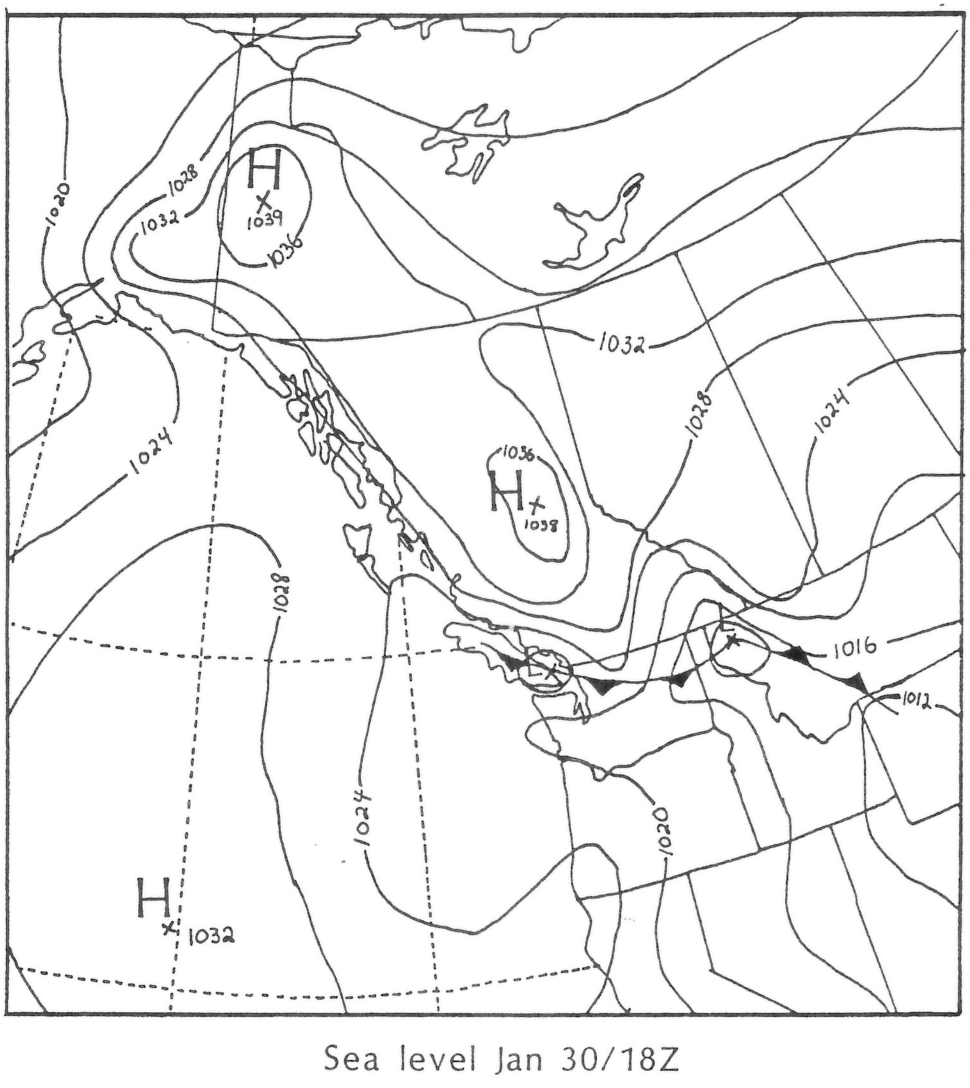


Figure 10. Wind rose for the AES buoy Pam Rocks located south of Anvil Island. Period of data is October 1987 to April 1988. Representation is wind frequency in various speed classes by direction. This bidirectionality of the diagram is a consequence of topographic channelling. The preponderance of northerly winds is due to Squamishes.



Figure

Figure 11. Surface weather map for January 30, 1988 at 10 a.m. PST, just before the onset of Squamish Winds in Howe Sound.

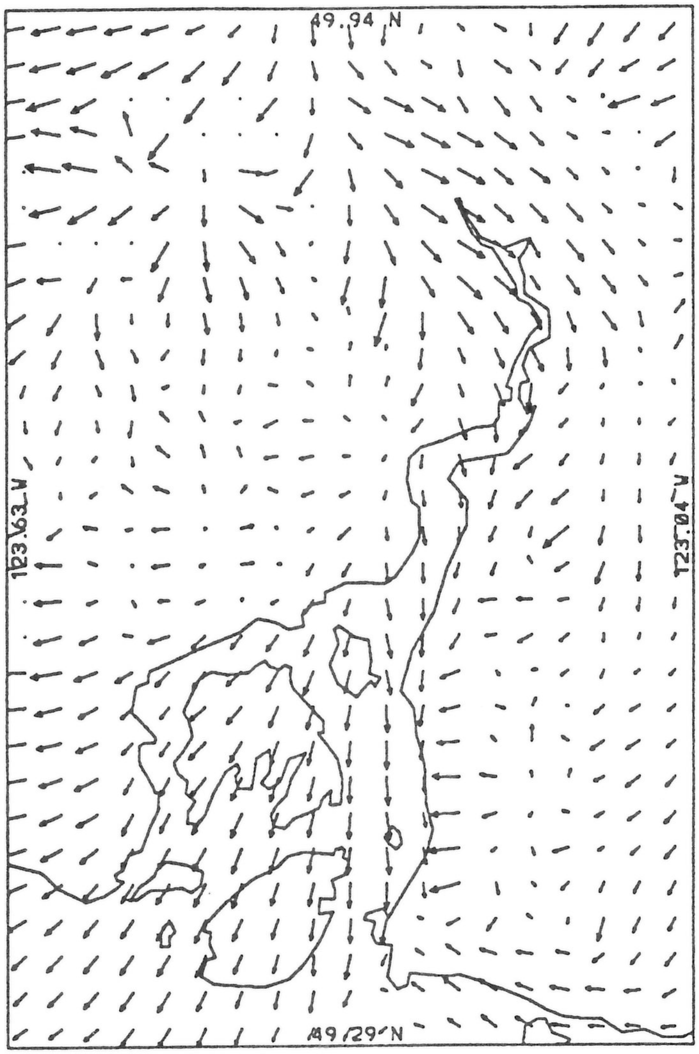


Figure 12. RAMS modelled wind at 16:00 PST, January 31, 1988. Wind represents average speed in the first 100 m above ground at the model atmosphere. The spacing between grid points indicates 14 m/s.

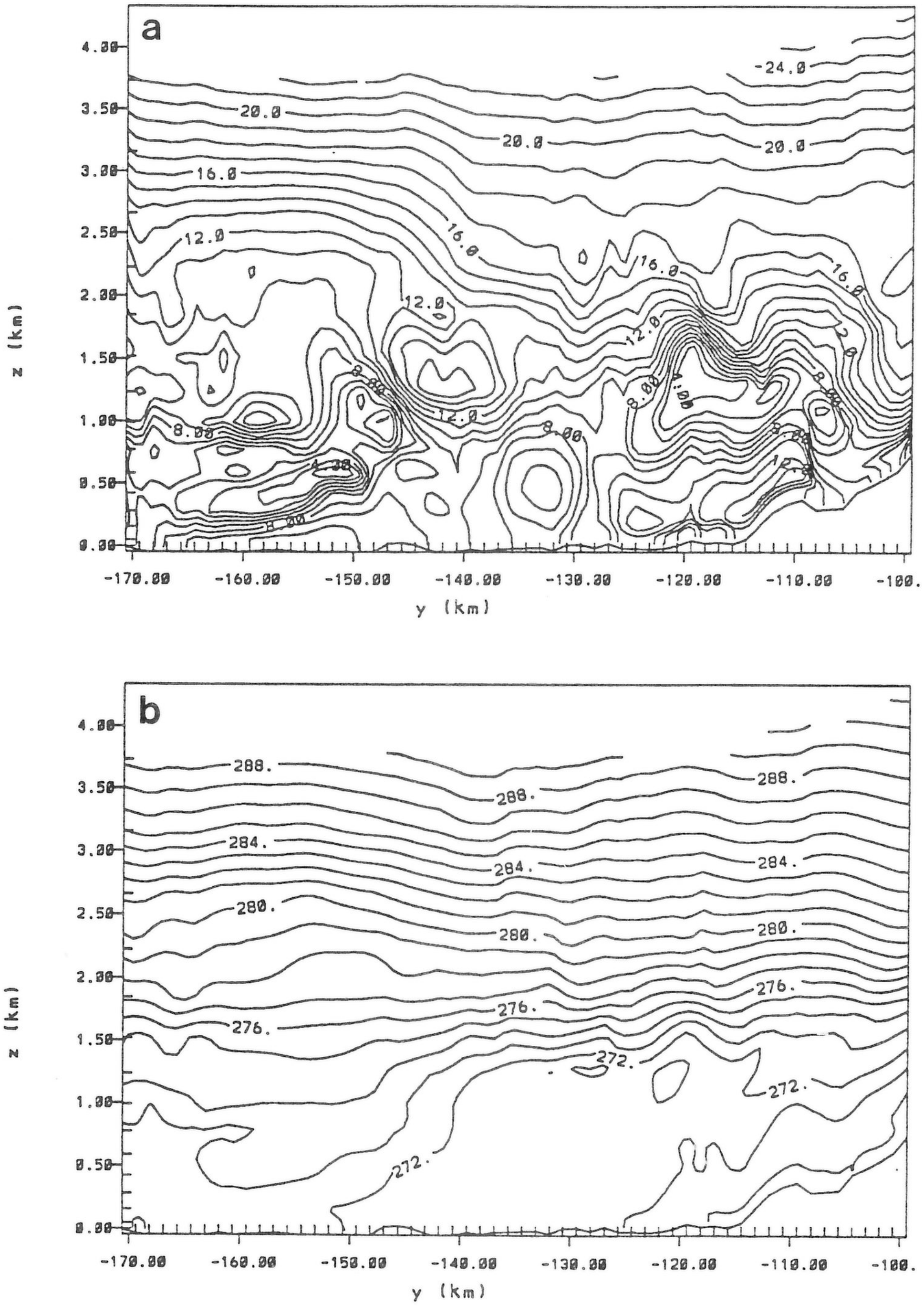


Figure 13. Vertical cross section oriented along the main channel of Howe Sound for January 31, 16:00 PST. The section runs from south on the left, to north on the right. a) Down channel wind component (units are m/s); b) Potential temperature (units are °Kelvin).

VOLCANISM IN THE HOWE SOUND DRAINAGE BASIN: HAZARDS FROM THE GARIBALDI VOLCANIC BELT

by

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ABSTRACT

The Howe Sound Drainage Basin is part of the geologically dynamic west coast of North America; the result of subduction of the Juan de Fuca Plate under Vancouver island. As a consequence of subduction, the region is subject to volcanism and earthquakes. A chain of volcanoes extend northward from California (the Cascade Volcanoes) into British Columbia where they are referred to as the Garibaldi Volcanic Belt (GVB). The GVB consists of three major strato-volcanoes; Mount Garibaldi (just north of Squamish), Mount Cayley (25 km west of Whistler), and Mount Meager (just north the drainage divide), and other smaller, less voluminous centres.

Volcanism in the GVB started some 3 million years ago and eruptions have continued into the Holocene Epoch (the last 10,000 years). The most recent well documented event, a Pelean eruption from Mount Meager, about 2,300 years ago, blocked the Lillooet River and spread ash across southern B.C. into Alberta. The geological record of lava flows and volcanic debris suggests that both basaltic eruptions, and infrequent violent explosive eruptions, may both occur in the future. Small basaltic eruptions may have little or no warning; explosive eruptions usually have associated earth tremors that will be detected on the regional seismic network. Subduction continues and with it, the potential for future volcanic eruptions.

A continuing hazard in the GVB is posed by the extreme relief of many vent areas and the unstable nature of volcanic deposits. The loose, unconsolidated nature of many of the deposits leads to sediment loading in surrounding drainages and leaching of more soluble elements into the groundwater. Landslides and debris flows from these volcanoes pose a very real threat. Landslides from Mount Cayley (Dusty Creek slide) and the "Barrier" blocked the Squamish and Cheakamus rivers during the 1800's. Debris flows originating on steep volcanic slopes have much greater run out distances than those generated in nonvolcanic areas. When human development is pushed into these drainages, this hazardous aspect of the volcanoes must be taken into consideration during planning.

INTRODUCTION

Canada has been spared the almost ceaseless volcanism characteristic of such places as Hawaii, Japan, or Indonesia, but it has not escaped completely. We are part of a continuous line of subduction zones and transform faults that encircle the Pacific Ocean. Our global position on this dynamic sphere, earth, gives rise to volcanoes, some of which lie along the axis of Howe Sound. These are the volcanoes of the Garibaldi Volcanic Belt (GVB) which is a continuation of the Cascade Volcanoes that extend northward from Lassen Peak in northern California to Mount Baker, just south of the Canadian border (Fig. 1). These volcanoes originate due to subduction (the process whereby oceanic crust is consumed beneath continental crust producing volcanoes and earthquakes) off the west coast of North America.

The short-term threat of a volcanic eruption occurring is low. As near as can be determined, return eruption intervals for the Garibaldi Belt are very long -- specific, individual centres may never erupt again. However, there has been significant volcanism in the geologically recent past and subduction continues to the present day. Within the belt, volcanism has not been concentrated at individual stratovolcanoes as is the case to the south, rather volcanism has occurred at centres that are closely spaced. Eruptions in the future may occur in close proximity to existing centres, but will probably not be coincident. Determining the details of the eruptive history of the Garibaldi Belt is a challenge that awaits further work.

Debris flows and landslides will pose the greatest short-term threat to downslope and downstream communities. The volcanoes are regions of rugged relief and unstable rock. Numerous rock avalanches and debris flows have been documented from all of the areas and these events will continue to pose a threat into the future.

VOLCANIC HAZARDS

Volcanoes, when they erupt, produce a number of hazardous events (Table 1). What hazard will occur at which volcano will depend to large degree on the composition of the erupting magma (Table 2). Basaltic eruptions (basaltic magmas are low in silica, an essential building block element of minerals) pose a minimal hazard in comparison with explosive felsic eruptions (felsic or the older term "acid" magmas are high in silica). Similarly, an andesitic eruption is less hazardous than a dacitic one but a number of caveats must be applied. Basaltic eruptions occurring during winter months in regions of heavy snow pack, such as Howe Sound, could produce devastating debris flows (lahars) or floods from rapidly melting snow.

Hazards from the eruption of intermediate to high silica content magmas (called Dacite and Rhyolite) can be moderate to extreme, depending on the size of the eruption. The size of an eruption is quantified using a scale called the Volcanic Explosivity Index (VEI; Newhall and Self, 1982). The VEI takes into consideration the volume of eruptive products, height of eruption cloud, duration of the main eruptive phase, and other parameters to assign a number from a linear, 0 to 8 scale. The May 18, 1980 eruption of Mount St. Helens, which destroyed 632 km^2 of land, expelled 1.4 km^3 of magma (dense rock equivalent, or DRE) and produced an eruption column which peaked at an altitude of 24 km, had an VEI of 5. Table 3 gives a listing of the VEI of some noticeable volcanic eruptions in relationship to the loss of life. It can be seen that the actual size of the eruption does not have a direct relationship to the number of lives lost; however, it is directly proportional to the economic losses sustained by the region.

VOLCANIC RISK

Erupting volcanoes only become a risk when there is something valued that may be destroyed -- either lives, property, or resources. Risk is usually assessed on the basis of the number of human lives which may be lost as a result of a hazardous event (Morgan, 1992). But, in actual fact, natural disasters throughout history have taken only a small fraction of the lives that have been lost in armed conflict. In 1,000 years of record keeping, volcanoes have taken less than 300,000 lives (Tilling, 1989).

Yokoyama et al. (1984) devised a method for assessing risk at a volcano (Table 4). High risk volcanoes "score" 10 or above. Using this scheme and our present knowledge level, no Canadian volcano falls into the high risk category. Growing populations, however, increase the risk posed by volcanos both here and abroad. For example, Mount Ruiz, Colombia, was not considered a high risk volcano, yet its eruption on November 13, 1985 killed 25,000 people -- the greatest volcanic disaster since the eruption of Mount Pelée at the turn of the century. A poignant point brought out in Voight's (1990) retrospection of this event was the observation that in 1845, a similar event wiped out 1,400 people -- all those that lived in the town at that time. In 1985, 30,000 people now lived in the same area and repeat of the 1845 event resulted in an order of magnitude escalation in the loss of life. In a similar vein, the Philippine volcano of Mayon produced pyroclastic flows during its 1814 eruption which killed 1,200 people -- 800,000 people now live in the same area (Voight, 1990).

GARIBALDI VOLCANIC BELT

The Garibaldi Volcanic Belt is the northward extension of the Cascade volcanoes. This chain of major andesitic to dacitic strato-volcanoes extends northward from northern California to British Columbia (Fig. 1). In Canada, the major volcanic edifices which make up the chain are mounts Garibaldi, Cayley, and Meager (Fig. 2). Composition of the magmas erupted in this region range from basalt to rhyolite. The arc appears to be segmented (Guffanti and Weaver, 1988; Sherrod and Smith, in press); the central portion is the most active (Scott, 1990) and the northern end least active (Sherrod and Smith, in press). Scott (1990) tentatively identified periods during which the entire arc appears to have been active during the last 15 ka.

The major edifices of the GVB and associated volcanoes which make up areas referred to as volcanic fields (Fig. 2), have been sporadically active over a time span of millions of years (Fig. 3). Mount Garibaldi (Fig. 4), one of the three major strato-volcanoes that make up the GVB, is the closest major explosive vent to the Sound. The edifice was built in several explosive (Pelean) phases during the waning stages of the last ice age (Mathews, 1952). These explosions built blocky, unconsolidated material up around the vent area and out onto the surrounding sheet of thick glacial ice. As the ice receded, the cone collapsed leaving the steep (600 m) front seen today. The faint layers that can be seen in this steep face are the layers of ash and blocks, some blocks of which are up to 6 m in diameter. This material readily landslides in addition to contributing enormous amounts of sediment to debris flows originating on the volcano's slopes. This debris built up Cheekeye Fan and continues to contribute to debris flows and rock failures.

The most recently documented eruption in the GVB was about 2,300 years BP at Mount Meager (Fig. 5), 50 km northwest of Pemberton. This eruption was very violent and may have been close in size to that of the May 18th, 1980 eruption of Mount St. Helens. Ash from this 2,300 year old event at Mount Meager can be traced as far east as western Alberta (Fig. 6). It has been recently suggested that some postglacial landslides and debris flows in the vicinity of Mount Cayley (Evans, 1990) and Mount Meager (Jordan and Bovis, pers. comm., 1991) may have been volcanically triggered; if true, it would indicate that the belt is more active than presently thought.

A number of studies address volcanism in the Garibaldi Volcanic Belt. Among these are work by Mathews (1952, 1958), Green (1981, 1990), Green et al. (1988), Souther (1980), Read (1978, 1990), and Stasiuk and Russell (1989, 1990). However, detailed physical volcanology studies have not been the principal focus of most of this work. Understanding eruptive processes and timing at individual volcanic complexes remains to be addressed. All of these studies have identified eruptive periods. (An eruptive period is "a single eruption or series of eruptions closely spaced in time at a volcano...that yield a preserved deposit and are differentiated from preceding and subsequent eruptive periods by one or more of the following criteria: (1) separated by an apparent dormant interval of decades to centuries, (2) distinguished by a change in vent location, and (3) marked by a distinct compositional change in eruptive products." [Scott, 1990].) These eruptive periods are compiled from Green et al. (1988) and shown diagrammatically in Figure 3.

Long repose periods, up to several thousand years, between major explosive events at the major volcanoes, appears to typify the Canadian portion of the arc. Mathews (1958) has also suggested there may be a causative link between glacial loading of the crust during ice ages and increased rates of volcanism in the Garibaldi belt.

However, this long history, coupled with continued subduction off the coast, suggests we have not seen the last of volcanism in the Garibaldi belt. Hot springs in the vicinity of mounts Cayley and Meager suggest that magmatic heat is still present. Recent seismic imaging from Geological Survey of Canada supporting Lithoprobe studies in the region of Mount Cayley produced a 'bright spot' which may be attributable to a magma chamber at approximately 15 km depth (R. Clowes, University of British Columbia, pers. comm., 1990).

In addition to possible future volcanic eruptions, the Garibaldi Volcanic Belt poses a considerable threat in the form of large rock failures (Evans, 1990; Clague and Souther, 1982; Read, 1981) and catastrophic debris flows (Jordan, 1990). The volcanoes are extremely rugged regions of high relief underlain by unstable, poorly consolidated and/or strongly jointed volcanic rocks. These conditions have already led to a number of failures and debris flows. Comparable debris flows generated in volcanic areas have much greater run out distances than those generated in nonvolcanic areas, in part, because of a greater percentage of fine material in "volcanic" debris flows (Jordan, 1990). These factors must be taken into consideration before any development in the vicinity of the volcanoes.

The volcanoes, by virtue of the composition and physical attributes of the rocks which compose them, are much more susceptible to weathering than the surrounding "granitic" rocks. Weathering leads to increased particulate matter in streams draining the edifices and higher concentrations of certain elements easily leached by percolating groundwater. Because of these attributes, streams draining volcanic areas may have significantly different trace element chemistry than nearby streams draining other regions underlain by more chemically stable rock types.

CONCLUSIONS

The Howe Sound Drainage Basin is blessed with some of the most spectacular scenery in the world -- but we must not forget this scenery owes its origins to cataclysmic events in the earth's interior. Uplift, mountain building, earthquakes, and volcanoes are all part of our heritage. Although we have been spared continuous volcanism on a human time frame, we have not on a geological one. We must try to look beyond the short recorded history of the human species when we are dealing with geologic hazards which have recurrence intervals longer than 50 years. Hazard zonation and planning must be an integral part of our future if we are to save lives and property. Detailed geological work at specific volcanoes that potentially threaten populations would help quantify the risk from future eruptions, rock failures, and debris flows. This work should be carried out before rezoning or major shifts in population occur. We may not see an eruption in this region in our lifetime, but we may -- shouldn't we be prepared?

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Parts of this paper were prepared and presented at the Geologic Hazards Workshop - 1991, University of Victoria, February 20-21, 1991. A longer version of this paper dealing with volcanic hazards throughout British Columbia can be found in the proceedings volume (Hickson, 1991).

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Table 1. Volcanic hazard summary (modified from Blong, 1984; Table 1.4, p. 12).

	Frequency of Adverse Effect/Damage/Death					
	Distance (km)					
	<10	10-30	30-100	100-500	500-1000	>1000
Volcanic hazard[1]						
Lava flows	F	C	VR			
Ballistic projectiles	C					
Tephra falls	VF	F	F	C	R	
Pyroclastic flows and debris avalanches	A	F	R	VR		
Lahars and jokulhlaups[2]	F	F	R	VR		
Seismic activity and ground deformation	C	C	VR			
Tsunami	A	F	C	R	VR	
Atmospheric effects	C	C	R	VR	VR	
Acid rains and gases	F	F	R	R	VR	VR

[1] Hazard level is based on the relative frequency of deaths given that the specific type of activity occurs.

[2] Lahar = debris flow; jokulhlaups = glacial outburst floods.

A = Always; VF = Very Frequent; F = Frequent; C = Common; R = Rare;
VR = Very Rare.

Table 2. General relationships between volcano types, predominant lava, eruption styles, and common eruptive characteristics (from Tilling, 1989; Table 1.1, p. 2).

		Predominant Lava		
Volcano type	Composition	Relative Viscosity	Eruption style	Common Eruptive Characteristics
Shield[1]	Basaltic (mafic)	Fluidal	Generally non-explosive	Lava fountains, lava flow (long) lava lakes and pools
	Andesitic	Less fluidal	Generally explosive but sometimes non-explosive	Lava flows (medium), explosive ejecta, tephra[3] falls
Composite[2]	Dacitic to rhyolitic (felsic)	Viscous to very viscous but can be non-explosive	Typically highly explosive but can be non-explosive, especially after a large explosion	Explosive ejecta, tephra falls, pyroclastic flows and surges, and lava domes

[1] Generally located in the interior tectonic plates ("intraplate") and presumed to overlie "hot spots", but also may occur in other tectonic settings (e.g., Anahim Volcanic Belt, Galapagos, Iceland, Kamchatka).

[2] Generally located along or near the boundaries of convergent tectonic plates (subduction zones); also called strato-volcanoes (e.g., Cascade-Garibaldi Volcanic Belt, Wrangell Volcanic Belt).

[3] Tephra = fragment or "clast" that is ejected from a volcano (includes all class sizes from ash to large fragments).

Table 3. Volcanic Explosivity Index (VEI) of Mount St. Helens and the deadliest eruptions since A.D. 1500 (modified from Tilling et al., 1990; p. 33)

ERUPTION	YEAR	VEI	CASUALTIES
Nevado del Ruiz, Colombia	1985	3	25,000
Mount St. Helens	1980	5	57
Mount Katmai	1912	6	0?
Mont Pelee, Martinique	1902	4	30,000
Krakatau, Indonesia	1883	6	36,000
Tambora, Indonesia	1815	7	92,000
Unzen, Japan	1792	3	15,000
Lakagigar (Laki), Iceland	1783	4	9,000
Kelut, Indonesia	1586	4	10,000

Table 4: Proposed criteria for identification of high-risk volcanoes (from Yokoyama et al., 1984). A score of 1 is assigned for each rating criterion that applies; 0 if the criterion does not apply.

HAZARD SCORE		SCORE
1)	High silica content of eruptive products (andesite/dacite/ rhyolite)	
2)	Major explosive activity within last 500 yr	
3)	Major explosive activity within last 5,000 yr	
4)	Pyroclastic flows within last 500 yr	
5)	Mudflows within last 500 yr	
6)	Destructive tsunami within last 500 yr	
7)	Area of destruction within last 5,000 yr is >10 km^2	
8)	Area of destruction within last 5,000 yr is >100 km^2	
9)	Occurrence of frequent volcano-seismic swarms	
10)	Occurrence of significant ground deformation within last 50 yr	
RISK RATING		
1)	Population at risk >100	
2)	Population at risk >1,000	
3)	Population at risk >10,000	
4)	Population at risk >1 million	
5)	Historical fatalities	
6)	Evacuation as a result of historical eruption(s)	
		TOTAL SCORE

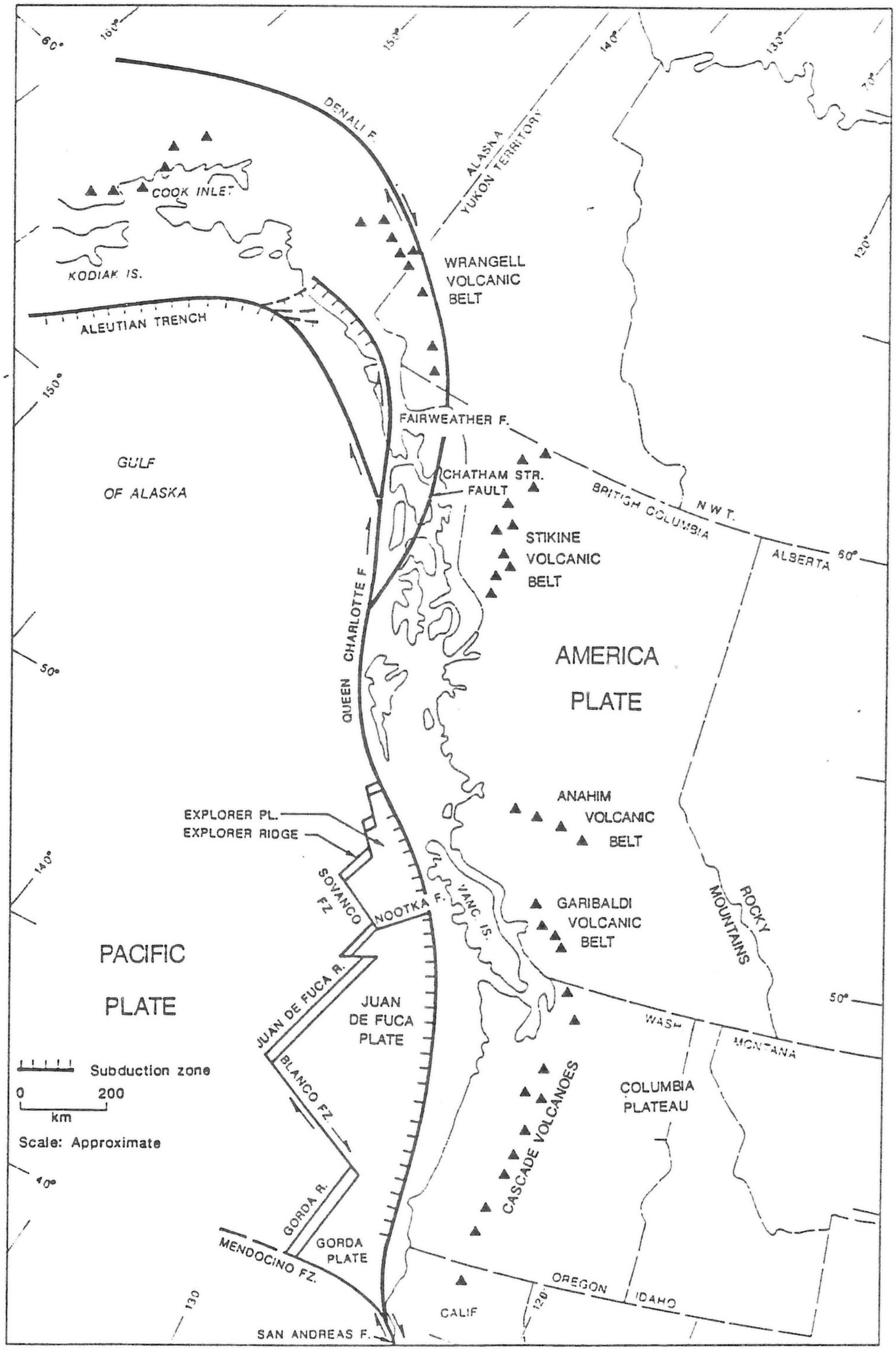

Figure 1. Major tectonic structural elements and volcanic belts, California to Alaska.

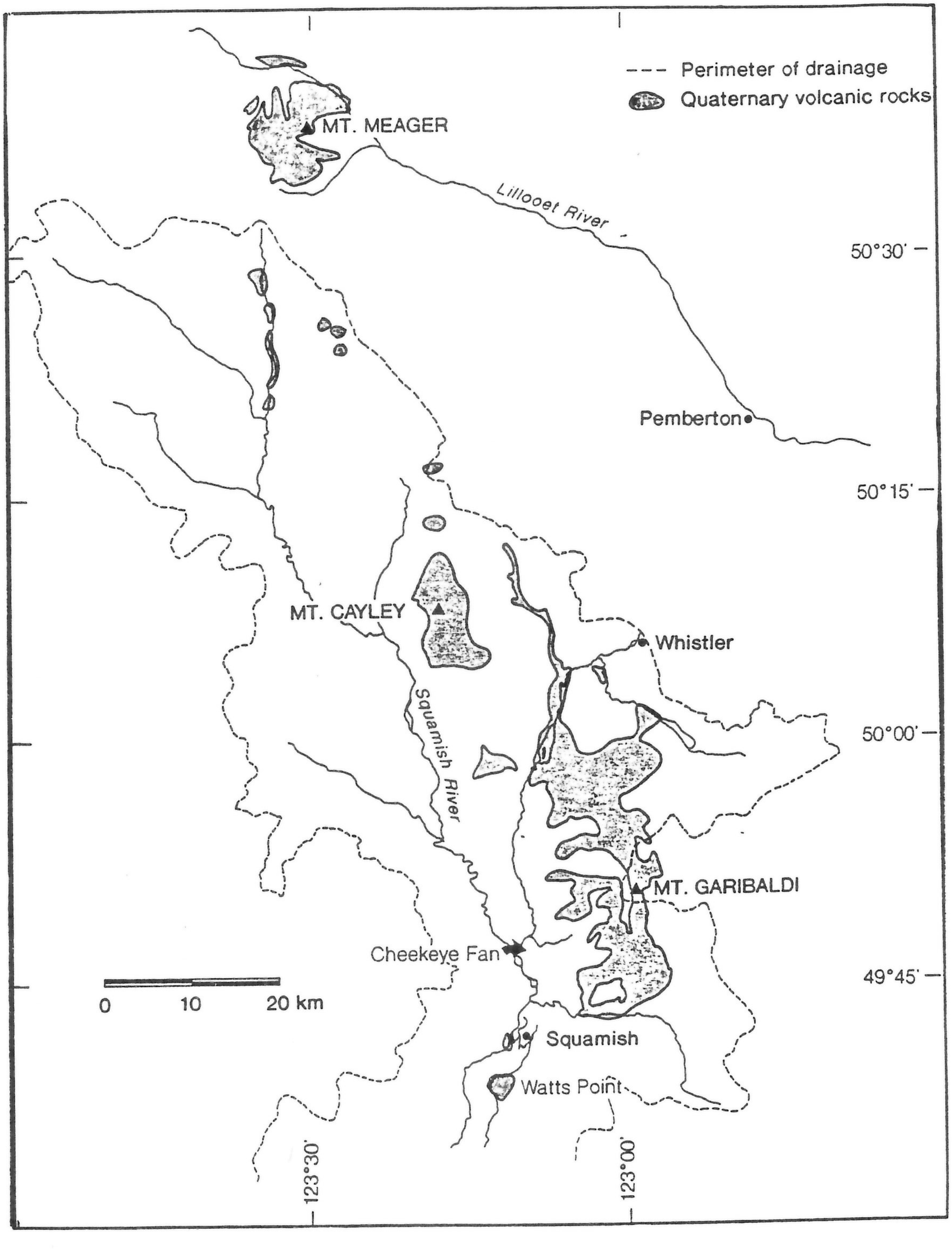

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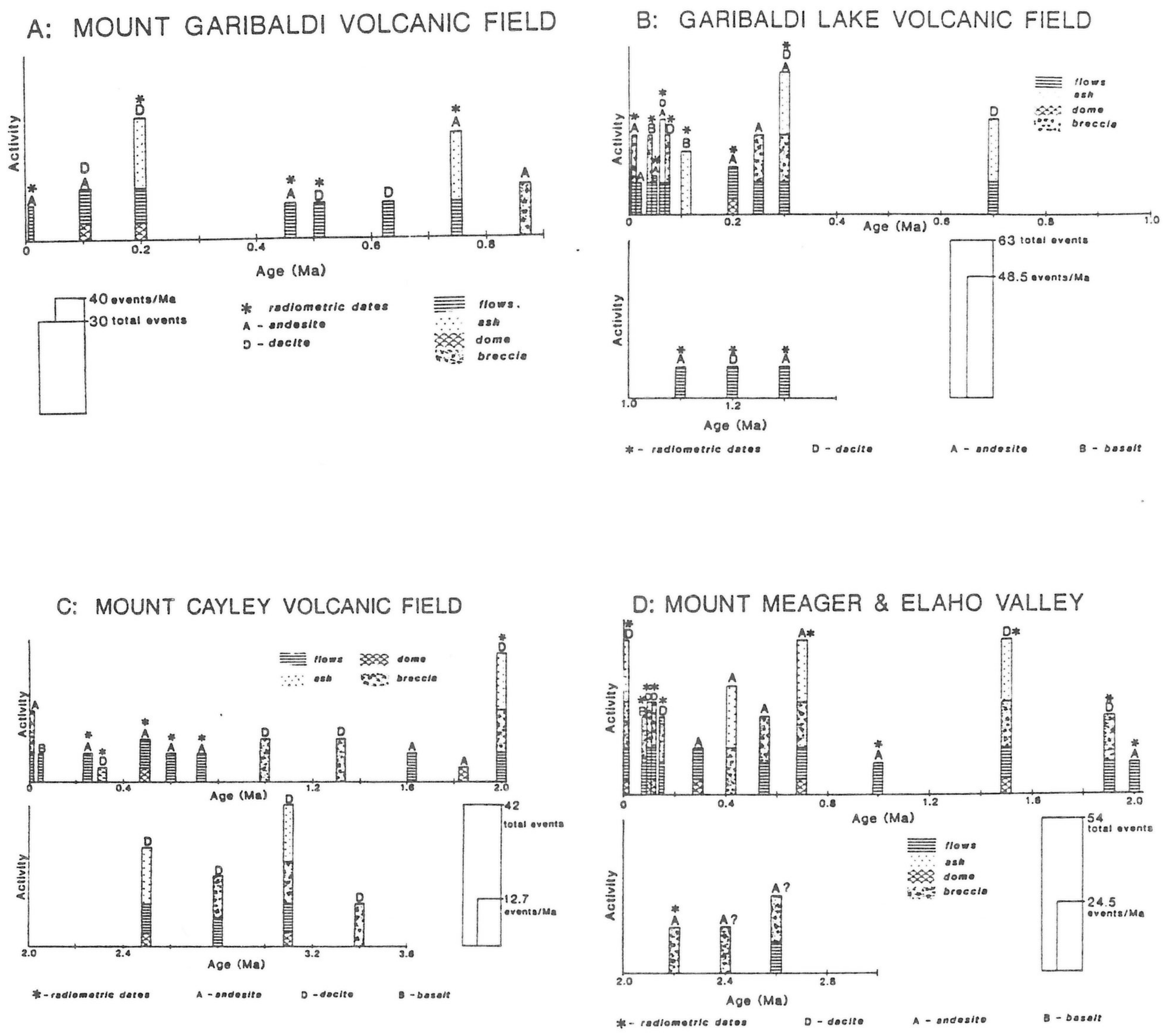
Figure 2. Simplified geological map of the Howe Sound Drainage Basin showing areas of Quaternary volcanic rock and the major volcanoes.



A: MOUNT GARIBALDI VOLCANIC FIELD

B: GARIBALDI LAKE VOLCANIC FIELD

C: MOUNT CAYLEY VOLCANIC FIELD

D: MOUNT MEAGER & ELAHO VALLEY

Figure 3. Diagrammatic representation of eruptive activity at Mount Garibaldi, Garibaldi Volcanic Field, mounts Cayley and Meager. Height of the histogram gives a very crude indication of the size of the eruption.

Figure 4. Mount Garibaldi and associated volcanoes, looking southward from Black Tusk, another volcano in the region.

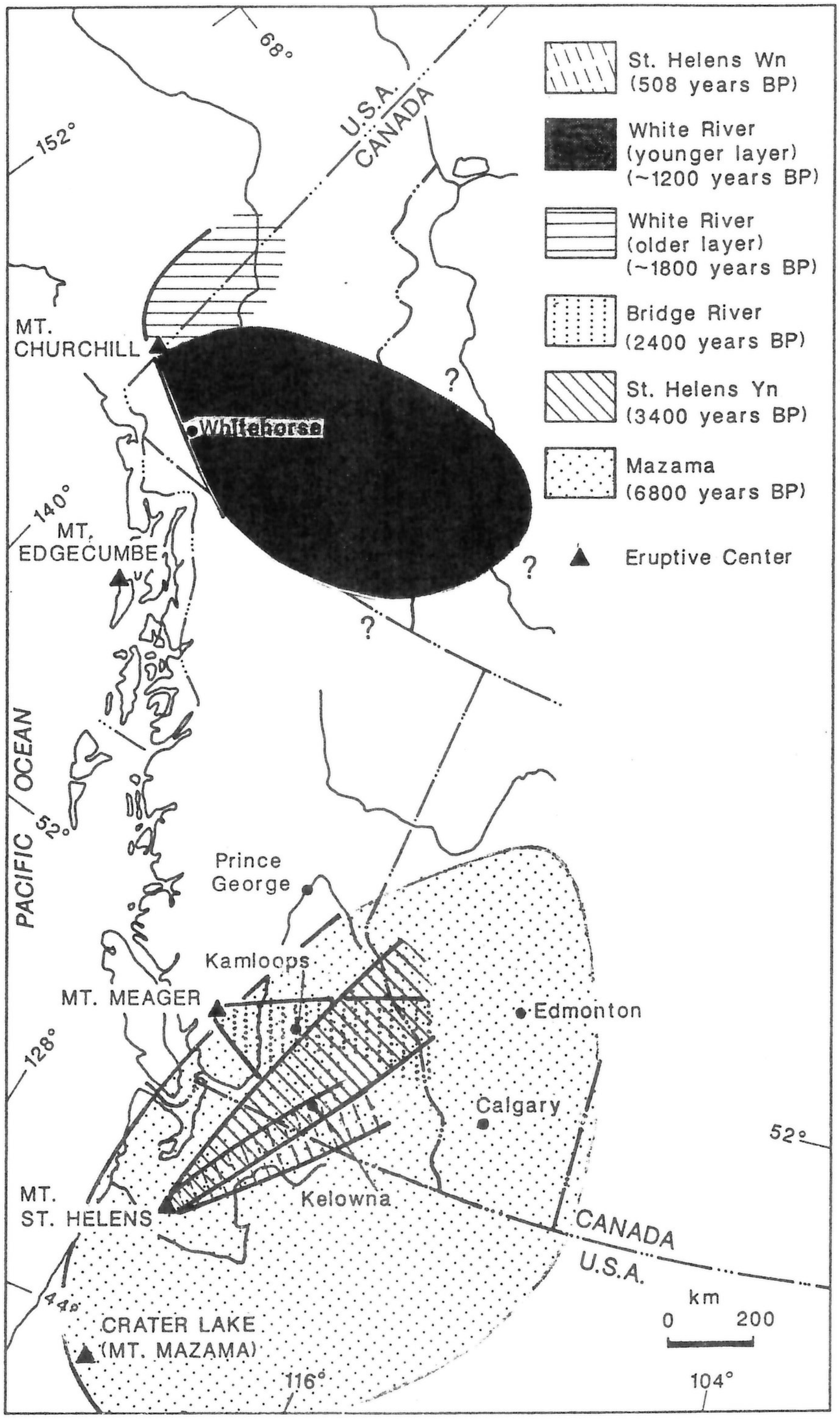


Figure 5. Current known distribution of Holocene tephras in the Canadian Cordillera.

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Figure 6. Vent area of the eruption from Mount Meager 2,300 years ago. Crater is 1.5 km wide at the rim.

INFLUENCE OF GEOLOGY ON METAL CONCENTRATIONS WITHIN THE HOWE SOUND WATERSHED

by

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ABSTRACT

Since 1976, the Geological Survey Branch of the British Columbia Ministry of Energy, Mines and Petroleum Resources have conducted regional (1 sample per 12 km^2) geochemical drainage surveys. These surveys presently cover approximately 65% of the province and involve the systematic collection, preparation, and chemical analysis of sediments and waters from first or second order drainages. Although primarily used by the mineral exploration industry to locate mineralized districts and individual mineral deposits, they have also been employed for delineating regional geochemical patterns throughout the province and as baseline information for environmental studies.

Primary and secondary streams of the Howe Sound drainage basins were sampled in 1981 and 1989 as part of two larger surveys covering NTS 1:250,000 scale mapsheets 92J and 92G. Results from these surveys indicate that statistically significant differences in copper and other metal concentrations exist between major geological units within the basin. These variations should be taken into account when establishing values for 'natural' levels of metals in the environment.

INTRODUCTION

The Geological Survey Branch of the British Columbia Ministry of Energy, Mines and Petroleum Resources has been involved in regional geochemical sediment and water surveys since 1976. The database represents multi-element (up to 35 metals) determinations and field observations of reconnaissance stream sediment and water sampling of first or second order streams from 41 1:250,000 National Topographic System (NTS) map sheet areas (Fig. 1). To date, over 1.3 million analytical determinations have been performed on 38,000 drainage sediment and water samples covering an area of 470,000 square kilometres at an average density of 1 sample per 12.6 km^2. These data are available on a 1:250,000 NTS mapsheet basis in digital and map format.

Although primarily used by the mineral exploration industry for outlining areas of high mineral potential or locating new mineral deposits, survey data are increasingly used to provide an estimate of background metal concentrations and to delineate regional geochemical patterns important for land use and environmental studies. Studies have shown (Day and Matysek, 1989; McMillan et al., 1990) that estimates for background metal concentrations in sediments and resultant regional geochemical patterns often reflect the underlying geology within the drainage basin. The objectives of this study are to illustrate the influence of different rock formations on mean metal concentrations within the Howe Sound watershed.

GEOLOGY

The Howe Sound watershed is predominantly underlain by granitic rocks (quartz diorite and granodiorite) ranging from Middle Jurassic to Middle Cretaceous in age (Monger, 1990). Isolated roof pendants of Jurassic to Cretaceous age metamorphosed volcanic and/or sedimentary rocks (Gambier Group, Cheakamus Formation, diorite and migmatite) occur throughout the study area. Quaternary age volcanic rocks of the Garibaldi Group mantle these older rocks and are especially prevalent in the Mt. Garibaldi area. Valley slopes and floors are covered with a variable thickness of unconsolidated sediment deposited during and after the Fraser Glaciation which ceased approximately 10,000 years ago.

METHODS

SAMPLE COLLECTION

Sediment and water samples are systematically collected by truck, boat, or helicopter from second order streams draining catchments averaging 10 km^2 in area. Fine grained sediments (<1 mm) weighing 1-2 kilograms are collected within the active stream channel and placed in kraft-paper bags. Weathered boulders, rotting logs and channel banks are avoided to prevent sample contamination; one field duplicate is routinely collected within each analytical block of 20 samples. Unfiltered water samples are collected in 250 ml nalgene bottles; precautions are taken to exclude suspended solids when possible. Field observations regarding sample site, media, and local terrain are recorded.

SAMPLE PREPARATION AND ANALYSIS

Sediment samples are air dried in the field and shipped to a sample preparation laboratory. Sediments are dry-sieved to -80 mesh (<177 microns), and analytical splits of the -80 mesh fraction are prepared. An analytical blind duplicate and a control reference standard are inserted in each block of 20 sediment or water samples at the sample preparation laboratory to assess precision and accuracy.

Prepared sediment samples are analyzed by a variety of methods at commercial laboratories for up to 38 elements. Total concentrations of metals are determined by instrumental neutron activation analysis (INAA) for a suite of 26 elements. Partial and total concentrations of metals are determined by aqua regia digestion - atomic absorption spectrophotometry (AAS) and a number of element-specific methods (Table 1). Waters are analyzed for fluorine, uranium, and pH.

RGS STUDIES WITHIN THE HOWE SOUND WATERSHED

Stream sediments within the Howe Sound watershed were collected during 1981 and 1989 as part of two Regional Geochemical Surveys conducted in NTS mapsheets 92J (Pemberton) and 92G (Vancouver), respectively. A total of 320 sites from the two mapsheets occur within the Howe Sound watershed. Stream sediment and water samples were collected at an average density of one sample per 16.6 km^2 in 92J, and one per 10.8 km^2 in 92G. Provincial parks were excluded from the sampling program.

Samples from both NTS 92G and 92J were analyzed for Sb, As, Co, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Ag, W, U, and Zn. Sediments from 92G were also analyzed for Au, Bi, Cd, Cr, F, Sn, and V. Analytical results from these surveys have been released as British Columbia Ministry of Energy, Mines and Petroleum Resources Open Files RGS 9 (NTS 92J - Pemberton) and RGS 26 (NTS 92G - Vancouver) (British Columbia Ministry of Energy, Mines and Petroleum Resources, 1982; Matysek, et. al., 1989).

Data for the Howe Sound drainage basin was compiled from RGS 9 and RGS 26 and subdivided into groups based on underlying geology. Basic statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) for each geologic subgroup were calculated for copper, arsenic, lead, zinc, iron, nickel, uranium, uranium in water, and pH. F and t-tests for each element were performed on the three prevalent rock types (number of sample sites > 40) of the watershed: quartz diorite (qd), granodiorite (gd) and Gambier Group (lKG) volcanics and sediments. Significant outliers were removed from the dataset to provide a more realistic estimate of variance. Probability plots were employed to determine the background concentration of copper in the three major rock types.

RESULTS AND DISCUSSION

Ten rock types are represented within the Howe Sound drainage basin. Of the 320 sample sites within the watershed, 210 are underlain or drain intrusive rocks, consisting of 165 quartz diorite (qd) and 45 granodiorite (gd) sites. Gambier Group (lKG) volcanic and sedimentary rocks comprise 43 of the sites, followed by Cheakamus Formation sediments (lKC: 19 sites), diorite (di: 12 sites), migmatitic rocks (ng: 12 sites) and Garibaldi Group volcanics (QG: 11 sites). The remaining three rock types each account for less than ten of the sample sites within the watershed. Statistical summaries of stream sediment data subdivided by rock type are shown in Table 2. Mean concentrations for each element vary considerably between rock type. F and t-tests carried out on samples draining the three most prevalent lithologies (quartz diorite, granodiorite, and Gambier Group) for eight elements (copper, arsenic, lead, zinc, iron, nickel, uranium, and uranium in water) and pH indicate that significant differences exist between rock types (Table 3).

Background copper concentrations, generated using probability plots, are shown in Table 4. At the 95% confidence level, mean background copper concentrations of the three main rock types are all significantly different (Table 5). Gambier Group rocks have a higher background copper concentration (32.6 ppm) than quartz diorite bedrock (23.7 ppm), whereas granodiorite has the lowest background copper content of the three (14.3 ppm). These differences in background concentrations represent inherent characteristics of each rock type and are directly related to their composition and origin.

CONCLUSIONS

Results from the Howe Sound watershed indicate that significant differences in metal concentrations exist between rock types of the basin. Failure to identify variation in the natural background concentration of metals within a watershed may lead to the establishment of unrealistic thresholds for acceptable metal levels in the environment.

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Table 1. Elements, analytical methods, and detection limits.

ELEMENT	METHOD OF ANALYSIS	DETECTION LIMIT	ELEMENT	METHOD OF ANALYSIS	DETECTION LIMIT
Antimony	AAS-H / INAA	0.2 / 0.1 ppm	Nickel	AAS / INAA	2 / 2 ppm
Arsenic	AAS-H / INAA	10 / 0.5 ppm	Rubidium	INAA	5 ppm
Barium	INAA	100 ppm	Samarium	INAA	0.5 ppm
Bismuth	AAS-H	0.2 ppm	Scandium	INAA	0.5 ppm
Bromine	INAA	0.5 ppm	Silver	FA-AAS	0.2 ppm
Cadmium	AAS	0.2 ppm	Sodium	INAA	0.1 pct
Cerium	INAA	10 ppm	Tantalum	INAA	0.5 ppm
Cesium	INAA	0.5 ppm	Terbium	INAA	0.5 ppm
Chromium	AAS / INAA	5 / 5 ppm	Thorium	INAA	0.5 ppm
Cobalt	AAS / INAA	2 / 5 ppm	Tin	AAS	1 ppm
Copper	AAS	2 ppm	Tungsten	COLOR / INAA	1 / 2 ppm
Fluorine	ION	40 ppm	Uranium	INAA / INAA	0.5 / 0.2 ppm
Gold	INAA	2 ppb	Vanadium	AAS	5 ppm
Iron	AAS / INAA	0.02 / 0.2 pct	Ytterbium	INAA	2 ppm
Hafnium	INAA	1 ppm	Zinc	AAS	2 ppm
Lantanum	INAA	5 ppm	Zirconium	INAA	200 ppm
Lead	AAS	2 ppm	LOI	GRAV	0.2 pct
Lutetium	INAA	0.2 ppm	pH - water	pH meter	0.1 pH unit
Manganese	AAS	5 ppm	U - water	FLUOR	0.05 ppb
Mercury	AAS	10 ppb	F - water	ION	20 ppb
Molybdenum	AAS / INAA	1 / 1 ppm			

METHODS OF ANALYSIS

AAS-H	Hydride AAS	**AAS**	Atomic absorption spectrophotometry
FA-AAS	Fire assay AAS	**INAA**	Instrumental neutron activation analysis
ION	Ion specific electrode		
COLOR	Colourometric method		
GRAV	Gravimetric method		
FLUOR	Fluorometric method		

Table 2. Summary statistics on stream sediment data, Howe Sound Watershed.

ROCK		Cu	As	Pb	Zn	Fe%	Ni	U	U-W	pH
qd	MIN	4	1	1	8	0.40	1	0.2	0.02	4.60
n=165	MAX	120	460	41	215	4.65	62	13.6	2.00	8.50
	MEAN	30	6	7	48	1.81	9	2.69	0.06	6.78
	SD	20	36	8	31	0.70	7	2.39	0.17	0.57
	CV%	68	582	121	64	39	82	89	283	8
gd	MIN	2	1	1	9	0.00	1	0	0.02	5.40
n=45	MAX	54	35	25	122	3.00	13	59	0.86	7.90
	MEAN	17	3	5	38	1.30	5	5.30	0.10	6.59
	SD	13	6	6	27	0.70	4	11.00	0.10	0.54
	CV%	75	182	125	70	54	66	208	100	8
IKG	MIN	5	1	2	13	0.85	1	0.6	0.02	5.20
n=43	MAX	1660	120	103	770	6.50	79	12.6	0.65	8.00
	MEAN	85	10	17	107	2.58	15	2.59	0.06	6.57
	SD	248	19	18	120	1.03	14	2.15	0.12	0.69
	CV%	293	189	105	111	40	97	83	200	11
IKC	MIN	13	1	1	11	0.90	4	0.4	0.02	6.80
n=19	MAX	270	45	128	255	3.70	310	5.0	5.30	8.20
	MEAN	59	8	12	75	2.04	32	1.69	0.34	7.42
	SD	59	11	29	65	0.86	70	1.06	1.20	0.40
	CV%	99	134	247	86	42	217	63	353	5
di	MIN	6	1	1	21	0.55	4	0.9	0.02	6.60
n=12	MAX	60	13	8	81	2.20	65	2.5	0.02	7.30
	MEAN	23	2	3	43	1.61	13	1.35	0.02	6.98
	SD	16	3	2	18	0.49	17	0.48	0.00	0.22
	CV%	70	142	73	41	30	131	36	0	3
ng	MIN	10	1	1	17	0.80	1	1.0	0.02	6.00
n=12	MAX	40	2	1	120	1.85	19	8.0	0.02	7.10
	MEAN	19	1	1	37	1.26	6	2.08	0.02	6.70
	SD	11	0	0	28	0.36	6	1.92	0.00	0.40
	CV%	57	33	0	74	29	103	92	0	6
QG	MIN	12	1	1	16	0.55	3	0.5	0.02	6.60
n=11	MAX	68	10	13	91	5.50	36	2.1	0.02	7.70
	MEAN	25	2	5	43	1.92	15	1.1	0.02	7.09
	SD	16	3	4	24	1.33	12	0.5	0.00	0.34
	CV%	63	113	91	55	69	81	45	0	5

SD = standard deviation; CV% = coefficient of variation

Table 3. Comparison of the three major rock types by element, Howe Sound watershed.

Element	Comparison	F value	F critical	Null Hypothesis	t-Test	Null Hypothesis
Arsenic	qd vs. gd	1.01	1.58	accepted	40.15	rejected
	qd vs. IKG	9.00	1.50	rejected	-	-
	gd vs. IKG	8.91	1.69	rejected	-	-
Copper	qd vs. gd	2.58	1.58	rejected	-	-
	qd vs. IKG	3.03	1.50	rejected	-	-
	gd vs. IKG	7.81	1.69	rejected	-	-
Lead	qd vs. gd	1.56	1.58	accepted	7.72	rejected
	qd vs. IKG	5.18	1.50	rejected	-	-
	gd vs. IKG	8.09	1.69	rejected	-	-
Zinc	qd vs. gd	1.32	1.58	accepted	30.31	rejected
	qd vs. IKG	3.82	1.50	rejected	-	-
	gd vs. IKG	5.08	1.69	rejected	-	-
Iron	qd vs. gd	1.00	1.58	accepted	0.22	accepted
	qd vs. IKG	2.16	1.50	rejected	-	-
	gd vs. IKG	2.16	1.69	rejected	-	-
Nickel	qd vs. gd	1.00	1.58	rejected	-	-
	qd vs. IKG	2.16	1.50	rejected	-	-
	gd vs. IKG	2.16	1.69	rejected	-	-
Uranium	qd vs. gd	21.20	1.50	rejected	-	-
	qd vs. IKG	1.24	1.58	accepted	2.35	rejected
	gd vs. IKG	26.2	1.69	rejected	-	-
Uranium (water)	qd vs. gd	2.89	1.58	rejected	-	-
	qd vs. IKG	2.01	1.58	rejected	-	-
	gd vs. IKG	1.44	1.69	accepted	0.11	accepted
pH	qd vs. gd	1.11	1.58	accepted	0.57	accepted
	qd vs. IKG	1.47	1.50	accepted	2.24	rejected
	gd vs. IKG	1.63	1.69	accepted	1.11	accepted

qd - quartz diorite gd - granodiorite IKG - Gambier Group
t-critical = 1.98 at 95% confidence level and n=120

Table 4. Background copper concentrations, Howe Sound watershed.

ROCK TYPE	Quartz Diorite (qd)	Granodiorite (gd)	Gambier Group (IKG)
MEAN	23.7	14.3	32.6
STD. DEV.	10.1	6.6	12.5
% OF SITES	87	100	79

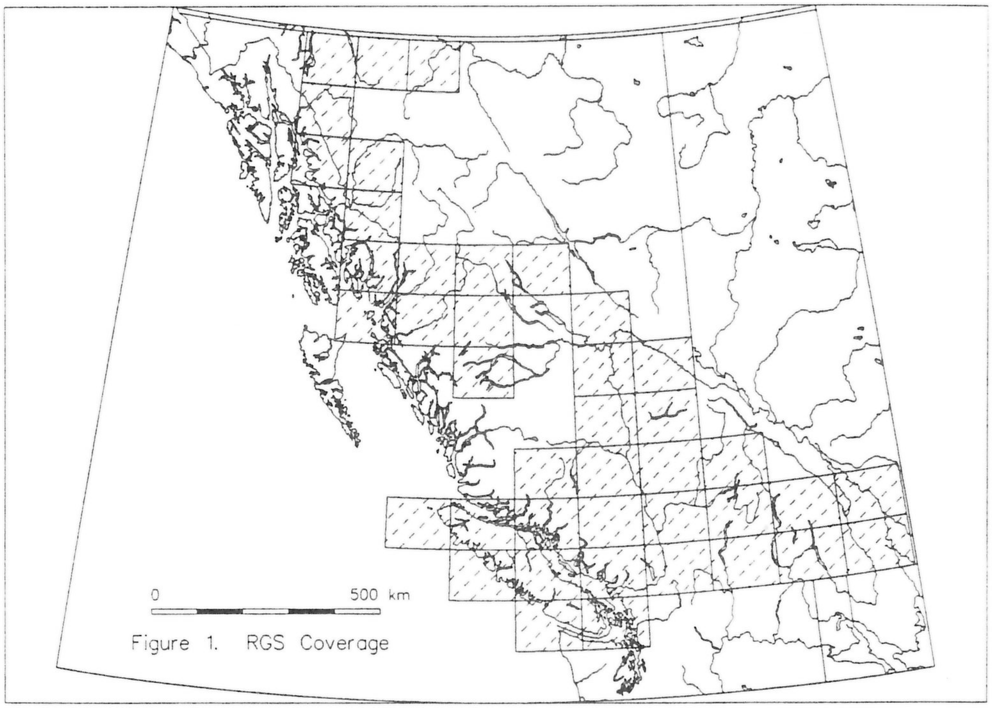
Values in ppm except where noted

Table 5. Comparison of background copper concentrations, Howe Sound watershed.

COMPARISON	F value	F critical	t-Test
qd vs. gd	2.34	1.68	-
qd vs. IKG	**1.53**	1.55	10.64
gd vs. IKG	3.58	1.84	-

t-critical = 1.98 at 95% confidence level and n=120

Figure 1. RGS Coverage.



AN INVENTORY OF RESEARCH CONDUCTED IN SQUAMISH BASIN

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INTRODUCTION

Since the mid-1970's faculty and graduate students of the S.F.U. Department of Geography have completed a variety of research projects in the Howe Sound-Squamish Basin region. These studies can be grouped into one of six types of activity:

1. Surficial geology and geomorphology and their control on sediment supply to Squamish River.
2. Process studies of flow and sediment deposition in the contemporary channel of Squamish River.
3. Sedimentology of the Squamish River floodplain.
4. Channel planform dynamics of Squamish River.
5. Process studies of flow and sediment deposition in Squamish Estuary.
6. Plant ecology of Squamish estuary.

The nature of the particular studies are briefly outlined below; all graduate theses cited are available in the S.F.U. Bennett Library.

THE RESEARCH INVENTORY

1. Surficial geology and geomorphology and their control on sediment supply to Squamish River.

This 4-year project will be completed in 1991 by Greg Brooks, a Ph.D. candidate in the Department of Geography. All of the data will be available in his doctoral thesis (Brooks, 1991) and subsets or extensions of it are available in two recent papers (Brooks and Hickin, 1991; Evans and Brooks, 1991). This major study documents the locations and volumes of fluvial sediment sources in Squamish Basin and describes the long-term rate of sediment delivery to Squamish River since deglaciation. Interpretations are based on Brooks' mapping and analysis of the surficial geology in the Basin and a large set of new C14 dates provides the dating control for reconstructing the geomorphic history and Holocene sediment budget. In addition to quantifying aspects of the paraglacial sediment supply, this study documents several catastrophic non-glacial sediment inputs which have very significantly influenced the character of the contemporary Squamish River.

2. Process studies of flow and sediment deposition in the contemporary channel of Squamish River.

Squamish River is a very useful outdoor laboratory for those interested in measuring river processes because the many glacierized first-order basins sustain predictable high flows for weeks at a time during the summer. Exploiting this convenient hydrology, Hickin (1978) obtained near-bankfull measurements of the primary and secondary velocity fields through a series of contiguous channel bends of varying curvature in the upper meandering reach of Squamish River. Although these measurements were collected to test various hypotheses about the fluid mechanics of helical flow through open-channel bends, they also highlight the occurrence of separated flows in parts of the channel which induce depositional sinks for the very fine suspended material being transported by the river. The depositional consequences of separated flows in Squamish River (concave-bank benches) are described in Hickin (1979). Other velocity measurements in Squamish River have been obtained by Rood (1980). He obtained a long (several hours) continuous velocity record using a magneto-type Ott current meter in order to spectrally characterize the macroturbulence in the flow near the Squamish River gauging station (Brackendale). This work also included a high-resolution depth-sounder profile of the bed for several hundred metres upstream of the gauging station.

Sorting of gravel in the bed and bars of Squamish River downstream of the Turbid Creek confluence is the subject of another study reported by Brierley (1984) and Brierley and Hicken (1985). Brierley's 1984 study included an inventory of bed material found in bars, full discussions of the sediment sampling problems involved, the mechanics of downstream bed-material sorting, and the nature of channel equilibrium/disequilibrium in Squamish River. The 1985 study summarizes the downstream bed-material sorting data in the context of a test of the exponential decay law of Sternberg.

3. Sedimentology of the Squamish River floodplain.

Gary Brierley, a former doctoral student in the S.F.U. Department of Geography (now at the A.N.U., Australia) completed a very detailed study of Squamish River floodplain sedimentology in the reach between the Squamish canyon and the meandering channel downstream (Brierley, 1989a). The study describes the sediments and internal structure of both the contemporary bars and the floodplain (from facies to element scales) based on hundreds of pits, trenches, and cut-bank exposures of the sediments above the basal river gravels. It is likely the most comprehensive sedimentological data set for a floodplain of this size ever assembled. An important thrust of this work involves tests of existing planform facies models and of architectural element analysis (none work very well in Squamish River) and of Markov-chain based modelling (found to be misleading). Various parts of this work are available (or will soon be available) in print (Brierley, 1989a, 1989b, 1991; Brierley and Hickin, 1991a, 1991b).

4. Channel planform dynamics of Squamish River.

The role that vegetation plays in a variety of erosional and depositional processes in Squamish River (and elsewhere) is discussed by Hickin (1984). Of particular interest here is the importance of the making and breaking of log jams to the secondary channel dynamics of the braided and wandering gravel bed reaches of the river. In another study, Sichingabula used sequential aerial photography to document channel boundary changes along Squamish River since the 1940's (Sichingabula, 1986). These data are summarized in a number of reach maps showing how the channel boundaries have shifted over a period of several decades. Some of the aerial photography used in this project was flown by the S.F.U. Remote Sensing Unit especially for the task at hand; it is in false colour 35 mm stereoscopic format and available from the S.F.U. Department of Geography. Fortuitously, one of these S.F.U. flights immediately preceded the 1984 October flood and this photography, together with additional post-flood photography, provided the basis for assessing the related channel changes (Hickin and Sichingabula, 1988). Channel changes were surprisingly modest in most single-channel reaches although major shifts of secondary channels occurred in the braided reach downstream of the Turbid Creek confluence. Some of these secondary-channel changes; however, likely were conditioned by earlier debris flows from Turbid Creek into Squamish River (Hickin and Sichingabula, 1989 and the preceding discussion by Cruden and Lu Z-y in the same journal).

5. Process studies of flow and sediment deposition in Squamish estuary.

Hickin (1989a) differenced Bell's Squamish River delta hydrographic charts and subsequent soundings to 1984 and 1988 to obtain an estimate of the annual rate of delta growth and, therefore, the sediment discharge from Squamish River to Howe Sound (1.3 x 106 m^3/year or 1.8 x 109 kg/year). This sediment-discharge estimate is consistent with the very limited suspended sediment data for Squamish Estuary and associated with a mean delta progradation rate of 3.86 m/year. C14 dating of delta sediments 2.75 km upstream from the front indicated an age of 620 ± 55 years BP (SFU 711) and thus an average progradation rate for this much longer period also of about 4 m/year. The concentration of suspended sediment in Squamish Estuary in relation to surface flow structures has been measured through the tidal cycle (Rood and Hickin, 1989). Concentrations as high as 3000 mg/L of sand can be found in boils near the delta front while at the same time ambient fluid suspended-sediment concentrations are an order of magnitude lower. This work continues.

6. Aspects of plant ecology of Squamish Estuary.

Hutchinson studied wetland vegetation in a large number of Strait of Georgia river deltas, including Squamish River delta (Hutchinson and Smythe, 1986). Working under his direction, Smythe (1987) has described various aspects of the plant ecology of Squamish River delta, has obtained measurements of plant growth rates, determined environmental tolerances for several plant species (*Carex lyngbei* in particular), and measured surface-sedimentation rates.

FUTURE WORK

Scientists of the S.F.U. Department of Geography continue to conduct studies in Squamish Basin and two major programmes currently are active. The first study, a continuation of Project 5 above, involves continuous measurement of suspended sediment concentrations and loads in relation to flow structures (boils and persistent longitudinal vortices) over the tidal cycle in Squamish Estuary. Measurements of suspended sediment concentrations are being obtained indirectly using an optical back-scattering sensor (turbidity meter) operated from a survey boat. It is hoped that this work will lead to the development of a new technique for measuring suspended sediment concentration and loads in boil-structured flows. The second study, also a continuation of Project 5, involves subsurface surveying of Squamish River delta. In addition to the drilling of several more 15-20 m holes for direct sampling of sediment and datable organics in the vicinity of Squamish, a ground-penetrating-radar (GPR) survey is planned for summer 1992; The GPR survey should provide the first high-resolution picture of the three-dimensional internal architecture of the delta.

ACKNOWLEDGEMENTS

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IMPACT ON A PRISTINE MOUNTAIN RIVER OF DOMESTIC WASTE WATERS FROM REMOTELY LOCATED, RECREATIONALLY ACCELERATED, DEVELOPMENT OF A WILDERNESS

by

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ABSTRACT

A four-year field study (1988-1991), using experimental stream-troughs, quantified the nutrient contribution of sewage effluent (with particular reference to phosphorus), from the recreational community of Whistler to the Cheakamus River, British Columbia. Downstream fisheries and aesthetics were adversely affected at periphyton biomass values exceeding 2,500 µg/cm^2. The latter was experimentally determined to occur given an upstream increase in ortho-P of 2.0 µg/L, equivalent to an increased sewage effluent discharge of 5,339 to 5,884 m^3/day (based on an effluent ortho-P concentration of 200 µg/L). Revealing the river's limited nutrient assimilative capacity, in view of proposed new development, resulted in a Liquid Waste Management Plan which proposed the discharge of sewage effluent into the adjacent Squamish River. A stream-trough study on the Squamish River was conducted in the summer of 1991 to assess how the effluent diversion would affect water quality, especially with respect to the development of undesirable algal growth. The latter could adversely affect fish spawning and rearing habitat.

INTRODUCTION

With respect to the disposal of agriculture and domestic wastewaters, society's concern has traditionally been with public health issues. Broadening of the term 'health' now encompasses the well-being of ecosystems, that is, eutrophication of aquatic communities subjected to treated and untreated nutrient effluents. The algal component of lotic periphyton frequently exhibits sensitivity to nutrient ratios and concentrations (McIntire et al., 1964; Steinman and McIntire, 1990). Since the periphyton community is an important energy producer and subsequent energy transducer between trophic levels in lotic ecosystems (Wetzel, 1983; Sinsabaugh et al., 1991), it has been used to characterize aquatic health responses to anthropogenic eutrophication (Perrin et al. 1987; Bothwell et al., 1989). Beginning in the 1980's a number of whole-system studies in streams and rivers have demonstrated positive correlations between phosphorus enrichment and increased periphyton biomass accrual and productivity (Lock et al., 1990; Stockner and Shortreed, 1978; Elwood et al., 1981). These and other works have demonstrated that, in coastal (and numerous interior plateau) oligotrophic regions of the Pacific Northwest, lotic environments exhibit phosphorus limited primary production during summer (Stockner and Shortreed, 1985; Bothwell 1985; Bothwell, 1988).

Productive and ecotoxicological aspects of lotic periphyton have growing relevance to water quality. Streams and rivers, especially those adjacent to large urban centres, are important for aesthetics, recreational activities such as fishing (spawning and rearing habitat), water supply, capacity for assimilation of nutrients (i.e., sewage disposal), and as a sensitive, integrating monitor of other potentially ecosystem-deforming land-use activities. Streams are the catchment for both point and non-point anthropogenic pollutants which also influence lake and ground water sources. Periphyton communities, by virtue of their sedentary and sensitive nature, reflect the health of surface waters by integrating such environmental parameters as nutrients, velocity, and turbidity (Horner et al., 1990).

Regulatory decisions are increasingly requiring collaboration of heretofore separate types of studies. Observational/natural studies are being designed in conjunction with in-field laboratory experiments (e.g., using micro- or mesocosms, split lakes, or streams) as a basis for modelling potential perturbation-induced ecosystem changes (La Point and Perry, 1989). Day et al. (1988) recommended that "biological testing and monitoring must be integrated with chemistry in a multi-disciplinary manner when applied in hazard assessment and regulatory control".

The Cheakamus River, located within one hour of Vancouver (British Columbia's largest metropolitan area), flows through an extensively used recreation area highly rated for stream fishing of coho, spring salmon, and steelhead. Since the early 1980's public concern about the effects of algal growth upon aesthetics and fisheries has been raised. The objective of the study reported here was to determine whether increased, treated-sewage effluent discharges to the upper Cheakamus River would increase existing, marginally acceptable algal production in the lower Cheakamus River (LCR). Should such a perturbation be identified, using in-situ experimental stream-troughs, an attempt would be made to determine the river's limiting-nutrient and its assimilative capacity for additional effluent.

HISTORICAL SETTING & SITE DESCRIPTION

The Resort Municipality of Whistler (RMOW) is located 125 km north of Vancouver, approximately 50 km north of the Town of Squamish, straddling parts of the Green and Cheakamus River catchment basins (Fig. 1). Originating in Cheakamus Lake, the Cheakamus River flows 11 km west to the Whistler Sewage Treatment Plant. At this point the river receives the treated effluent, then bends southward and joins Millar and Callaghan Creeks before flowing into Daisy Lake. The latter, 10 km downstream of the effluent discharge, is a B.C. Hydro reservoir from which 80% of the pre-1990 annual discharge was diverted via a 12 km tunnel under Cloudburst Mountain to the Squamish River, approximately 40 km upstream of the Squamish Estuary. The headwaters of the LCR (from Daisy dam downstream to the Cheakamus-Squamish confluence) consist of Daisy Lake water that is allowed to spill through the dam, with a minimum (winter) discharge of 200,000 m^3/day (80 cfs).

The Cheakamus and Green River watersheds are characterized by high glaciated peaks and steep valleys, typical of the Coast Mountains, whose extensive volcanic intrusions and often phosphorus rich parent material, when weathered, contribute higher than normal background concentrations of phosphorus into the aquatic environment (Squamish Estuary Management Plan, 1981). The RMOW experienced significant residential and commercial development in the early 1980's and is now used on a year-round basis. This existing and proposed expansion has resulted in the need to treat and discharge additional volumes of sewage (Fig. 2), a condition likely to continue in the immediate future. RMOW access is via Highway 99 (which carries more summer traffic than any other highway north of the trans-Canada highway in B.C.), which parallels the heavy growth section of the LCR; the B.C. Rail Line also parallels this 7 km section of the river. Heightened public concern about adverse effects on fisheries by highly visible, extensive periphyton growth, has been directed to Fisheries Management.

Post-1970 periphytic algal growth in the upper reaches of the Lower Cheakamus resulted in a field study to assess the sewage effluents' acute toxicity, bacteriological and algal growth-enhancing effects, and aesthetic impacts (Nordin, 1984). The result of this study was identification of a 100 m zone of acute toxicity and aesthetic deterioration immediately below the STP discharge. Also identified was a perception that construction of the Daisy dam in the late 1950's likely enhanced LCR algal growth by stabilizing water depth, velocity, and flow regimens.

Algal growth in the Lower Cheakamus had been determined to be marginally below the criterion established to maintain optimal lotic water quality. Of principal concern was whether projected dissolved ortho-phosphorus and inorganic nitrogen increases, discharged by the RMOW STP, would aggravate downstream algal growth. Although the STP's contribution was approximately 10% of riverine N and P, it was hypothesized that marginal ortho-P increases would markedly enhance algal production.

STUDY OUTLINE

The 1987-1991 study objectives included establishing lotic sampling stations on the Cheakamus River, some tributary streams, and Daisy Lake, at which physical, chemical, and biological parameters were measured. Limnological sample sites were located 0.5 km upstream, and 100 m and 4 km downstream of the STP; 500 m, 6 km, and 12 km downstream of Daisy dam; on Millar, Callaghan, Brandywine, and Rubble creeks; at the STP point-of-discharge; and on Daisy Lake. In 1987, a whole-river study was conducted to determine whether increased sewage-based ortho-P would increase algal growth. Pickling liquor, normally added as a phosphorus precipitator to post-secondary effluent, was temporarily omitted and downstream ortho-P concentrations and algal production monitored.

In 1988, 16 nutrient-dosing troughs were established at the base of the Daisy dam, within which N and P were added to correlate nutrient concentration with algal production. These experiments were conducted in 1988, 1989, and 1991; the 1988 and 1989 results of which are presented here.

METHODS

In-situ experimental stream-troughs were used to measure algal production at increasing nutrient concentrations (Bothwell and Jasper, 1983; McIntire et al., 1964). All troughs received siphoned lake water, passed once through each trough at a flow of 1.0 L/sec; this flow is similar to that typically measured in the LCR shallow side channels. The gravity-feed, nutrient-dosing apparatus consisted of carboys (20 L) containing stock solutions of nitrogen ($NaNO_3$), phosphorus ($NaHPO_4$), or both, in conjunction with a drip feed system (Flexiflow gravity gavage set (Ross Co., Ohio)). Stock N and P solutions were added to de-ionized water in the carboys; nutrients from the carboys dripped (1.5 ml/min) into supply manifolds to achieve thorough mixing prior to flowing through the trough. Carboys were replenished weekly and drip feed rates monitored and altered as necessary. Nutrient enhancement was based on P additions above an average background (1.0 µg/L) P and (25 µg/L) N concentration. The 1988 nutrient-dosing regimen consisted of 3.10, 1.80, 1.04, 0.70, and 0.50 µg/L P; 3.75:0.50 µg/L N:P, and 4.25 µg/L N. These values represent the actual concentrations added to each trough during the experiment. While slight fluctuations in nutrient additions occurred, nutrient-dosage rates were reasonably consistent across time. The 1989 nutrient-dosing study concentrations were 0.40, 0.42, 0.25, 0.12, 0.08, and 0.02 µg/L P and 1.0 µg/L N. The 1991 concentration was 0.25 µg/L P. Control troughs received only lake water.

Natural river rock had been previously collected, cleaned, dried, and placed within the troughs. Periphyton was collected from this sampling surface by scraping the algae from within a measured, circular area (Ertl, 1971). Every effort was made to standardize substrata depth, solar angle, and velocity. Growth estimates were obtained by splitting each sample volumetrically to provide equal aliquots for measuring biomass and chlorophyll a.

Water chemistry and periphyton analyses were conducted by the British Columbia Environmental Laboratory and Zenon Environmental Inc.; all chemistry and periphyton analyses were conducted in accordance with procedures set out in A Laboratory Manual for the Chemical Analysis of Water, Wastewater, Sediments and Biological Tissues (Ministry of Environment, 1989). Low-level nutrient samples were collected in laboratory-prepared amber glass bottles, field filtered (apparatus prewashed in 10% hydrochloric acid), with samples measured in a dedicated analytical "stream". Minimum detectable concentrations (MDCs) of inorganic N and ortho-P were 5.0 and 1.0 µg/L, respectively.

RESULTS

Since the early 1980's the quantity of treated effluent discharged during the months of July and August has increased approximately 400% (Fig. 2). With the exception of a slight reduction in 1990, mean monthly effluent discharge has steadily increased.

An aesthetics standard was established (Fig. 3) at a maximum biomass of 2,500 $\mu g/cm^2$, for the LCR. The standard was determined by plotting the weekly biomass data from 1987 to 1989 at two stations in the LCR to assess the average biomass level during this period. In general, the average biomass was similar to that at which public complaints were received by government agencies. The 1989 average summer biomass was 2,365 $\mu g/cm^2$ (or 5.7% less than the 2,500 $\mu g/cm^2$ maximum).

Data summaries from the 1988 and 1989 trough studies are shown in Figures 4a and b, respectively. The 1988 data indicate that additional nitrogen induced minimal increase in biomass accrual. When P was added at any concentration there was a significant increase in production, even when combined with N. Growth in the two 50% P additions were similar until the last sampling period, when the treatment with N was subject to earlier than normal sloughing of the periphyton community, as indicated by the reduction in accrued biomass. The overall trend in the control was for biomass to increase slowly for four weeks until a more rapid increase was observed in the last ten days of the experiment. Addition of phosphorus produced the same trend; however, with each higher P addition the slope of the accrual curve steepened, indicating an earlier onset of enhanced production. In 1989 a significant increase in growth (relative to that of the control) occurred at a P concentration of 8% above background. Significantly less biomass had developed by late August 1989 than had occurred in the previous year.

The trough data showed that a 13% biomass increase could result from a 0.5% increase in background ortho-P concentration. Based upon Cheakamus River water chemistry data, it was known that Upper Cheakamus River ortho-P concentrations (immediately above Daisy Lake and below Brandywine Creek (Fig. 1)) were approximately 4 times the values observed at the dam. (The remaining 75% is thought to be retained within the sediment load which settles out within the lake.) The Upper Cheakamus ortho-P values, at a position in the river closest to Daisy Lake, are approximately 42% of the values measured immediately below the STP discharge. Based upon this downstream ortho-P gradient, a 0.25% ortho-P increase at the dam site would be equivalent to a 2.35% ortho-P increase immediately downstream of the STP discharge. The average summer (1989) effluent discharge of 5,339 m^3/day received an average 670:1 dilution with river water, based upon an average summer flow calculated on river flows from the 1924-48 and 1982-88 period (Water Survey of Canada). The average ortho-P concentration of the 1989 effluent was 200 $\mu g/L$, while the average background ortho-P concentration was 1.0 $\mu g/L$. Therefore, for the latter effluent quality to effect an increase in riverine ortho-P by 2.35%, effluent discharge would need to be increased by approximately 10.2%. The linkage between the permissible biomass maximum in the Lower Cheakamus (as a result of increased P upstream) and discharge of treated effluent from the STP is characterized in Figure 2. Thus, should effluent discharge (at a P of 200 $\mu g/L$) exceed 5,884 m^3/day, the downstream assimilative capacity would be surpassed; these flows were achieved in 1991 (Fig. 2).

DISCUSSION AND CONCLUSIONS

The sensitivity of many coastal British Columbia lotic and lentic habitats to phosphorus-based eutrophication has been well documented (Stockner and Shortreed 1978; Shortreed et al., 1984; Perrin et al., 1984 and 1987; Mundie et al., 1991). Bothwell et al., (1989) demonstrated the sensitivity of the Thompson River periphyton community to phosphorus-mediated eutrophication. The 1988-1989 data reported here confirm these authors' findings, of lotic periphyton sensitivity to ortho-P, for the Cheakamus River.

The 1988 stream-trough data were too robust to permit the accurate quantitative assessment of the LCR's assimilative capacity for ortho-P. These data indicated that the sensitivity of this portion of the river to ortho-P was significantly less than the lowest concentration used (0.5 µg/L) and were the latter concentration to occur in the Lower Cheakamus, growth would substantially exceed maximum permissible criteria for the maintenance of water and habitat quality. It is suggested here that maximum acceptable increases are best discussed in terms of percent addition over background, rather than as absolute increase in algal production, since additional algal growth could partially mask ortho-P concentration elevations by increased P uptake. Thus, further study was required to assess algal production at below detectable ortho-P concentrations, which would not exceed acceptable values.

The 1989 study explored algal production at ortho-P concentrations below 0.5 µg/L (Fig. 4b). Given the consistent correlation between increases in ortho-P and biomass, it was possible to estimate proposed nutrient loading and assimilation rates, based upon biomass accrual. Provincial Fisheries Management staff have indicated 1989 LCR algal production was approaching that which could significantly alter or reduce fry habitat in shallow river margins and side channels; this value was also aesthetically undesirable (Fig. 3). A preliminary assessment of periphyton community structure indicates the upper Cheakamus River (above and below the STP) is diatom dominated with minimal chlorophyte canopy development. The LCR and all troughs exhibited a periphyton assemblage consisting of an adnate and stalked diatom understory and a well developed chlorophyte canopy. The latter was the dominant contributor to periphyton biomass. A detailed assessment of periphyton community structure, including diversity, is being conducted. Macroinvertebrate biomass in 1987 in the upper Cheakamus (downstream of the STP) ranged from approximately 100 to 670 mg dry weight per 0.45 m^2 (to a depth of 0.05 m) compared to lower Cheakamus values of approximately 40 to 300 mg. Although not presented here, data on the seasonal changes in dissolved P, N, total dissolved solids, selected conservative ions, velocity, light, dissolved oxygen, turbidity, temperature, bacteriology, and periphyton biomass (AFDM and chlorophyll) are being analyzed to permit an improved understanding of periphyton dynamics in the river.

The considerable differences in periphyton community function and structure between the upper and lower Cheakamus are thought to result from hydrological changes effected by the dam and the diversion a major portion of Cheakamus River/ Daisy Reservoir surface water into the Squamish River. The principal flow from the reservoir into the lower Cheakamus occurs through a deep water discharge at the base of the dam. These hydraulic alterations reduce and stabilize water flow in the LCR resulting in increased temperature and reduced episodic scouring. They also cause the reservoir to function as a sediment trap and barrier to surface macroinvertebrate dispersal. The latter results in decreased grazing of periphyton and the former in decreased turbidity, which in turn increases photosynthesis and water temperature in the LCR. Also, the deepwater discharge to the lower Cheakamus River is known to contain an elevated nutrient supply, contributing to increased LCR algal growth. Unfortunately, minimal research has been undertaken to elucidate the effects of lake circulation patterns, drawdown procedures (and associated sediment/water column nutrient flux), dissolved ion and glacial flour interactions, plankton uptake, internal nutrient recycling, and sequestering of nutrients into the sediments, on periphyton dynamics in the lower Cheakamus.

As a result of the demonstrable LCR eutrophication which would result from additional ortho-P increases, a Liquid Waste Management Plan (LWMP) was adopted which sought to eliminate the STP discharge of ortho-P into the Cheakamus River. This would be accomplished through the construction of a pipeline adjacent to Highway 99 (beginning at the STP and ending at the B.C. Hydro tunnel) which would transport treated effluent from the STP to the Hydro penstocks (Fig. 1). The effluent would be diverted directly into the Squamish River, thereby avoiding any STP-based nutrient loading of the Cheakamus River. It was postulated that because of the high turbidity and larger flows in the Squamish River, that the additional nutrients entering the Squamish would not create a potential algal production problem. Since nothing is known about the structure and function of Squamish River periphyton communities, or how the attributes of these communities would respond to nutrient additions, a program of study similar to that conducted on the Cheakamus River was initiated in the summer of 1991. Sample sites upstream, within the tailrace of the Hydro-generating station, and downstream of the latter's confluence with the main river channel were established. Physico-chemical and periphyton production data were collected to establish background trends. A stream-trough facility was constructed below the tailrace and a nutrient-dosing study conducted. Preliminary findings indicate that the summer of 1991 was non-typical both climatically and hydrologically. In particular, it would appear that the necessary overlap between a "climatic window" and a "hydrologic window", within which environmental conditions would be favourable for periphyton productivity, did not occur. Thus, although the 1991 river and stream-trough data for the Cheakamus indicate similar growth patterns to previous years (1987-1990), growth patterns in the Squamish were significantly atypical to those which would likely have occurred.

Although not presented here, our data show that downstream, dam-modified, environmental parameters affected algal production through i) post-freshet, nutrient rich, deep-lake discharges to the Lower Cheakamus (Marsden, 1989): ii) clear water discharge whose reduced turbidity resulted in higher Secchi depth values (Horner et al., 1990); and, iii) discontinued downstream drift of macro invertebrates, thereby reducing grazer stress on periphyton biomass accrual (Steinman et al., 1987). The LCR's extensive shallow sidechannel zones (Biggs and Close, 1989), with minimal riparian canopy, provide optimal habitat for enhanced periphyton growth. These shallows thus minimize both velocity (Antoine and Benson-Evans, 1982) and flow (Whitford, 1960) and maximize irradiance, important considerations in periphyton community development (Hill and Harvey, 1990). Riber and Wetzel (1987), studying boundary layer and internal diffusion effects on phosphorus fluxes in periphyton, suggested that, while internal nutrient cycling will sustain periphyton communities, net accumulation of biomass requires episodic P additions.

ACKNOWLEDGEMENTS

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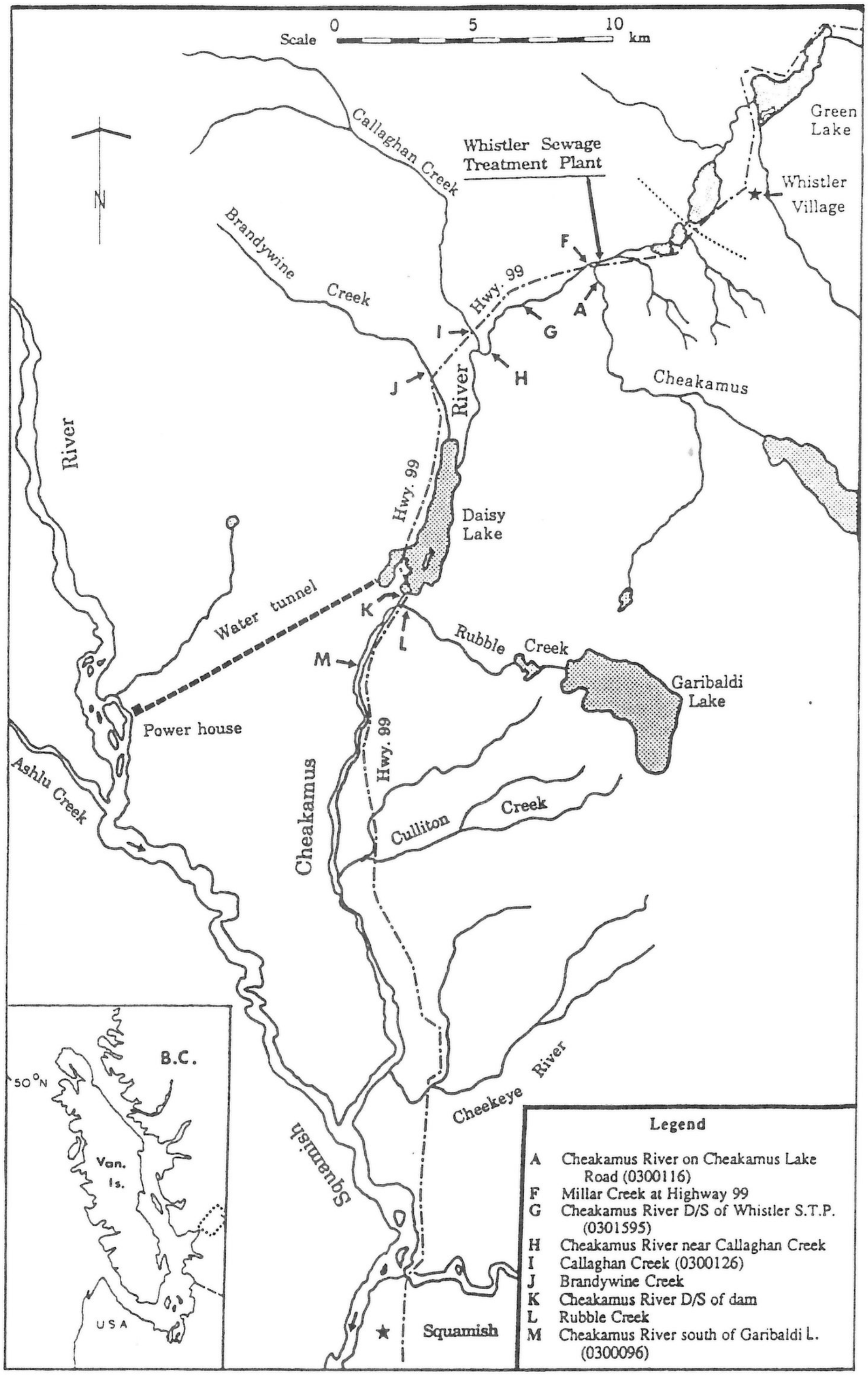

Figure 1. Cheakamus River sample sites (A-M), principal tributaries, Whistler Village (RMOW), Sewage Treatment Plant (STP), B.C. Hydro water tunnel, stream-trough facility (adjacent to K); small box on insert = Cheakamus R. watershed. Numeric codes = M.O.E. unique sample site designation; D/S = downstream; arrow = flow direction; dashed line = watershed boundary between Cheakamus and Green Rivers.

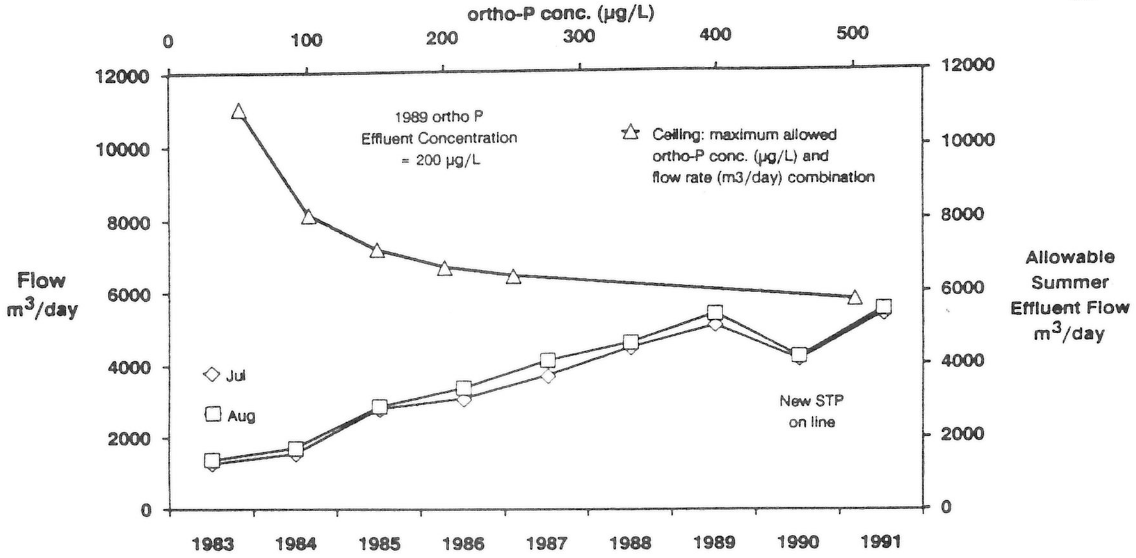

Figure 2. Comparison of i) treated sewage-effluent discharges, from the RMOW STP, into the Cheakamus River during the summer months of July and August, 1983 to 1991 (left-hand axis) with ii) allowable effluent flows (at different ortho-P concentrations), which would effect a maximum permissible biomass (2,500 $\mu g/cm^2$) in the LCR.

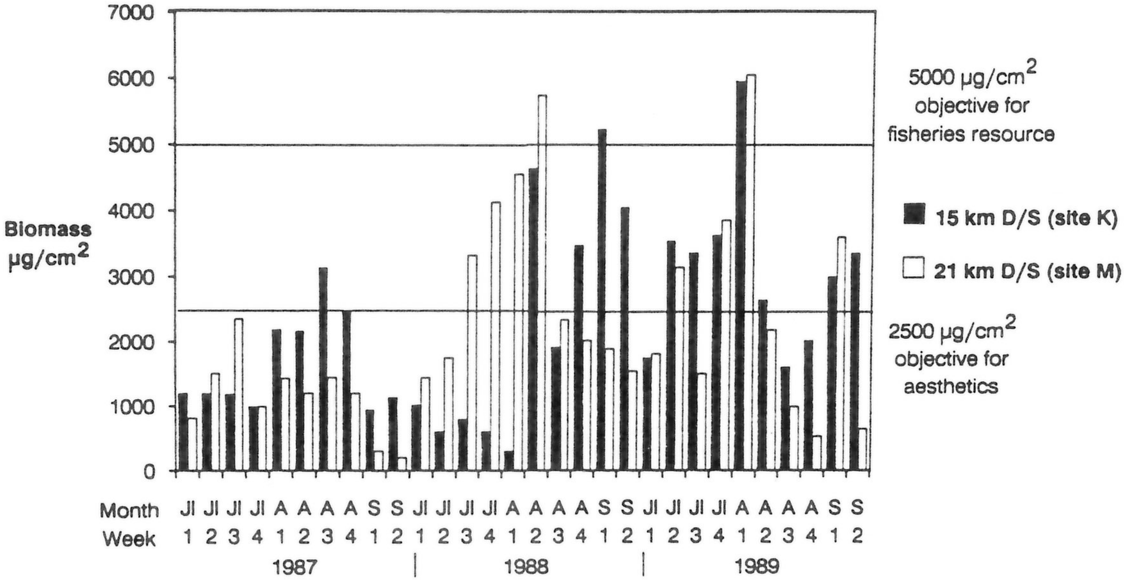

Figure 3. Weekly algal biomass production for the months July (Jl), August (A), and September (S) 1987 to 1989, at two sample sites on the LCR. 15 km = site K; 21 km = site M (Fig. 1). In 1987 and 1988 accelerated production occurred earlier at site M, whereas in 1989 site K production was higher throughout the summer.

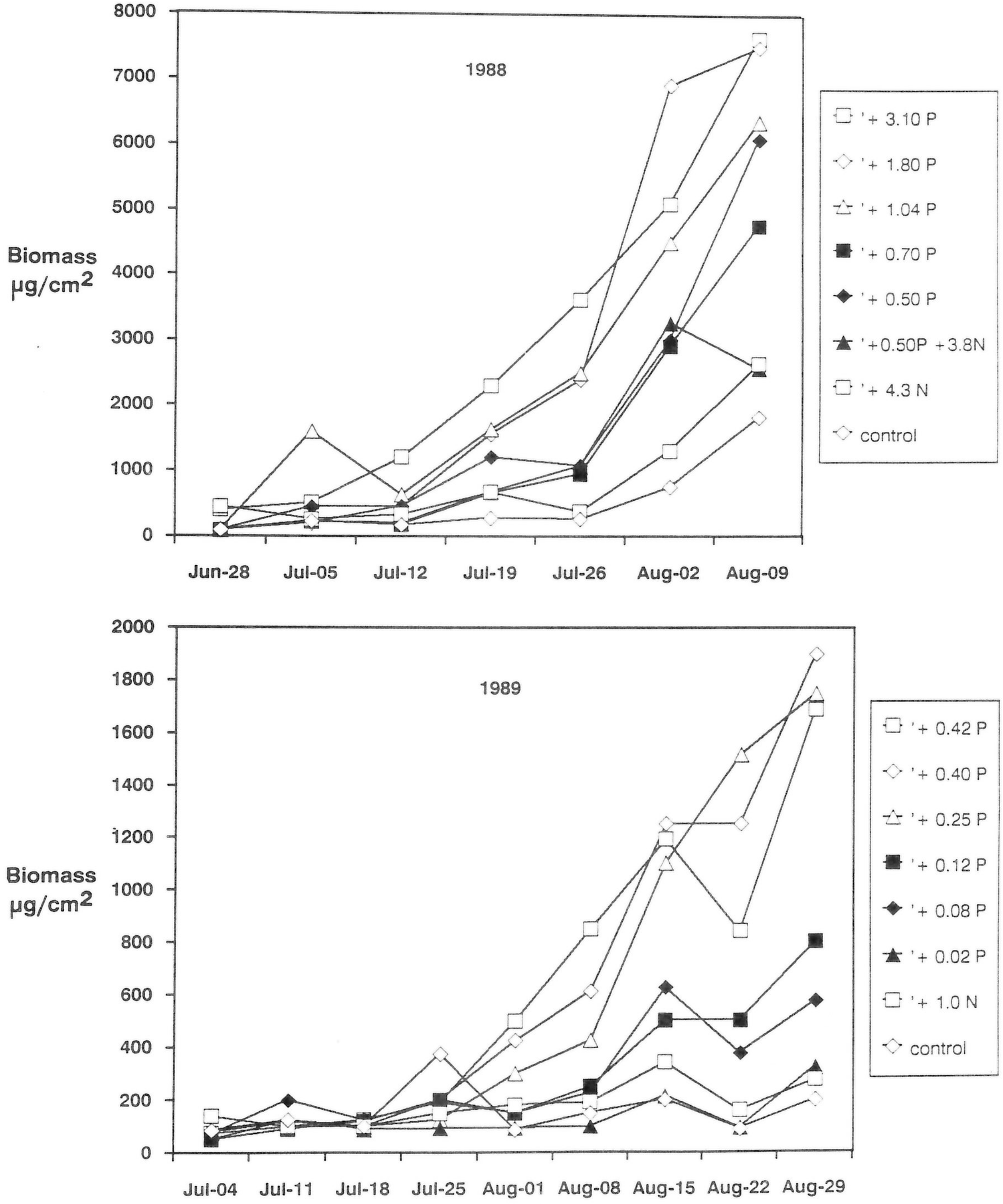

Figure 4. Biomass increases, obtained for 1988(a) and 1989(b), at different ortho-P and inorganic N concentrations within paired stream-troughs; each value is the replicate average; values in legend are dosage concentrations in µg/L. The latter were over and above the mean background nutrient concentrations of P = 1.0 and N = 25 µg/L.

WILDLIFE DIVERSITY IN OLD-GROWTH AND SECOND-GROWTH FORESTS ON THE SOUTH COAST OF BRITISH COLUMBIA

by

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SUMMARY OF RESULTS

Forest harvesting in the Howe Sound drainage has converted extensive areas of old-growth Coastal Western Hemlock forest into a mixture of recent clearcuts and second-growth forests ranging from 10 to 100 years of age. There is increasing public concern that many wildlife species are dependent on old-growth forests and that harvesting of these forests is reducing biological diversity in coastal British Columbia.

We have been studying the abundance and diversity of vertebrate species in old-growth forests, second-growth forests and clearcuts on the south coast of British Columbia. Forest birds were counted during the breeding season by recording birds heard singing within 75 m of census points. Small mammals and salamanders were captured using a variety of traps. Special survey techniques were used for marbled murrelets and spotted owls. In this paper, we provide information on the species for which we have collected sufficient data to formulate conclusions.

Some species, such as montane shrews, deermice and Ensatina salamanders are common and ubiquitous in all forest types (Tables 1 and 2). Other species of small mammals and birds are most abundant in clearcuts. It is likely that populations of species that prefer early seral habitats, such has long-tailed voles, juncos and MacGillivray's warblers, have increased in response to forest harvesting.

Other wildlife species live primarily in forest habitats but many are present in similar numbers in old-growth and 40-80 year old second-growth stands. For species such as Golden-crowned kinglets and Townsend's warblers that feed on foliage insects and build their nests in the branches of trees, second-growth forests and old-growth forests apparently provide similar habitat values.

Forest bird species such as woodpeckers, creepers and nuthatches, that nest in tree cavities and forage for insects living in snags, occur in both old-growth and second-growth stands. However, some cavity-nesting species appear to be more abundant in old-growth stands, presumably due to a greater abundance of snags (Seip and Savard 1991).

Current forest harvesting methods and intensive silvicultural treatments, such as spacing and thinning, may not produce second-growth forests that are comparable to the second-growth stands resulting from logging and forest management practices of 40-80 years ago. In the past, low value trees were often left unharvested and the naturally regenerating forests were not spaced or thinned. It is likely that more recent forest harvesting and management practices will not produce second-growth forests that provide abundant snags. Consequently, there is increasing interest in implementing modified harvesting and silvicultural practices that provide snags and other wildlife habitat attributes in second-growth stands.

Although most vertebrate species appear to be able to live in clearcuts or second-growth forests, there are at least two species, the spotted owl and the marbled murrelet, that appear to be dependent on old-growth coastal forests. Old-growth Douglas-fir forests on south-facing slopes also provide the best winter range for black-tailed deer during severe winters.

Extensive research in Oregon, Washington, and northern California has demonstrated that spotted owls live almost exclusively in old-growth forests (Thomas et al., 1990). Spotted owls are classified as an endangered species in Canada. The historic range of spotted owls in Canada was limited to the southwest corner of British Columbia and barely extended into the Howe Sound area. Past logging has eliminated most of the old-growth forest along the shores of Howe Sound so any spotted owls that may have lived there were eliminated long ago. Recent surveys have failed to find any of these birds in remaining old-growth forests in the Squamish River watershed. Almost all of the spotted owls remaining in British Columbia are in the Fraser Valley and lower Fraser canyon.

The marbled murrelet is a seabird that feeds and spends most of the year at sea but in summer nests on mossy platforms in the branches of large conifer trees along the coast. Although nests are very difficult to locate, marbled murrelets can be detected in the early morning hours during the breeding season as they fly from the nest to the sea. Detection rates are much greater in areas with old-growth forest, which suggests that marbled murrelets nest primarily or exclusively in this habitat. Although marbled murrelets are currently abundant, with an estimated population of 45,000 birds in B.C., they are classified as a threatened species because the continued harvesting of old-growth forests may endanger the species in the future (Rodway, 1990).

Marbled murrelets are present on the water in Howe Sound but to date, no surveys have been conducted in the surrounding forests. Marbled murrelets have been detected in old-growth stands in the nearby Capilano Valley and those birds may feed in the waters of Howe Sound.

FOREST MANAGEMENT IMPLICATIONS

Most forest-dwelling wildlife species in the Howe Sound area can probably be maintained in second-growth forests if those forests are managed to provide important wildlife habitat attributes. However, there is a need to protect some old-growth forests in the watershed if all native species are to be maintained. Important deer winter ranges and marbled murrelet nesting habitat needs to be identified and protected.

Provision of a mixture of clearcuts, old-growth forests and an age range of second-growth forests in the watershed would provide habitat for a diverse mix of wildlife species. Extensive, progressive clearcuts do not produce a good mixture of habitat types.

Modified harvesting and silvicultural practices that provide important wildlife habitat characteristics, especially snags, in second-growth forests are likely required if those forests are to provide good habitat for cavity-nesting bird species. Practices such as leaving small patches of snags and trees in clearcuts during harvesting and retaining firm snags during thinning would enhance wildlife habitat characteristics in second-growth stands.

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Table 1. Breeding birds detected in coastal forests on the South Coast, B.C.

	Old Growth	40-80 Year Old	Clearcuts
MacGillivray's warbler			♦
Orange-crowned warbler			*
Dark-eyed junco	*	*	♦
Swainson's thrush	*	*	*
Winter wren	♦	♦	*
Pacific slope flycatcher	♦	♦	
Townsend's warbler	♦	♦	
Chestnut-backed chickadee	♦	♦	
Golden-crowned kinglet	♦	♦	
Red-breasted sapsucker	*	*	
Hairy woodpecker	*	*	
Brown creeper	*	*	
Red-breasted nuthatch	*	*	
Varied thrush	♦	*	
Spotted owl	*		
Marbled murrelet	*		

* present
♦ common

Table 2. Small mammals and amphibians captured in coastal forests on the South Coast, B.C

	Old Growth	40-80 Year Old	Clearcut
Montane shrew	♦	♦	♦
Cinereus shrew	♦	♦	♦
Wandering shrew	*	*	
Shrewmole	*	*	*
Deermouse	♦	♦	♦
Jumping mouse	*	*	*
Long-tailed vole	*		♦
Red-backed vole	*	♦	*
Chipmunk			♦
Douglas squirrel	♦	♦	*
Flying squirrel	*	♦	
Short-tailed weasel	*	*	*
Ensatina salamander	♦	♦	♦
Red-backed salamander	*	*	*

* present
♦ common

SALMONIDS AND THEIR HABITATS IN HOWE SOUND BASIN:
STATUS OF KNOWLEDGE

by

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V9R 5K6

INTRODUCTION

In this paper we review the current status of salmon populations and their habitats in Howe Sound and rivers draining into the fjord. Before closure of commercial fishing in Howe Sound in 1968, the Sound was a major harvest area for salmon, particularly for chum, pink, and chinook salmon (Anon, 1980). Since 1963, salmon produced in rivers flowing into the Sound are taken in net and troll fisheries outside the fjord, including U.S. waters. Recreational fishing for salmon is still pursued in the Sound and freshwater sportsfishing for steelhead and trout is important in the watershed. In 1957 a limit (two fish per day) was placed on chinook salmon caught by sports fishing in the inner part of the Sound in July and August. In more recent years this has been extended to a complete closure for chinook salmon sports fishing in summer and fall in the inner Sound. Because of the depressed condition of the chinook salmon stocks of the Squamish River we have provided a detailed review of their population dynamics and recommendations for research to improve knowledge on this topic.

DISTRIBUTION OF SALMONIDS IN HOWE SOUND BASIN

Chum salmon (Oncorhynchus keta): Chum salmon have been reported as spawners in almost all the rivers and creeks draining into Howe Sound, except those with very steep gradients near their mouths (Fig. 1). An exception is Britannia Creek where acidic water draining from copper deposits has apparently prevented colonization by fish (Broughton, 1992). Since 1984, spawning chum salmon have been reported from Mill Creek, at Woodfibre, where they were previously excluded due to pulp mill pollution (F. Vosey, DFO., pers. comm., November 1991). The majority of chum salmon using Howe Sound basin spawn in the lower reaches of the Squamish River and its tributaries. Chum fry use the Squamish Estuary as a rearing area (Goodman and Vroom, 1972; Kask and Parker, 1972; Levy and Levings, 1978; Ryall and Levings, 1987) and have been reported using foreshore habitat near the mouth of the Rainy River (Birtwell and Harbo, 1980).

Coho salmon (Oncorhynchus kisutch): spawning coho salmon have been reported from streams draining directly into Howe Sound (Fig. 1). In the Squamish River system, spawning coho have been reported from a number of tributaries, including some on the upper reaches such as Shovelnose Creek (Argue and Wilson, 1978). Coho salmon fry rear in freshwater for at least one year and there is evidence from Howe Sound that this species also uses the estuary in the fry and smolt stages. Argue and Armstrong (1977) and Clark (1981) reported that the Little Stawamus River and several tributaries to the Cheakamus, Squamish, and Mamquam Rivers were major rearing areas for coho salmon fry. The Squamish River Estuary has also been reported as a rearing area for coho salmon fry (Ryall and Levings, 1987) and smolts (Levy and Levings, 1978; Kask and Parker, 1972).

Pink salmon (Oncorhynchus gorbuscha): Spawning pink salmon were abundant in past years in the Squamish River but now are scarce. Clark (1981) reported adult pink salmon from four tributaries, in addition to the mainstem river. Pink salmon were also reported from the Rainy River and McNab Creek (Knapp and Cairns, 1978). Pink salmon move to the sea almost immediately after emergence and do not rear in estuaries.

Chinook salmon (Oncorhynchus tshawytscha): Chinook salmon spawn throughout the Squamish River, especially in the mainstem river above the confluence with Ashlu River and in the Cheakamus River above Culliton Creek. However spawning adults have also been reported from several other tributaries, including the Mamquam River where adults originating from a net pen rearing facility at Porteau Cove operated by the Salmonid Enhancement Program were observed in autumn 1990 (C. West., DFO., pers. comm., November 1991). Juvenile chinook salmon have been observed in the Squamish River in autumn (Clark, 1987) and these fish were probably about to begin winter rearing. Juvenile chinook salmon have also been found in the Squamish Estuary during late spring and summer (Levy and Levings, 1978).

Sockeye salmon (*Oncorhynchus nerka*): There are a few observations of adult sockeye salmon in the Cheakamus River (DFO, 1988). If sockeye salmon are present in the Squamish River watershed this species would be rearing in the river as there are no major lakes in this system.

Steelhead and rainbow trout (*Oncorhynchus mykiss*): Steelhead are widely distributed in the Squamish River watershed and have been reported as juveniles or adults in 28 tributaries as well as the mainstem Squamish River. Steelhead also use the Little Stawamus River (Clark, 1981). Rainbow trout have been stocked in many of the lakes of the Squamish River watershed. Rainbow trout have been reported from 14 tributary streams in addition to the mainstem Squamish River (Hartman and Gill, 1968; Clark, 1981). Steelhead have also been reported from the following streams on the west side of Howe Sound: Potlatch Creek, McNab Creek, Rainy River, McNair Creek, Dakota Creek, and Langdale Creek (DFO, 1991)

Cutthroat trout (*Oncorhynchus clarkii clarkii*): Cutthroat trout have been reported from 16 streams in the Squamish River drainage basin as well as the mainstem Squamish River (Hartman and Gill, 1968; Argue and Armstrong, 1977; Clark, 1981). The presence of cutthroat trout has been noted in almost all the small streams on the west side of Howe Sound and on Bowen and Gambier Islands. (DFO, 1989 and 1991). The fish observed were probably a mixture of resident and anadromous forms of cutthroat trout. The anadromous form has been reported from the Squamish Estuary (Levy and Levings, 1978). Spawning cutthroat trout have been observed in the upper portion of the central basin of the estuary (CDL, unpublished data).

Dolly varden char (*Salvelinus malma*): Dolly Varden have been recorded as adults or juveniles in 15 tributaries of the Squamish River. Dolly Varden are found throughout the length of the Squamish River, including the upper reaches of the river not utilized by other salmonids. This species has also been reported from Potlatch Creek and Rainy River, on the west side of Howe Sound (DFO, 1991) and from the Little Stawamus River (Argue and Armstrong, 1977). Levy and Levings (1978) recorded Dolly Varden in the Squamish River Estuary.

Eastern brook trout (*Salvelinus fontinalis*): Eastern brook trout have been introduced to certain lakes in the Squamish River watershed (B. Clark, B.C. Ministry of Environment, Lands and Parks, pers. comm., October 1991). Josephine Creek, on Bowen Island, was also reported to support a population of this species (Anon, 1980).

STATUS OF KNOWLEDGE OF HABITAT CONDITIONS

SPAWNING HABITATS

Few specific data are available on the amount, availability, and condition of the natural spawning habitats for any of the salmonids in the Squamish River watershed or the smaller drainage basins on Howe Sound. For example, the Stream Summary Catalogue for the Squamish River (DFO, 1988) only provides general information on spawning areas in the Squamish River basin. This catalogue also provides observations or anecdotal information on the type of disruption that might be affecting freshwater habitats. The most frequently mentioned disruptive influences include gravel removal, urban development (e.g., housing), linear development (especially dyking in the lower reaches of the Squamish and Mamquam Rivers, but also road, railway, pipeline, and powerlines), flow diversions, and logging.

Some quantitative data on steelhead spawning habitat in the Squamish River are available. Clark (1988) stated that Reach 3 (19 km reach between the confluence with Ashlu Creek and the "32 mile rapids") contained the majority of the habitat suitable for steelhead spawning and rearing in the mainstem Squamish River.

One of the problems for salmon spawning may be on the Cheakamus River, where diversion of water from Daisy Lake through a hydroelectric facility has modified the mean flow and the range of flows. The flow modifications are thought to have major effects on spawning success and egg survival for chinook salmon which spawn in the lower Cheakamus (Hirst, 1991) but detailed data are not available on this topic. Fall and winter freshets in the Squamish River, which are thought to be more frequent and intense in recent years, may affect chinook salmon spawning habitats in the mainstem river. Chum and coho salmon tend to use tributaries and side channels as spawning areas.

Spawning channels have been developed by the Salmonid Enhancement Program (SEP) in the lower Squamish and Mamquam Rivers. Approximately 15,000 m^2 of spawning habitat were developed by modification of existing gravel or by importing graded gravel (Bonnell, 1991). These channels were built to enhance chum production but are also being used by coho salmon (Bonnell, 1991). Incubation boxes were built to increase coho salmon production on a number of smaller systems within the Howe Sound watershed.

The Rainy River was dammed in the early 1900's for water storage for the Port Mellon pulp mill which created a migration block for coho and chum salmon. A fishway was built on the river. Urbanization has affected spawning habitat on some of the small creeks on the west side of Howe Sound (e.g., Langdale Creek) but most of these systems have supported small spawning populations of chum salmon in recent years (Gould et al., 1991).

REARING HABITATS

A. Freshwater Rearing Habitats

A few quantitative studies on fry rearing habitat for coho salmon and steelhead have been conducted in the Squamish River watershed but almost no information is available for the other species of salmonids. As mentioned above, the Stream Summary Catalogue (DFO, 1988) provided anecdotal information on freshwater disruption that might be affecting freshwater rearing of juvenile salmon.

Based on electrofishing surveys in October in several habitat types within Reach 3 of the Squamish River, Clark (1988) found that the abundance of salmon fry varied between habitats (Fig. 2). Steelhead and coho salmon fry were most abundant in tributaries and groundwater-fed side channels, whereas chinook salmon fry were more numerous in mainstem habitat downstream of the canyon near the confluence with the Elaho River. In the mainstem above the canyon, Dolly Varden char and steelhead were the only species caught. Clark (1988) observed that steelhead fry from groundwater-fed sites off the main channel were larger than those using the mainstem and inferred the former habitats were more productive. Although the groundwater-fed channels comprised only 7% of the available habitat, they were thought to producing 57% of the steelhead fry from Reach 3. Steelhead fry were found to be the most abundant salmonid in a 16 km reach of the mainstem Cheakamus River below Daisy Lake in October 1988 (Clark, 1989). Mean density (number/100m^2) over 7 sites was as follows: steelhead - 164; coho salmon fry - 16; chinook fry - 2; and Dolly Varden - < 1.

Quantitative data on the density of coho salmon smolts that were produced from fry reared in streams were obtained by Argue and Armstrong (1977) in three areas near Squamish. The mean density of coho salmon smolts in the Little

Stawamus River was 54 fish 100/m^2; in Meigan Creek, 44 fish 100/m^2; and in Tenderfoot Creek (including Mosley Lake), 59 fish 100/m^2. Argue and Armstrong (1977) concluded that the three systems they studied, especially Tenderfoot Creek and its headwater, Mosley Lake, provided valuable habitat for natural production of coho salmon.

B. Estuary and Marine Rearing Habitat

In 1972, when total development of the estuary was proposed for a major coal port, sampling in the intertidal portion (Goodman and Vroom, 1972) and offshore at the mouth of the Squamish River (Kask and Parker, 1972) showed that the estuary was used extensively as rearing habitat for young salmon. Later studies showed the salmon fry and smolts were dependent on invertebrate food such as amphipods, mysids, and insect larvae (Levy and Levings, 1978; Ryall and Levings, 1987) which in turn relied on detritus from the sedge plants that dominate the flora of the estuary. The abundance, timing, and growth patterns of salmon fry using the estuary were closely related to the patterns of plant and invertebrate production. Levings and Moody (1976) described levels of primary production in the sedge marshes (Carex lyngbyei) which dominate the intertidal zone of the estuary. Stanhope and Levings (1985) described secondary production of an amphipod, one of the key invertebrates used by juvenile salmon in the estuary.

Loss of estuarine habitat began in the Squamish Estuary near the turn of the century when the settlers built dykes to protect their homes and farms from flooding (Deans, 1992). Since then, landfilling, port construction, and log storage have alienated further areas of rearing habitat. According to maps prepared by the B.C. Ministry of Environment based on aerial photos from 1976 (Anon, 1980), approximately 26.4% (2,545.7 ha from 9,636.9 ha) of the backshore/lowland and intertidal areas within the estuary boundaries were considered disturbed or developed.

Judging from research conducted in the 1970's and 1980's, water quality degradation due to disposal of pulp mill effluent discharged into the intertidal zone at Port Mellon was implicated in behavioural and physiological changes of juvenile salmon using littoral habitats for rearing (e.g., Birtwell and Kruzynski, 1989; Davis and Mason, 1973). Effluent from both the Port Mellon and the Woodfibre pulp mills is now discharged well below the surface (Swain et al., 1992; Rempel, 1992) which is thought to be less hazardous for salmon. Use of shorelines by juvenile salmon in Howe Sound has not been adequately researched but is likely to be significant. For example, Birtwell and Harbo (1980) found that juvenile chum salmon were the most abundant salmonids in beach seining surveys on Thornbrough Channel. Shorelines have been permanently disrupted by disposal of mine tailings at Britannia Beach, acid rock drainage at the mouth of Britannia Creek and dock construction at several other locations (Levings and McDaniel, 1976).

STATUS OF KNOWLEDGE: CHINOOK STOCK DYNAMICS

In theory, assessment of a salmon population involves determining the rate of adult returns from fish reproducing (spawners) in the previous generation, determining the desired number of spawners to maximize annual returns (the management goal), and comparing the present number of spawners with this goal. The Ricker production curve (Ricker, 1954), commonly applied in managing Pacific salmon, is exemplified in Figure 3. In this figure, lines B and C represent two production curves (adult returns per spawner); line B having higher productivity (i.e., greater returns per spawner at low spawning numbers). Line A is referred to as the replacement line where the adult returns only equal the number of spawners. The greatest difference between line A and lines B or C (line segments D and E, respectively) estimates the maximum catch allowable while maintaining the desired number of spawners. The number of spawners which maximizes the allowable catch is called the optimum number of spawners and is the management goal. A population with high productivity has greater allowable catch at a lower optimal number of spawners; indicating that the population can sustain a higher exploitation rate than a less productive population. Ideally, a management agency would determine such productivity curves for each salmon population thereby maximizing the total available catch if each population could be harvested separately (Ricker, 1958). However, in actuality, we seldom have the data necessary to accurately estimate these curves because the catch of each population is unknown and the number of spawners difficult to estimate. Consequently, management of most salmon populations assumes the above theory but assessment frequently depends on the trends in escapement estimates, and comparing recent escapements to the management goals. Further, these goals are seldom based on production curves but may be based on habitat capacity or simply be interim management goals established to protect a population while biologically-based goals can be determined.

Assessment of Squamish River chinook is uncertain because the vast majority of the adult returns are caught in large mixed-stock fisheries and because the visual estimation of spawners is highly unreliable in the glacially turbid water. However, visual estimates of spawners may be a consistent index of escapement trends (Healey, 1982). Consequently, the marked decline in spawning escapement of Squamish chinook (Fig. 4) is considered strong evidence that chinook production is very depressed; present escapements being less than 10% of pre-1970 levels. Recoveries of coded-wire tagged chinook (Jefferts et al., 1963) from Tenderfoot Hatchery demonstrate that these chinook are widely distributed northward along the coast (Fig. 5), and tend to be caught further north at older ages.

Average catch distribution of Tenderfoot Hatchery chinook cohorts from the 1981 through 1984 brood years. The average distribution is unweighed between brood years and represents the distribution over ages 2 through 5.

Fishery	% of Total Catch
Strait of Georgia Sport	39.0%
North & Central B.C. Nets	23.4%
Alaskan Troll, Net, Sport	12.6%
North & Central B.C. Sport	9.5%
North & Central B.C. Troll	6.4%
Strait of Georgia Troll	4.4%
Southern B.C. Nets	3.4%
Northern Washington State Nets	1.0%
West Coast Vancouver Island Troll	0.2%

Results from this tagging indicate that Squamish chinook differ from other local chinook populations (for example Cowichan, Nanaimo, or Big Qualicum chinook) in that a larger portion of the Squamish population migrate outside of the Strait of Georgia at an earlier age. Over 50% of the age 2 recoveries from these brood years were from northern and central B.C. net fisheries, whereas the majority of the other populations are recovered in the Strait of Georgia sport fishery.

Future chinook returns may be assisted by the increase in chinook released from the Tenderfoot Hatchery on Cheakamus River but significant returns from the hatchery releases have not yet been observed. Hatchery expansion in the mid-1980's increased chinook releases from approximately 200,000 to over 1 million annually (Fig. 6). Further, the implementation of sea-pen rearing of chinook smolts, commencing with the 1987 brood year, seems to be improving the survival rate of these smolts.

Prognosis for Rebuilding Chinook Production

Efforts to control exploitation of Squamish chinook have been undertaken since 1968 when Statistical Area 28 (including Howe Sound) was closed to commercial fishing for all salmon. In the early 1980's sport fishing for chinook was also closed, and since 1985 two additional programs have been implemented to rebuild chinook escapements. These programs follow from the coast-wide chinook rebuilding program implemented by the Pacific Salmon Treaty (Pacific Salmon Commission, 1986) and the 1988 chinook conservation program implemented by the Department of Fisheries and Oceans. The objective of the former program was to reduce the brood year exploitation rate on chinook salmon by 15 percentage points through catch limitations in ocean troll, ocean sport, and northern net fisheries, and harvest rate limitations in southern B.C. net fisheries. The latter program was specifically targeted at reducing the harvest rates in the principal fisheries exploiting chinook salmon originating from the southern portion of the Strait of Georgia. For both of these programs, an interim spawning escapement goal was established as twice the average escapement during the 1979-1982 period. The rebuilding goal is consistent with a Departmental policy decision which recognized the limitations of our biological information but the need for fishery management objectives. For most chinook populations in British Columbia, doubling the 1979-1982 average escapements resulted in a goal below previously observed escapements, but doubling was considered to be a large enough change in escapements that the resulting production could be assessed. Unfortunately, spawning escapements since 1985 have not increased as anticipated (Fig. 7).

In Figure 7, the estimated number of spawners (line with open squares) are the same values as in Figure 4, but the total return includes the spawning escapement plus the catch by Native peoples and chinook removed from the natural spawning populations for brood stock in the hatchery. The expanding difference between these lines indicates greater recent removals as the Native catch and brood stock requirements increased. The dashed straight line at 6,860 spawners is the management goal and, under the Pacific Salmon Treaty, was to be achieved by 1998. The straight dotted line from the base period (1979-1982) average escapement in 1984 to 6,680 spawners in 1998 is simply a linear approximation to the rebuilding rate required to achieve the goal by 1998. It is immediately obvious that since 1985 the number of spawners has not progressed towards the escapement goal.

Achieving the aggregate escapement goal for chinook in the lower Strait of Georgia (aggregate goal for the Nanaimo, Cowichan, and Squamish river chinook) is a requirement in the Pacific Salmon Treaty. However, to achieve the goal will require a substantial increase in the Squamish chinook escapement, possibly not to its goal but certainly above recent levels. This may be accomplished by relying on hatchery returns since the facility has been expanded and sea-pen rearing is now being used; or by further reducing exploitation in fisheries. The latter, however, would be a serious action with significant socio-economic implications particularly in the Strait of Georgia. Within the Strait, recreational fishing alone is estimated to generate $0.5 billion per year and involve over 400,000 persons (Price Waterhouse, 1990). It is, therefore, essential to investigate all possible explanations to the lack of rebuilding before further management actions are implemented. Explanations may include escapement estimation procedures that are simply insensitive to changes in small population sizes (recent escapements being less than 1,000 chinook), or more complex problems such as habitat alterations that have reduced the productive capacity for chinook salmon in the Squamish River. Habitat change is an important consideration since productive capacity and exploitation rates are inter-related. For example, in Figure 3, if curve B was the original production curve for Squamish chinook but productivity was reduced (curve C) due to habitat changes, then fishing plans resulting in exploitation rates sustainable by curve B would over exploit a population represented by curve C. The result would be that the population size of the lower productivity population would stabilize at a value below the optimum and the population would not rebuild because of insufficient numbers of spawners.

Salmon habitat in the Squamish river (recurrent major floods, altered flow in the Cheakamus River, logging, etc.) and the estuary has been lost or disturbed. Consequently, an important assessment issue is to differentiate habitat and exploitation causes of the continued low spawning escapement. A multi-disciplinary and agency approach to such a large scale project may be the only way to initiate the required studies and would be a important recommendation from this workshop. The Squamish chinook stock is the only significant summer-run timing chinook stock remaining in coastal southern B.C. and could be an invaluable resource if rebuilt to previous abundances.

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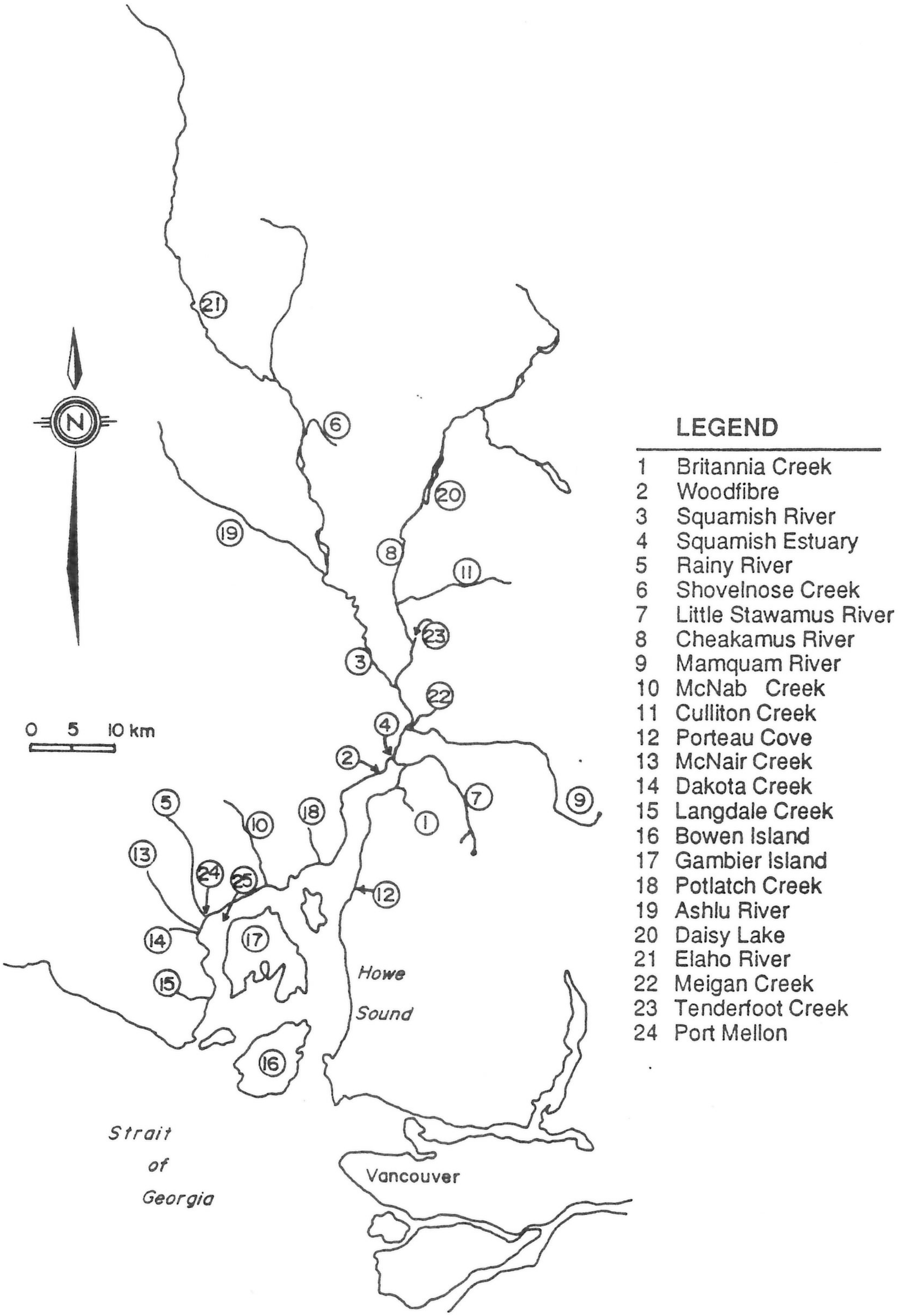

Figure 1. Map of Howe Sound showing some creeks and rivers used by salmonids.

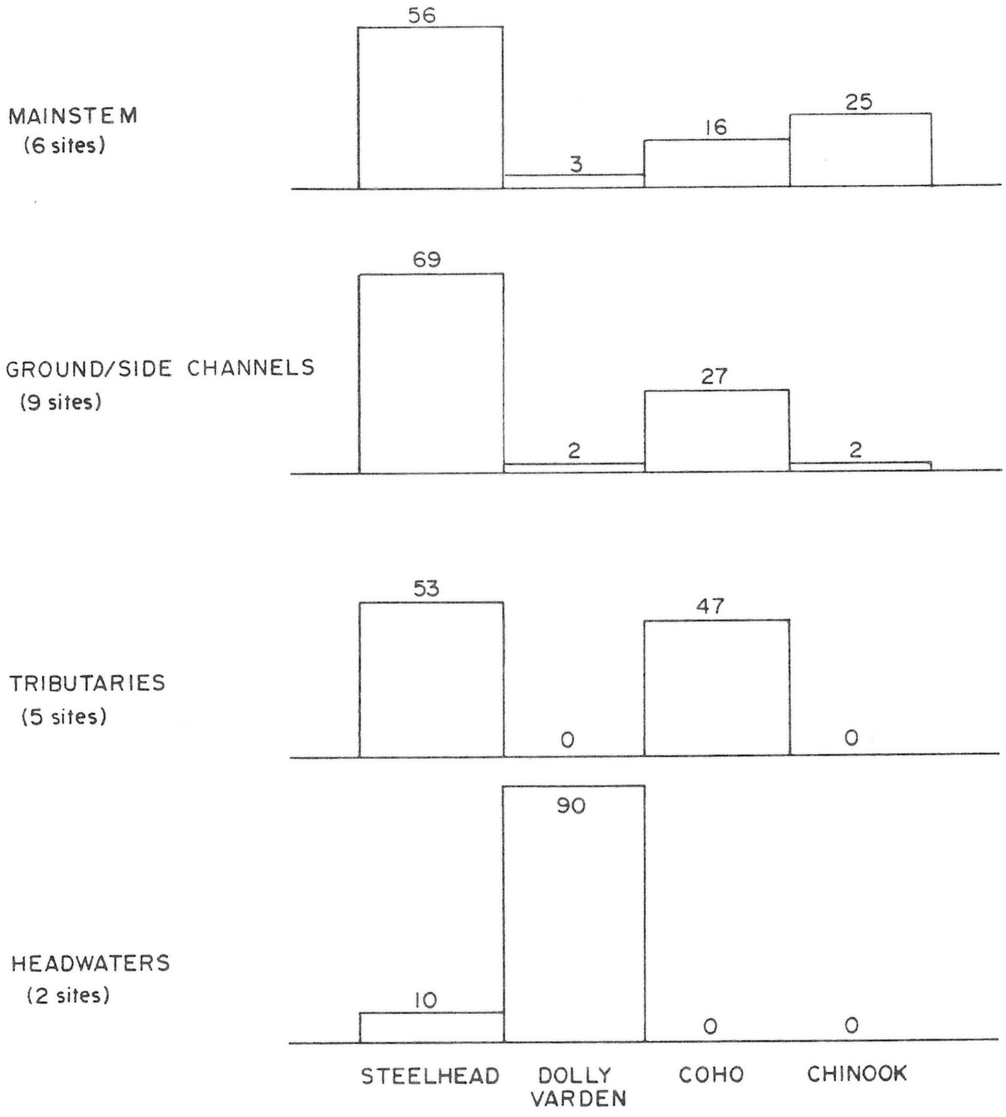

Figure 2. Percentage abundance (numerical data) of juvenile chinook, coho, steelhead, and Dolly Varden in various habitats at Reach 3 in the Squamish River (From Clark, 1988).

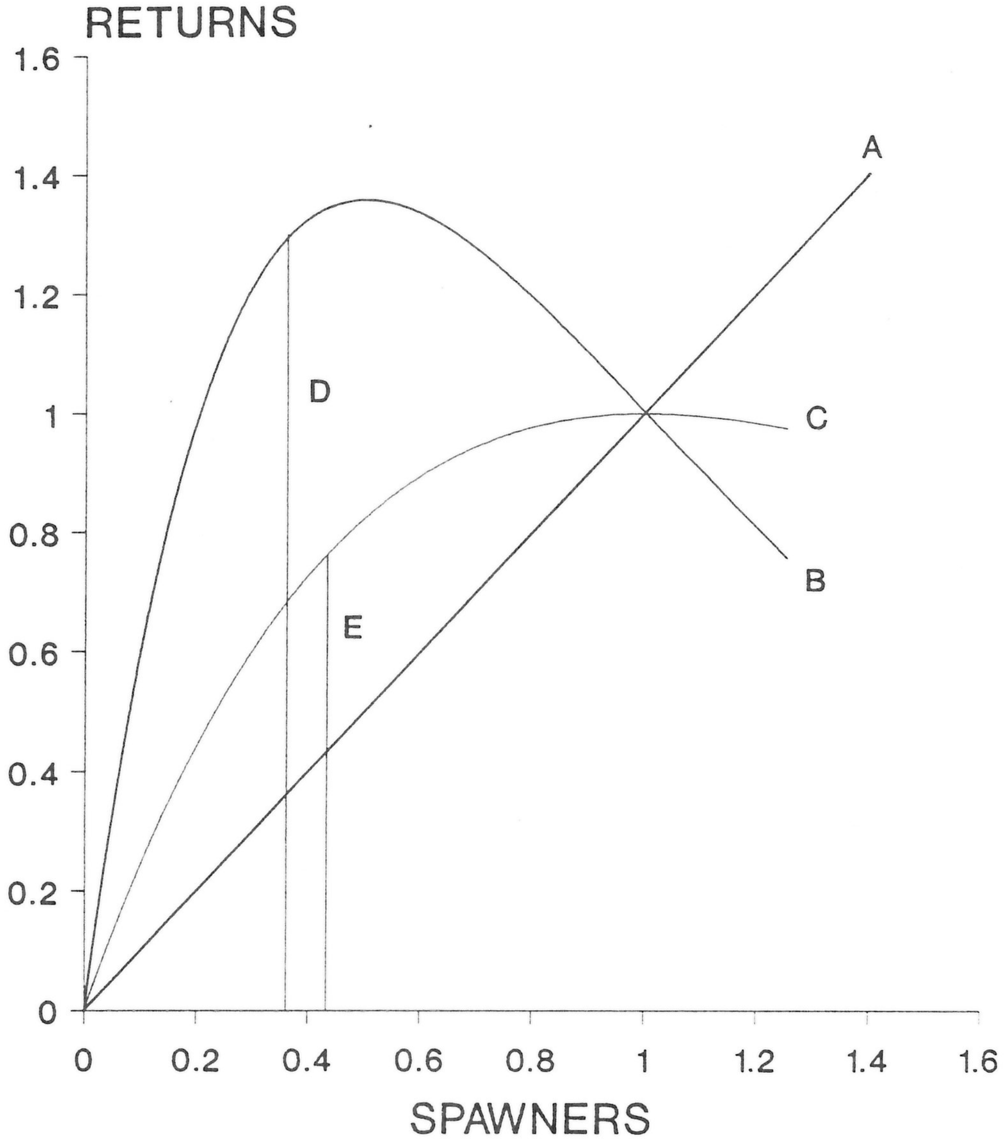

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Figure 3. Schematic Ricker production curves relating the expected adult salmon returns to the number of reproducing fish (spawners) in the previous generation. Letter labels are explained in the text.

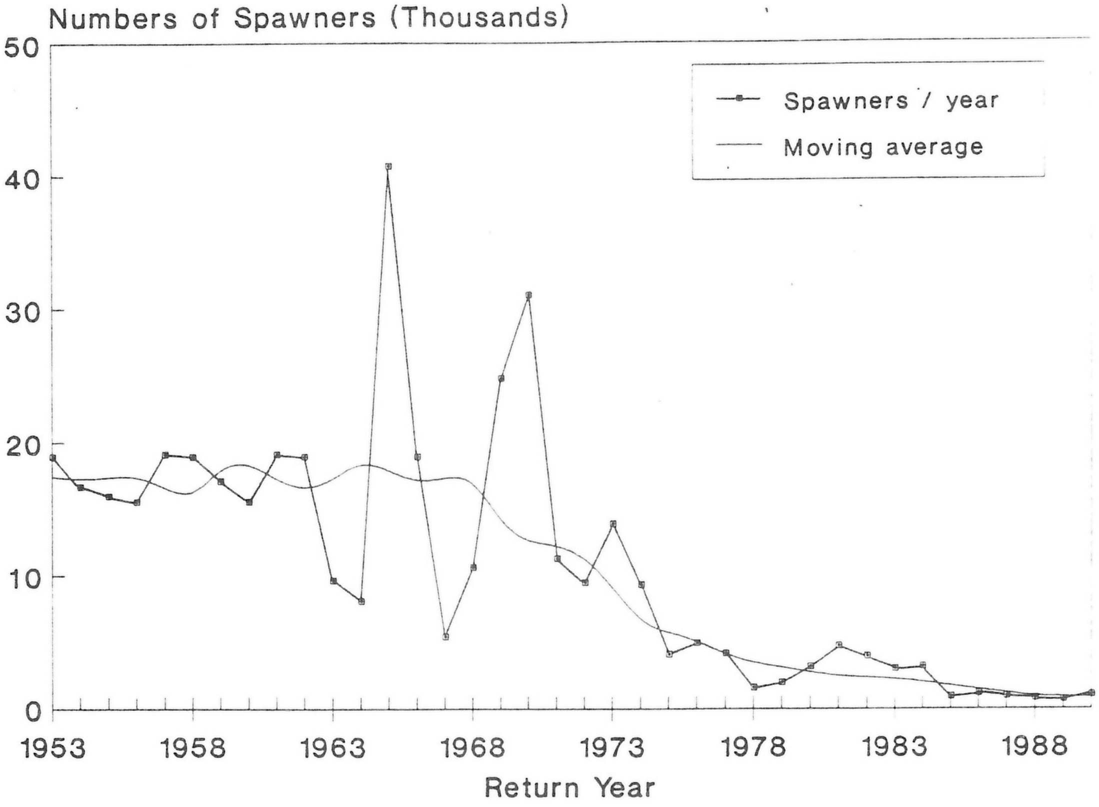

Figure 4. Annual number of chinook salmon reported to reproduce (number of spawners) in the Squamish River (including all tributaries), and a 9-point moving average to smooth the annual variability. Nine years was selected because of the multiple ages at spawning in chinook (usually over 3 major age classes) and the age-at-maturation in this stock (up to 6 years).

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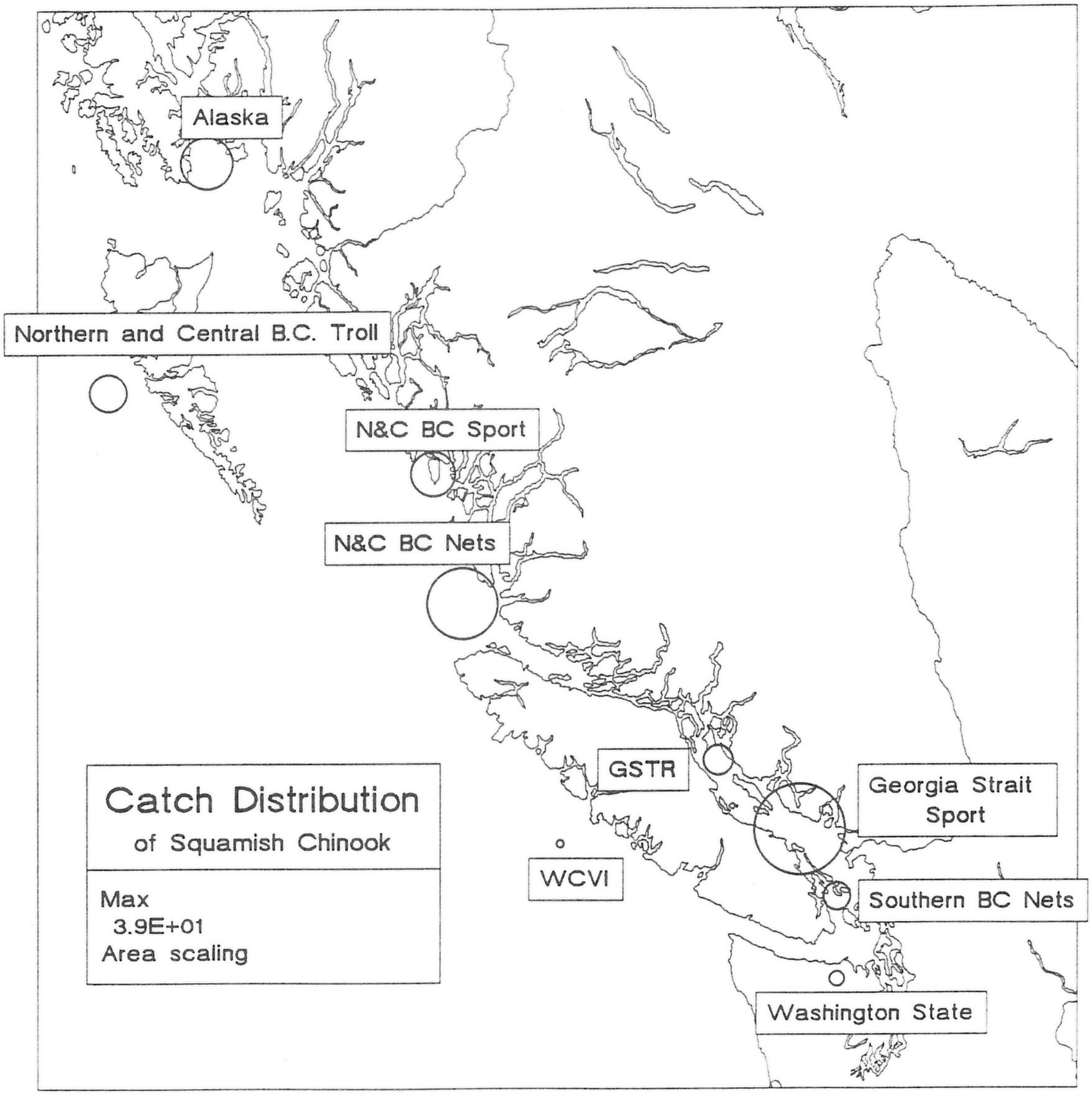

Figure 5. Catch distribution of tagged Tenderfoot Hatchery chinook salmon from the 1981 through 1984 brood years. The diameter of each circle is proportional to the largest circle (Georgia Strait Sport) which reported 39% of the total recoveries over all ages and years.

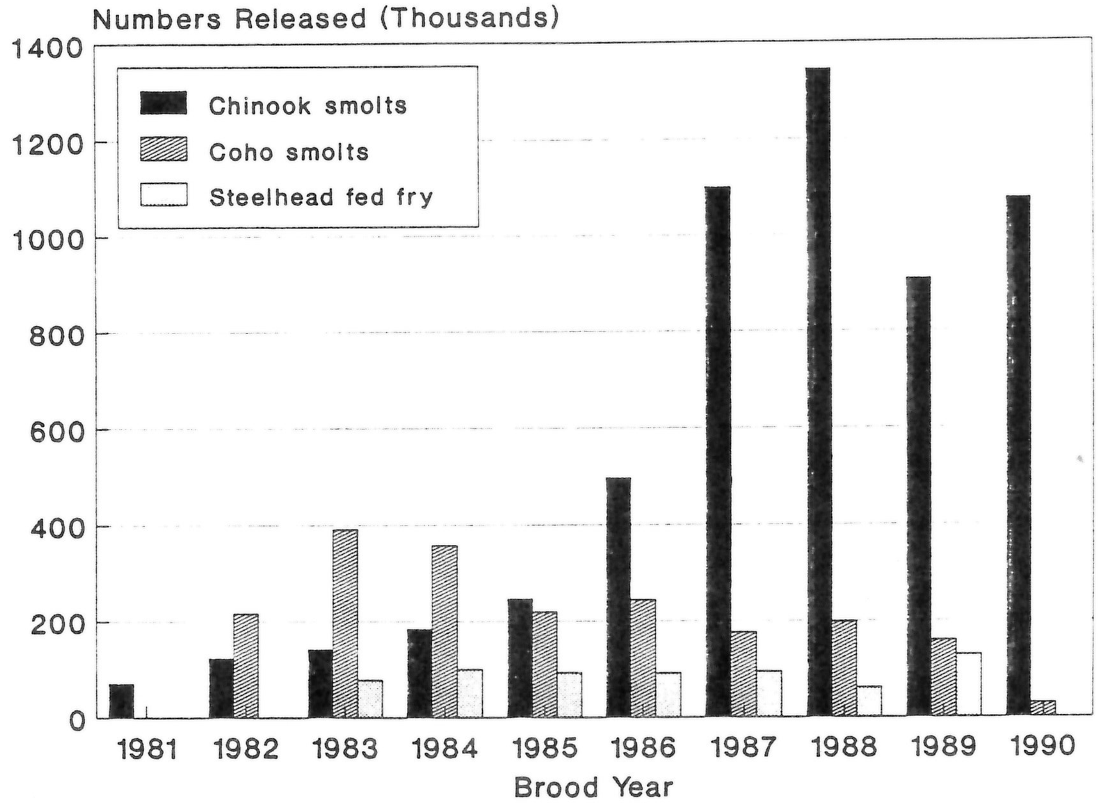

Figure 6. Numbers of Chinook smolts (underyearlings), Coho smolts (yearlings), and Steelhead fed fry released from the Tenderfoot Hatchery.

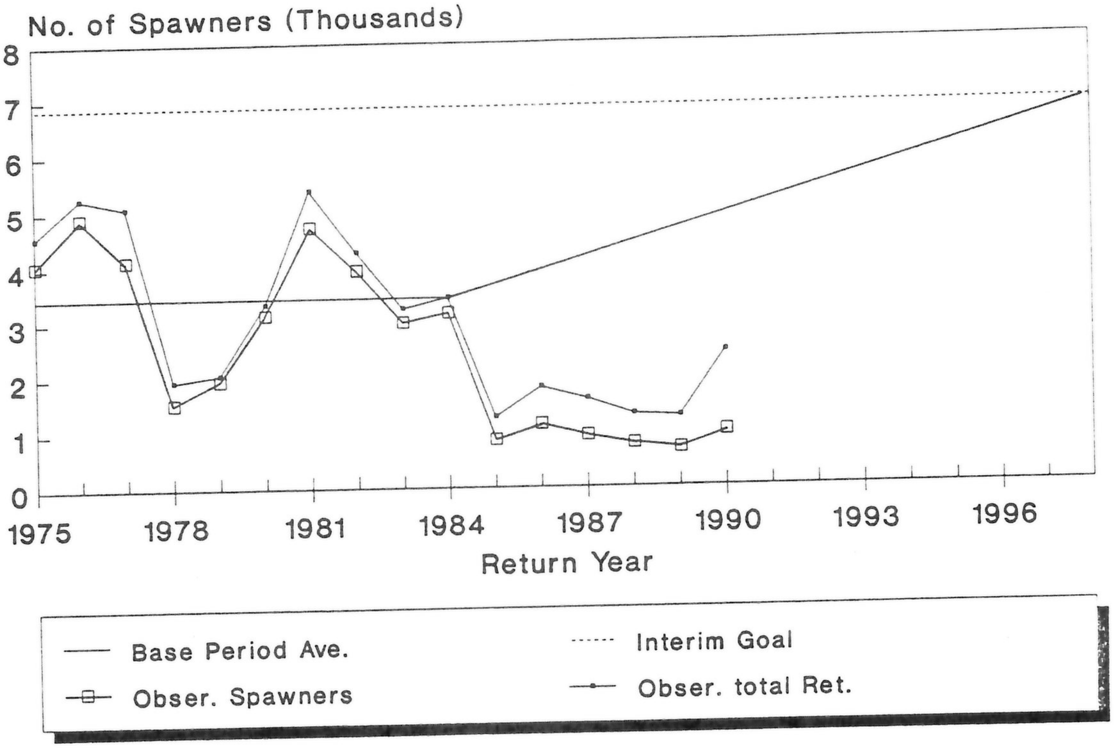

Figure 7. Numbers of chinook spawning (Obser. spawners) and total chinook return to the Squamish River (Obser. total ret.) since 1975, and a linear approximation to the rebuilding schedule required to comply with the chinook rebuilding program in the Pacific Salmon Treaty.

SQUAMISH ESTUARY MANAGEMENT PLAN: HISTORY AND CURRENT STATUS

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BACKGROUND

Ever since the white man landed at the mouth of the Squamish River, there have been incursions in the Squamish estuary. Some of the types of economic activity which put pressure on the estuary over the past 100 years or so include log storage, deep sea port development, industrial activities, flood protection, and many small foreshore developments. These types of projects are still being dealt with by habitat managers today.

In the early years, development of estuary lands was seen as a necessity. In later years, development activity was met with a growing determination to protect the natural estuary values. The most recent significant alteration of the estuary occurred between 1968 and 1972 when the Squamish Terminals and B.C.Rail's "Training Wall" (Fig. 1) with its infamous "dredge spoil site" were constructed without a great deal of successful opposition.

However, more recently stronger environmental legislation has been passed by government and regulations and guidelines have become factors to be dealt with. This has led to the development of the Squamish Estuary Management Plan.

THE PLAN

In May 1979 the federal and provincial governments announced their intention to establish the Squamish Estuary Management Plan. The Plan was to be a decision making framework for determining the best use for the lands and waters of the Estuary. The process was to have its foundations in the results of four technical reviews. These were: air and water quality, land and water use, recreation, and habitat. The technical documents reviewed the current situation and contained recommendations for managing activities which fell under their purview.

The proposed Plan was to have several key features:

- an environmental review process
- public involvement
- an amending process that could involve Ministers
- all approving agencies were to be involved
- major property owners were to be part of the process
- area designations were to be used to identify expectations for the entire estuary

In 1982 the Plan was completed and, while some might say that it was never ratified by the Ministers of the day, it is the process that is being used to manage the Estuary at this time.

THE PROCESS

The Plan is managed by the Squamish Estuary Coordinating Committee (SECC) with the support of a technical sub-committee called the Squamish Estuary Environmental Assessment Committee (SEEAC). The land and water covered under the plan is called the "Estuary Study Area" (Fig. 1). All work proposed for the study area must be reviewed by these two committees. At the request of SECC, SEEAC reviews each proposal and works with the proponents to ensure that all impacts are properly considered. Their recommendations are presented to SECC who then give the proposal its approval or denial.

This process is similar to those now used in the other project review processes in the British Columbia, under federal or provincial legislation. There is, however, one minor difference.

As mentioned above, the guides used in the Plan are the "Area Designations". As shown in Figure 1, the estuary has been divided into three categories: Conservation, Planning and Assessment, and Industrial/Commercial. These designations establish the expectations for the usage of habitats with differing values. The designations provide the foundation for the decisions made by people using the Plan.

A unique feature of the SECC is membership. All the environmental agencies are represented on the SECC as well as the major land holders in the estuary and those ministries which have mandates for economic development in the province. This membership provides the ingredients for "Environmentally Sustainable Development". The Committee, therefore, could well represent the first, if not the only, environmentally sustainable development process in the province. In the SECC forum, all of the objectives associated with a given development are placed on the agenda, discussed, and decisions made by concensus.

The public are also asked to participate in the process by commenting on a proposed development. Information is made available from the public registry at the local library.

SECC members have found that not all citizens agree with decisions made by the Committee. However, in general the SECC seems to be a workable forum for dealing with development issues in the estuary.

Examples of proposals reviewed

The following describes three examples of actions taken as a result of the SECC. They have been chosen because they represent three different directions the Committee has taken.

1. The West Barr Industries Expansion in 1986 (Fig. 1):
    - the outcome was the expansion of the dry-land sort operation in the central delta.
2. The Squamish Terminal Expansion (Fig. 1):
    - The proposal was rejected and the company was encouraged to redefine the way in which products were handled and stored.
    - Improved procedures for handling material were implemented and expansion was not needed.
3. Dredging of the Mamquam Channel and filling of the northern portion of the land, commonly called Site B, on the east shore of the Mamquam Blind Channel (Fig. 1)
    - A decision was made to allow the site to be filled. Subsequently, because of difficulties after the fill was placed, a fund of $30,000 was established to restore habitats on the west side of the central delta, designated as Conservation. The restoration action is still outstanding because the owner of the land refused to allow the habitats to be restored.

Recent Deliberations

The refusal of the land owner to allow remedial work to be undertaken in the conservation zone made SECC members realize that, in spite of the Plan, all the issues had not been tabled and fully discussed.

Subsequently, two new issues emerged. First, the land owners did not feel that the current draft of the Plan gave the certainty they needed to be able to attract developers and second, the area designations with the definitions of their use needed further resolution by further review.

The review began in 1985 with an attempt to refine the area designations. Additional studies were undertaken by the SEEAC and a proposal was tabled with the SECC by the SEEAC in 1986. The proposal was never accepted by SECC. The review stimulated discussion of the more fundamental question of just how much of the Estuary should be turned over to the developers. Discussions also involved the issue of how developers would be expected to contribute to the opportunity to establish environmentally sustainable economic stability in the Estuary.

In 1986 the SECC went "underground" and the minutes of SECC meetings at this time were not put into the local library. This action was taken in order to get to the heart of the issues, which had to be done confidentially. The land owners had to table their long range plans which were considered to be proprietary information that could have led to unhealthy speculation in the community. Without the tabling of the company's plans the issues could not be resolved.

In essence, the land owners wanted to know all the encumbrances on their properties before developing them. This was especially true for the environmental encumbrances related to possible habitat compensation. They felt that the properties would be more marketable if these environmental compensations were addressed at the time the Plan was fully implemented. Then their customers would only be responsible for the good environmental practices that are required of any development in order to mitigate impacts due to construction and operation of the facilities.

Area designations then had to be made and habitat classified so that environmental values could be attached to the various parcels of land and lead to the integration of the environmental and economic values of the Estuary. Once this was done, comparisons to the long-term goals and objectives of the land holder could be discussed.

The process is not yet complete. The SECC presented the proposed area designation plan and a revised management strategy for public comment in early November 1991. The Plan was available as a public document at that time (SECC,1991). The principle of the proposed Plan is based on categorizing part of the Estuary for conservation and part for economic development. The Plan also includes compensation schemes to ensure no net loss of habitat values.

REFERENCE

Squamish Estuary Coordinating Committee. 1991. The Squamish Estuary Management Plan: questions and answers. B.C. Environment, Surrey, B.C.

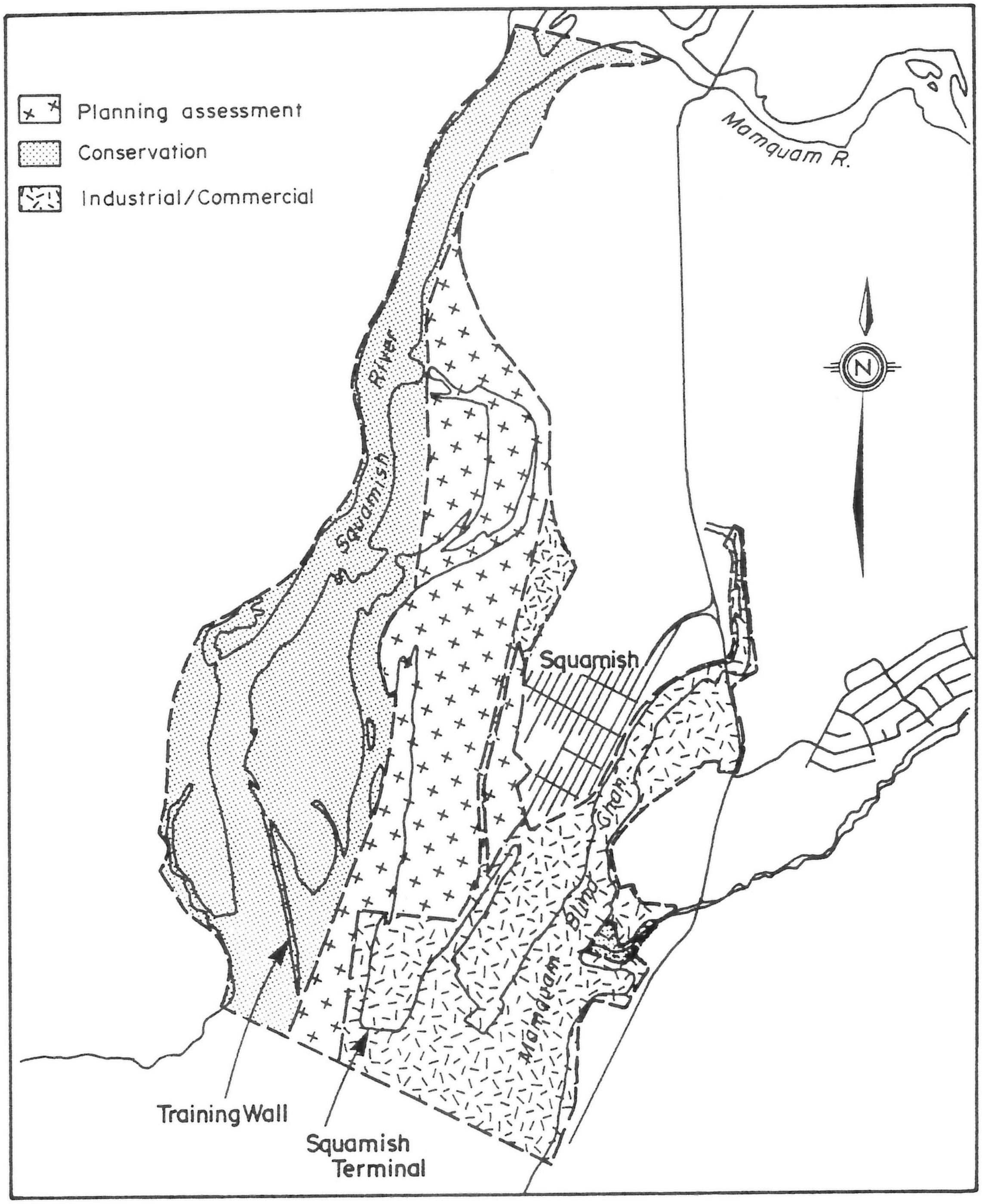

Figure 1. 1981 Squamish Estuary Management Plan area designations.

RECONNAISSANCE GEOCHEMICAL STUDIES IN THE HOWE SOUND DRAINAGE BASIN

by

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ABSTRACT

Geochemical surveys involving samples of water, sediment, seaweed, and tree tissues were conducted to identify sources and dispersion of natural and anthropogenic inorganic constituents throughout Howe Sound. All contained anomalous levels of Cu and Zn near the Britannia mine site, although no seaweed was present on shores for 1.5 km north and south of Britannia Beach, presumably due to metal poisoning. Surface waters in the Sound have significantly lower salinity than those below a few metres' depth, and chemical stratification of some elements occurs (e.g., As). The seaweed <u>Fucus gardneri</u> (Common rockweed) lines the shores of the Sound and is a sensitive indicator of many elements in the tidal environment.

A detailed study of waters and precipitates around the abandoned Britannia copper mine disclosed up to 44 ppm Cu and 26 ppm Zn in waters at the mine portals. Concentrations are reduced to 300 ppb at the mouth of Britannia Creek through dilution and co-precipitation with amorphous oxides. With the exception of Britannia, creeks flowing into Howe Sound contain low concentrations of most elements determined.

INTRODUCTION

In July 1991, geochemical investigations of the 42 km-long Howe Sound fjord were initiated to identify sources and map dispersion of natural and anthropogenic inorganic constituents. Surveys were conducted at two levels: a) low density regional sampling of sediments, waters, and vegetation close to the shores of the Sound; and b) local sampling of waters and precipitates from the Britannia mine site (Fig. 1). This report concentrates on the distribution of Cu and Zn, since these metals were mined at Britannia and show greater regional variation than other elements in the drainage basin. Summary statistics are presented on the multi-element data sets that are being developed. Details of techniques, instrumentation, and element concentrations at individual sites are given in Percival et al. (in press).

REGIONAL GEOLOGY

The Howe Sound drainage basin is located in the southwest Coast Belt, divided into three NNW-trending tracts which, from south to north, are the Sechelt, Howe Sound and Squamish River (Fig. 1a; Monger, 1991). The Sechelt tract is composed of Lower and Middle Jurassic interbedded clastic sediments and volcanic rocks of the Bowen Island Group, with minor metabasalt and marble, which form a series of NNW-trending pendants within Late Jurassic and Early Cretaceous granitic plutons. The northern part of the drainage basin is underlain by the Howe Sound tract, consisting of Lower Cretaceous volcanic and sedimentary rocks of the Gambier Group and Early Cretaceous felsic plutons (Monger, 1991). The Gambier Group consists of a lower volcanic complex, a middle sedimentary interval and an upper volcanic complex (Roddick, 1965; Lynch, 1991) which hosts the Britannia Cu-Zn-Pb-Ag-Au orebodies.

SAMPLE COLLECTION AND METHODS

All sampling was conducted during July, 1991. Sediment samples (100 - 200 g) were collected with a Ponar grab sampler from a small boat and placed into plastic bags. They were freeze-dried and pulverized in an agate dish. Major element analyses were obtained by ICP-ES (inductively-coupled plasma emission spectrometry) following a $LiBO_2$ fusion, and trace elements were determined by ICP-ES following aqua regia extraction. The mineralogy was determined using X-ray diffraction analysis of oriented, air-dried mounts.

Precipitates or coatings on pebbles were collected from stream and mine waters in the Britannia area. The pebbles were cleansed using an ultrasonic bath and the residues were concentrated by centrifugation and freeze-dried. Chemical and mineralogical determinations were similar to those applied to the bottom sediments.

Two water samples were collected at each site: one 250 ml volume for cation determination and one 125 ml volume for anion determination and pH. Electrical conductivity and pH were determined in the field. The waters were filtered through 0.45 µm Millipore filter paper and the 250 ml samples were acidified with Ultrex nitric acid to a concentration of 0.1%. Determinations were made by flame atomic absorption spectrometry (FAAS) for Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn. Arsenic, Bi, and Sb were determined by hydride generation followed by quartz tube AAS.

Seaweed samples (100 - 200 g) were plucked from the rocky shores at intervals of approximately 5 km during periods of medium to low tides. Basal holdfasts were removed with pruning snips, and any biota (mostly mussels, *Mytilus* spp.) were removed. Samples were placed in 'ziploc-type' plastic bags while at sea, and later placed into cloth bags to facilitate drying. Partially dried samples were placed in aluminium trays and ignited for 24 hours in a kiln at 470°C. Ash portions weighing 0.5 - 1 g were transferred into plastic vials and submitted for multi-element instrumental neutron activation analysis (INAA). In addition, an ash split of similar size was submitted for analysis by ICP-ES, following digestion in aqua regia, to obtain data for base metals and other elements. The INAA gives total element contents, whereas the acid extraction for the ICP-ES analysis is partial for a few elements (e.g., Al, Ti).

Along the shore, close to each seaweed sample, twigs and foliage of western red-cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) were collected. Analytical procedures were the same as for the seaweed.

REGIONAL SURVEYS

Sample sites are shown in Figure 1a, and the distribution patterns of Cu and Zn in nearshore sediments, waters, and seaweed are shown in Figures 1b, 1c, and 1d, respectively. Summary analytical data are given in Table 1.

NEAR-SHORE BOTTOM SEDIMENTS

Thirteen sediment samples were dredged from nearshore sites in the Sound (Fig. 1b). Sampling was limited by the great depth of water, the nature of the bottom sediments (commonly coarse sand, pebbles, and bark fragments), and the type of sampling device. Samples were taken to: i) look at the nature and possible source of the materials being deposited in the bays; and ii) determine their geochemical signature and identify natural background versus point source contamination.

Table 1 shows a wide range in Cu (12 to 1,750 ppm) and Zn (32 to 1,500 ppm) concentrations, with the highest values occurring near Britannia Beach (Fig. 1b; sites 38 and 39) reflecting the presence of near shore submarine mine tailings. In the southern basin two clay-rich sites (4 and 12) yielded higher Cu and Zn than elsewhere, possibly because of the high surface area of particles available for metal adsorption. Zinc concentrations are generally higher than Cu, reflecting the greater natural abundance of Zn. However, the elevated values may also reflect an undeveloped copper deposit that occurs on eastern Gambier Island between these two sample sites.

Barium and Cd concentrations co-vary with those of Cu and Zn, respectively; Pb and Sb are enriched at Britannia Beach. Most other trace elements are present at levels close to typical background values for sediments.

Mineralogical determinations show the presence of quartz, feldspar, chlorite, mica and amphibole. Syvitski and Macdonald (1982) suggested that the mica indicates a Squamish River sediment source whereas chlorite is derived from the Fraser River.

WATERS

Of the 44 water samples collected, 20 focused on drainage of the Britannia copper mine and are discussed later. Samples were taken mostly from the main streams that drain into the Sound, except for a few taken from the surface and at depths up to 50 m in bays to examine the effect of mixing river or creek outflow with seawater. Surface waters in the Sound have low salinity due to the high influx of fresh waters from the surrounding mountains.

The highest levels of major cations and, hence, conductivity, were obtained in samples from the Squamish River harbour mouth (sites 40, 41), Britannia Creek side channel, and Gambier Island and are due to mixing with seawater. The influence of the Britannia mine is seen in the more acidic pH levels and in the elevated contents of major cations due to acid leaching (sites 38, 39, 39a). Iron and Mn concentrations show little variation throughout the Sound and are in the low ppb range.

The only significant levels of Cu and Zn in the drainage basin waters occur in samples taken at the mouth of Britannia Creek where they rise to a few hundred ppb (sites 38, 39, 39a; Fig. 1a and 1c). Most of the waters contain insignificant amounts of Bi and Sb (near the detection limit of 0.1 ppb), except for a high value of 4.3 ppb of Sb at a depth of 20 m at site 37; the source is perplexing as the values above and below in this water column are low. Arsenic concentrations are near the detection limit of 0.1 ppb for most samples, but approach 1 ppb with depth due to the influence of more saline waters (sites 4 and 37). Cadmium, Ni, and Pb were below detection limits of 2, 10, and 20 ppb, respectively.

SEAWEED

Investigations into the use of seaweed (macroalgae) chemistry in mineral prospecting (e.g., Bollinberg and Cooke, 1985) and environmental monitoring (e.g., Bryan, 1969; Fuge and James, 1974) are few but have yielded positive results. Of the three types of seaweed (brown, red, and green) investigated in western Canada it is the brown variety that accumulate the highest concentrations of most trace elements (Dunn, 1990). Fucus gardneri (Common rockweed) is a species of brown seaweed that grows in abundance, particularly around Howe Sound, and was selected as the sample medium for this study. Rockweed clings to rocks in the intertidal zone, and within the Sound it is the only seaweed at most locations because of its high tolerance to the relatively low salinity of the Howe Sound surface waters.

Seaweed data in Table 1 are element concentrations in ash; the ash yield of dry tissue is approximately 30%. Figure 1d shows low Cu levels in the southern part of the Sound (60 - 70 ppm), whereas near Britannia Beach they locally exceed 3,000 ppm Cu. Similarly, high concentrations of Zn (up to 1,540 ppm) are present in samples near Britannia Beach, whereas to the south Zn contents range from 300 - 400 ppm. Dispersion of these elements from the mineralized rocks at Britannia is evident; winds and currents have transported some elements northward, and some toward the south as far as Anvil Island. It is noteworthy that the shoreline is devoid of any seaweed for a distance of 1.5

km both north and south of Britannia Beach, presumably because of its intolerance to the influx of metals. At the north end of the Sound, relative U enrichment (up to 15 ppm) is probably derived from the granitic plutons. Iron and Ba are also more enriched in samples from the north than those from the south. Conversely, As, Pb, and Ni concentrations are lowest in samples from the Britannia area (sites 26, 27, 28; Fig.1a). The low As and Pb levels are probably due to their precipitation with bottom sediments and on pebbles and rocks (Table 2), thereby removing them from waters draining into the Sound. The higher Ni content of samples in the southern basin may reflect the relatively mafic composition of the local volcanic and sedimentary rocks or anthropogenic nickel transported in the Fraser River plume that invades the southern sound as noted by Syvitski and MacDonald, 1982.

TREE TISSUES

Preliminary data on a few samples of western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) from the Britannia Beach area indicate enrichment of Cu, Zn, Au, and As, especially in the hemlock twigs. Data on samples from the regional survey are pending.

BRITANNIA MINE SITE

Mineralization at the Britannia mine site was discovered more than a century ago. The deposits occur as volcanogenic Cu-Zn massive sulphide orebodies that were deposited by hydrothermal and exhalative solutions. They were emplaced into the Britannia shear zone, which is a NW-trending zone of flattening (Payne et al., 1980; Lynch, 1991). Copper was first reported in 1888 by Forbes, and in 1898 Oliver Furry staked five claims (Ebbutt, 1935). Underground and open pit production began in 1905 and continued until the mine closure in 1974. About 50 million tonnes of ore grading 1.1% Cu, 0.65% Zn, 6.8 g/tonne Ag, and 0.68 g/tonne Au were produced (Payne et al., 1980).

During the mining operations, mine waters from the 2,200 and 4,100 levels (sites 6 and 7 and 13 to 15, respectively, in Fig. 2a) flowed through two Cu precipitation plants which contained scrap metal (tin and iron). This process reduced the amount of dissolved Cu discharged to receiving waters. Currently, acidic mine waters exiting from the 2,200 and 4,100 levels supply high concentrations of Cu and other metals to nearby surface waters. The acidic water results from the oxidation of pyrite by O_2 and is characterized by low pH, high SO_4^{2-} in solution, and the presence of a yellowish-red precipitate of amorphous Fe oxide (limonite). The low pH causes metals to be leached from the mine workings and transported to receiving waters, although their concentrations in solution may be reduced by co-precipitation or sorption with limonite (Fig. 2b; Table 2).

The highest metal and lowest pH values occur in waters emanating from the mine portals at the 2,200 and 4,100 levels (site 6 and 13; Fig. 2a) and in the mine museum tunnel (site 16). The lowest concentrations occur in waters above and slightly east of the open pit area (sites 1 and 2), in Britannia Creek near Marmot Creek (site 3), in Mineral Creek (site 12), and in the town drinking water (site 17). All other samples show elevated levels of Cu and Zn. Concentrations of As, Bi, and Sb are low to non-detectable, and Cd covaries with Zn. The acidic mine waters have elevated levels of the major elements (Table 2), especially Fe and Mn (sites 6 to 9 and 13 to 16).

The effect of dilution by receiving waters is readily observed at the Mount Sheer site. Water emanating from the 2,200 level portal (site 6) is highly acidic and carries high concentrations of dissolved metals. Over a short distance (<10 m) the Cu concentration drops from 44 to 30 ppm (site 7). When the mine water mixes with Jane Creek (site 8) the concentration of Cu decreases again, down to 20 ppm. The Cu level is stable until the combined waters mix with Britannia Creek (site 10). At this point, a major decrease from over 19 ppm to 1.2 ppm indicates strong dilution by the larger creek.

The decrease in dissolved metal loadings may also reflect co-precipitation with sorption of metals by amorphous Fe oxides (limonite; yellowish red) or Al oxides (white) that occur ubiquitously in the stream bed as coatings or precipitates on pebbles. Zinc concentrations in precipitates correspond to high Al_2O_3 values, and elevated Cu levels are associated with high Fe_2O_3 and Al_2O_3. Levels of the other trace elements are highly variable, ranging, for example, from non-detectable to more than 1,500 ppm Pb (Table 2). Major element concentrations, other than those of Al_2O_3 and Fe_2O_3, are generally low (Table 1). These samples may contain trace amounts of clay (kaolinite or chlorite), quartz, and feldspar but are dominated by the amorphous oxides.

Although there is a natural decrease in the loadings of the metals from the Britannia mine to the Sound, the data show that levels of metals entering Howe Sound are elevated relative to the background values. The concentrations of Cu and Zn emanating from Britannia Creek (Fig. 2a) are within the drinking water guidelines (Cu <1 ppm; Zn <5 ppm) but exceed safe limits for freshwater aquatic life (Cu <2 - 4 ppb; Zn <30 ppb; Canadian Water Quality Guidelines, 1987). Also, Britannia Creek experiences high flows in the spring and fall, as well as periodic flooding. During these events, it is highly probable that the precipitates would be flushed out and released or deposited in Howe Sound.

SUMMARY

Regional geochemical studies of the Howe Sound drainage basin involved the collection and analysis of near-shore bottom sediment, water at several depths from within the Sound, the brown seaweed 'rockweed' (*Fucus gardneri*), stream water and tree tissue. A more detailed study was conducted around the abandoned Britannia copper mine to examine local variations in stream water chemistry, and the precipitates on rock surfaces. This study places emphasis on the distribution of Cu and Zn in and around the Sound, because of the significant influence of the Britannia area from where these metals were mined.

Except near Britannia Beach, waters of the Sound contain low concentrations of most of the elements determined, although major cations are enriched at the north end. Surface waters have low salinity due to the influx of fresh waters from the surrounding mountains, and concentrations of some elements (e.g., As) increase with depth and increasing salinity. High levels of Cu and Zn were found in all sample media from the vicinity of the mine; no seaweed grows on the shores either side of Britannia Beach for a total distance of 3 km presumably because of metal poisoning. In the southern basin, Zn concentrations in sediments and seaweeds are higher than those of Cu in accord with the relative crustal abundances of these metals. The rockweed appears to be a sensitive indicator of the chemistry of the environment exhibiting enrichment of Cu, Zn, Fe, U, and Ba in the north basin.

Waters flowing from the mine portals are acidic and contain high concentrations of dissolved metals. Metal concentrations decrease through dilution by receiving waters and/or precipitation with Fe or Al amorphous oxides. Periodic flooding probably flushes the precipitates into the Sound, resulting in temporal variations in the chemistry of the Howe Sound water, sediment, seaweed, and biota. Consequently, monitoring of these media is required in order to establish long-term patterns of chemical variability.

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Table 1. Regional study - element concentrations in bottom sediments, seaweed (ash), and waters.

	Marine Sediments[1] (Nearshore)		Seaweed (Fucus gardneri)			Waters (Bays and streams)	
	n=12		n=36			n=27	
	Range	Median	Range		Median	Range	Median
	%	%	%		%	ppm	ppm
SiO_2	37.3-65.9	58		-	-	-	-
TiO_2	0.32-0.66	0.5	Ti	0.001-0.06[2]	0.007	-	-
Al_2O_3	11.9-16.2	14.5	Al	0.02-0.8[2]	0.10	-	-
Fe_2O_3	3.1-9.3	5.2	Fe	0.05-1.1	0.18	<0.02-0.14	<0.02
MnO	0.06-0.12	0.09	Mn	0.02-0.08[2]	0.04	<0.01-0.05	<0.01
MgO	1.6-3.9	2.3	Mg	4.2-7.2[2]	5.0	0.1-1110	0.5
CaO	2.4-7.9	4.2	Ca	4.4-10.8	6.9	1-340	3
Na_2O	2.5-4.9	4.1	Na	4.8-14.5	10.7	0.4-8460	1.0
K_2O	1.4-1.9	1.6	K	10.4-26.2	15.0	0.1-375	0.3
P_2O_5	0.10-0.29	0.16	P	0.2-1.1[2]	0.7	-	-
LOI	0.8-33.4	8.2		approx. 70	-	-	-
pH	-	-		-	-	5.3-8.1	6.4
Cond[3]	-	-		-	-	7-49400	270
	ppm	ppm		ppm	ppm	ppb	ppb
As	5-46	15		7-28	17	<0.1-1.1	<0.1
Ag	<0.2-1.4	<0.2		1.3-2.7	2.0	-	-
Au	-	-		<5-58(ppb)	7(ppb)	-	-
Ba	35-590	95		<20-1200	220	-	-
Bi	-	-		-	-	<0.1-0.3	<0.1
Cd	<0.2-7.7	1.0		<0.1-8	2	<2	-
Co	4-17	12		10-25	13	-	-
Cr	9-41	16		<1-8	<1	-	-
Cu	12-1750	49		64-3210	147	<5-378	<5
Mo	<1-19	2		<1-4	<1	-	-
Ni	6-33	12		<1-36	20	<10	-
Pb	10-120	16		<2-14	3	<20	-
Sb	7-17	9		<0.1-0.4	<0.1	<0.1-4.3	<0.1
Sr	49-310	85		2900-6100	4100	-	-
U	-	-		3-15	5	-	-
Zn	32-1500	80		220-1540	420	<2-323	2

\- not determined

[1] Excludes one Al-rich sample (59% Al_2O_3) from Britannia Beach

[2] Partial extraction: aqua regia - ICP-ES

[3] Conductivity in µS/cm

Table 2. Britannia mine drainage - element concentrations in precipitates and waters.

	Precipitates		Waters		
	n=12		n=20		
	Range	Median	Range		Median
	%	%	ppm		ppm
SiO_2	1.8-62.9	17.5	-		-
TiO_2	0.01-0.28	0.09	-		-
Al_2O_3	1.1-34.5	10.5	-		-
Fe_2O_3	1.1-58.8	8.3	Fe	<0.002-16.1	0.015
MnO	0.04-1.2	0.2	Mn	<0.001-0.45	0.01
MgO	0.04-2.8	0.4	Mg	0.1-7.2	10
CaO	0.15-6.5	0.8	Ca	0.9-420	20
Na_2O	0.02-4.3	0.4	Na	0.3-450	3
K_2O	0.02-0.95	0.2	K	0.1-17	0.4
P_2O_5	<0.05-0.32	<0.05	-		-
pH	-	-	2.3-7.5		5.2
Cond.[1]	-	-	7-2560		600
	ppm	ppm	ppb		ppb
As	22-170	51	<0.1-1.0		0.1
Ag	0.4-11	1.4	-		-
Ba	5-460	32	-		-
Bi	<5-230	<5	<0.1-0.2		<0.1
Cd	2-18	5	<2-160		4
Co	<2-14	3	-		-
Cr	7-360	27	-		-
Cu	100-131000	4500	<5-44000		380
Mo	1-46	7	-		-
Ni	<1-240	21	<10-70		30
Pb	<2-1570	150	<20-190		<20
Sb	<1-99	17	<0.1-0.4		<0.1
Sr	<1-120	10	-		-
Te	<1-110	14	-		-
W	<2-53	<2	-		-
Zn	31-9900	240	3-26500		550

[1] Conductivity in μS/cm

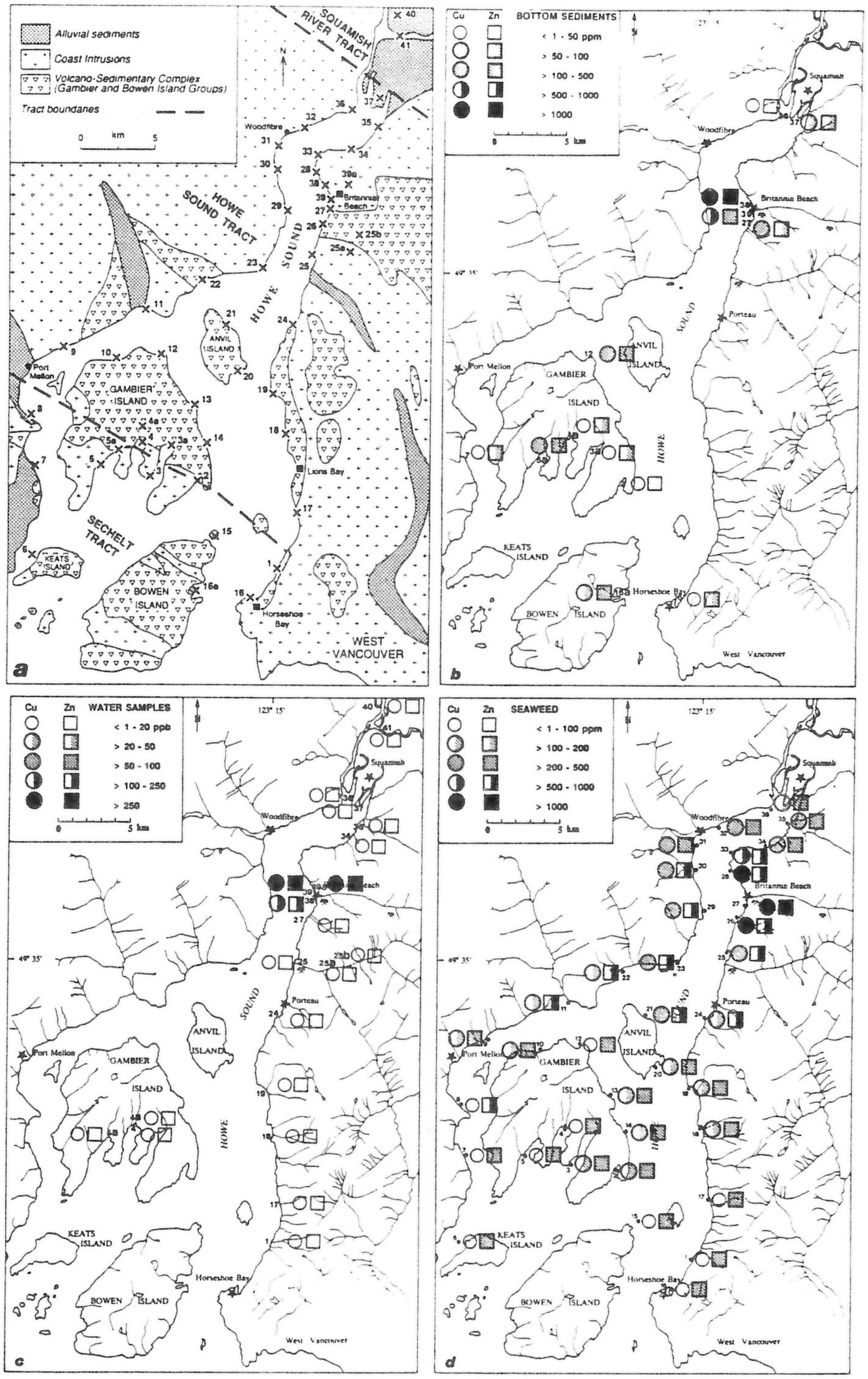

Figure 1. Sketch map of Howe Sound showing: 1a) regional geology (after Armstrong, 1990; Monger, 1991) and sample sites; 1b) Cu and Zn in bottom sediment; 1c) Cu and Zn in water from streams and bays; 1d) Cu and Zn in ash of common rockweed (<u>Fucus gardneri</u>) from the shores.

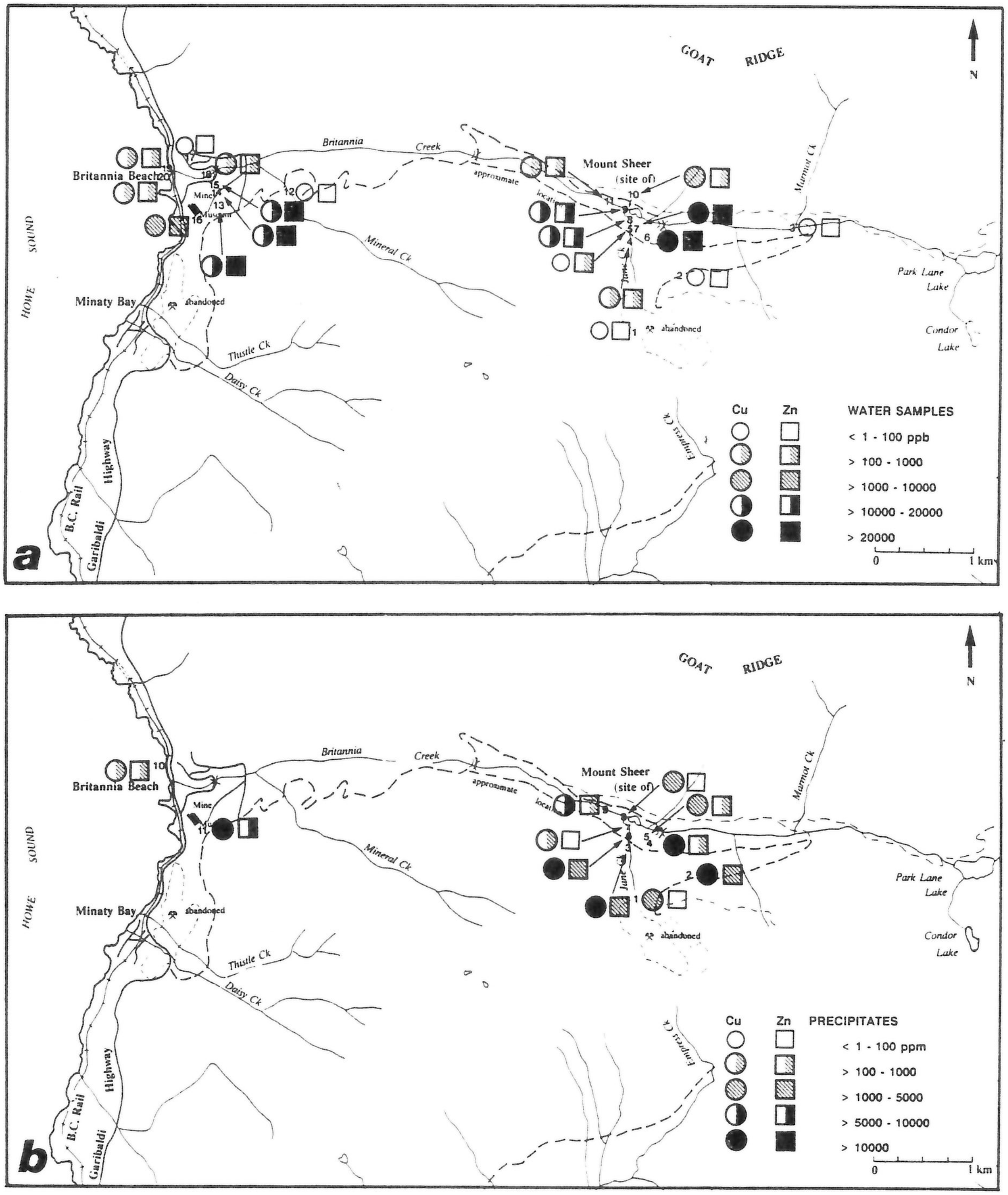

Figure 2. Britannia Mine area showing: 2a) Cu and Zn in water; 2b) Cu and Zn in precipitates.

BRITANNIA BEACH FLOOD: 29-31 AUGUST 1991

by

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INTRODUCTION

Britannia Beach is located at the mouth of Britannia Creek about 7 km south of Squamish at the end of Howe Sound. The creek has a total watershed area of 28.5 km^2 and travels through a narrow canyon before flowing over its alluvial fan to the ocean (Fig. 1). The lower townsite, built on the fan, includes residences, offices, museum, gas station, and stores. One railway bridge and two road bridges cross the creek in this area and the recent flood washed out a smaller foot bridge.

THE 1991 FLOOD

Heavy rainfall caused severe flooding in the Howe Sound Basin between August 29-31, 1991. The Squamish highway was blocked for 36 hours and initial damage estimates totalled $7-$11 million for the Howe Sound Basin and Pemberton areas. The flooding at Britannia Beach was marked by the avulsion of Britannia Creek through the lower townsite, severe debris deposition, and several million dollars damage.

Flooding is not new to Britannia Beach. Damaging floods of Britannia Creek occurred in 1906, 1921, 1933, and on four occasions during the 1960's (Jackson et al., 1983). The 1921 flood followed 146 mm of rainfall in 24 hours. A flood caused by the failure of a railway embankment released a surge of water that destroyed half of the 170 houses in the settlement and washed some into Howe Sound. It is likely that activities related to the mine development such as logging in the watershed, logging debris in the creek channel, water supply dams and other interference with the stream channel, contributed to the disaster (Jackson et al., 1983).

The five dams built on the creek are now completely or partly infilled with sediment. In 1989, one dam was purposely breached because of stability concerns; however, the breach was larger than expected causing a spectacular flood downstream.

The recent flooding was unusual in that it occurred in August. Preliminary data for August 1991 shows widespread precipitation with the heaviest rain falling between August 29-30. The Squamish airport reported a 24-hour maximum of 103 mm, and Woodfibre 88 mm. By comparison, the highest previously recorded 24-hour rainfall for Squamish was 164 mm (November 10, 1990). Although the rains were heavy, the unusually wet August conditions most likely caused the exceptionally high runoff. When the August 29-30 rains came, the already saturated ground provided no attenuation. Warm temperatures precluded precipitation falling as snow, and almost all the precipitation became direct runoff. The heavy runoff contributed to severe erosion and debris transport. After passing through the narrow canyon, the reduced gradient on the alluvial fan caused debris deposition in the creek channel, severely reducing capacity. The creek then flowed over its banks, through the townsite to pond behind the railway embankment, which eventually failed.

Bank erosion, channel erosion, and slide debris partly associated with past mining road construction, appeared to be the main sources of sediment supply. There was some speculation that the 1989 dam breach may have either loosened up the channel bed and/or transported additional debris down channel. Temporary debris dams may have also contributed to surges.

FUTURE CONSIDERATIONS

The sediment and debris sources remaining upstream are considerable and severe flooding with debris will undoubtedly recur (Fig. 2). A possible rock avalanche on the Jane Creek tributary also is of concern. The lesson to learn is that reconstruction and further development must wait until suitable zoning and/or engineering works, such as setback dykes and a dredging program, are in place. One possible solution is to restrict flood prone areas to day use activities with no overnight residences.

ACKNOWLEDGEMENTS

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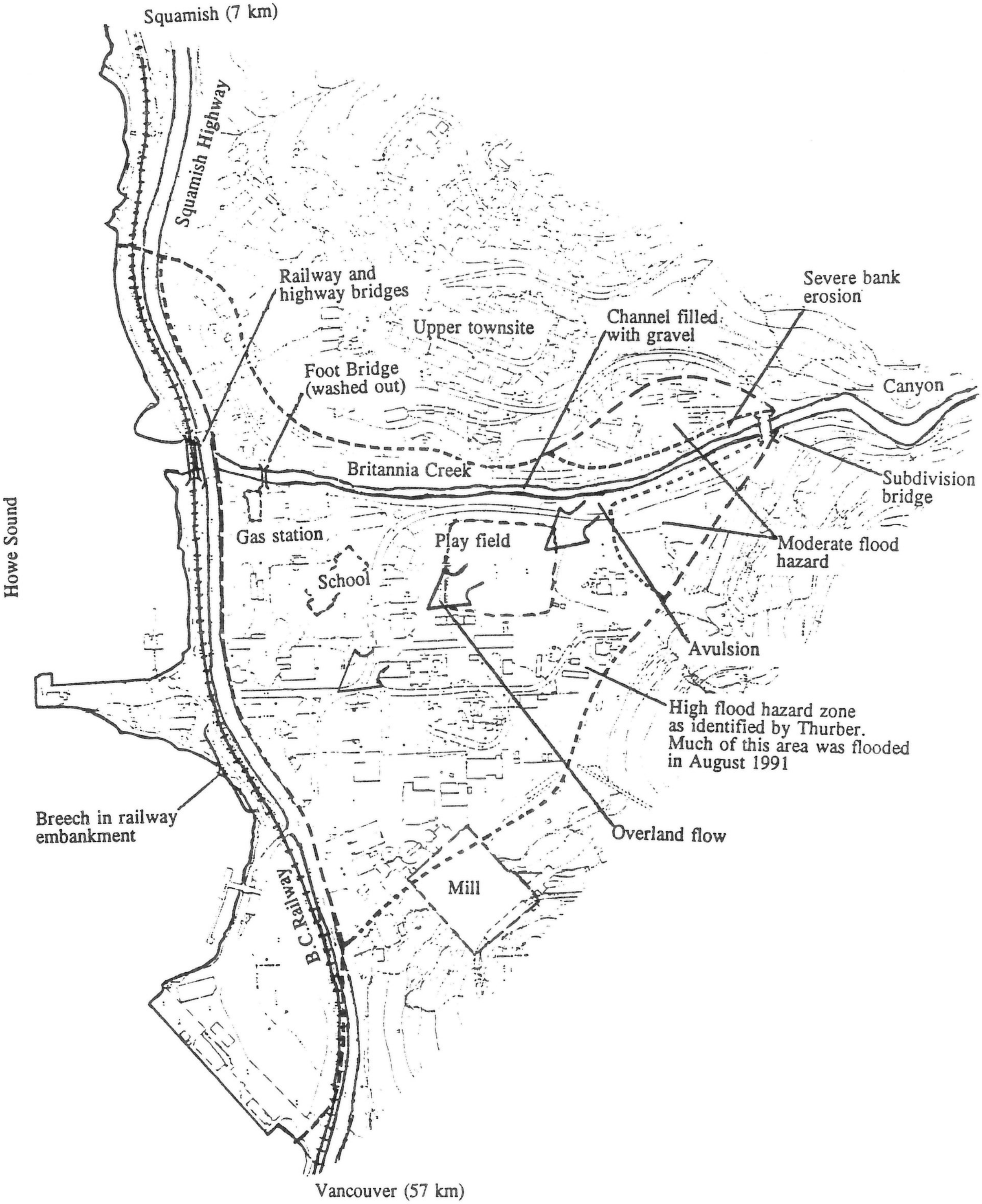

Figure 1. Sketch map of effects of Britannia Beach Flood August 29-31, 1991. (Base map after Thurber, 1983)

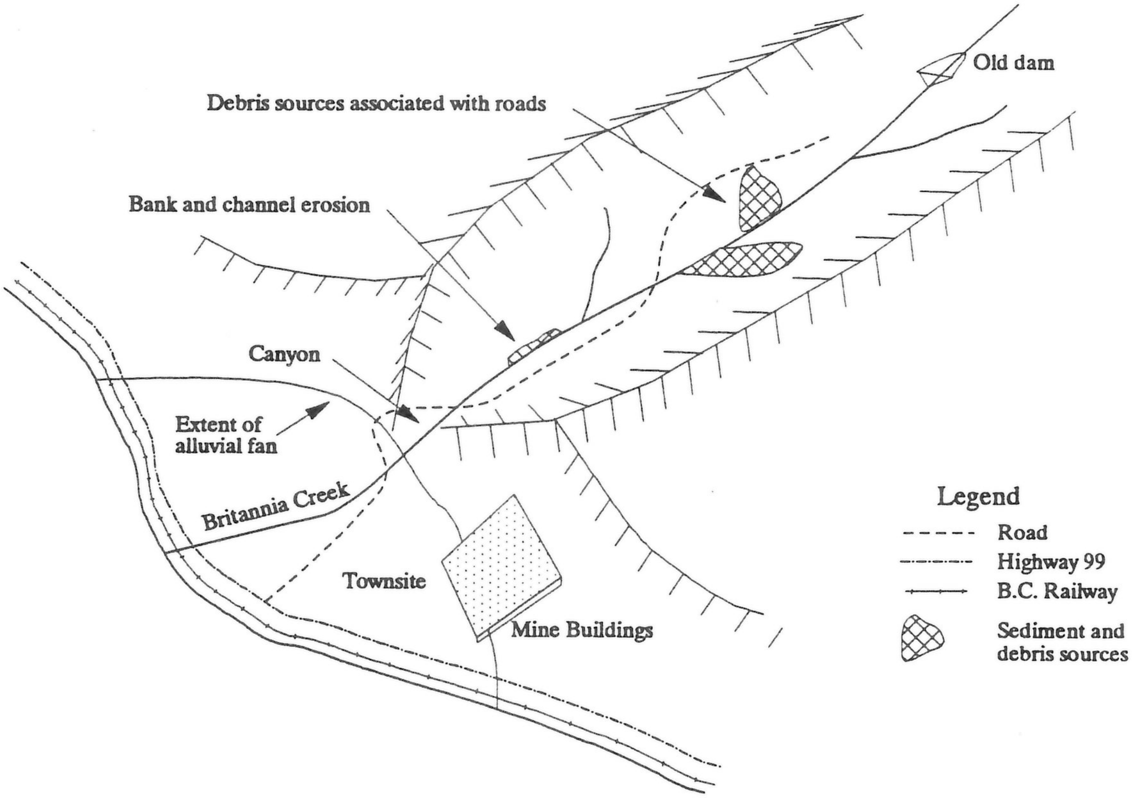

Figure 2. Schematic illustration of debris sources along steep mountain streams such as Britannia Creek that discharge across raised fan deltas into a fjord.

DEBRIS TORRENT HAZARDS AND PROTECTIVE STRUCTURES ALONG THE SQUAMISH HIGHWAY, LIONS BAY AREA, B.C.

by

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The eastern shore of Howe Sound south of Brunswick Point is a remarkably steep mountain wall. Drainages along this mountain wall are short and steep, and catchment areas south of Brunswick Point are small. Further north, drainages are somewhat larger and the mountain front less steep. From Brunswick Point south to Charles Creek, less resistant metamorphic rocks underlie the lower slopes while cliff forming granitic rocks form the upper slopes and peaks (Roddick and Woodsworth, 1979). A mixture of rock, till, and colluvium is found in headwater regions. Fans or cones of fluvial and colluvial debris have been constructed in the lower parts of drainages since glacier ice retreat 10,000 years ago. Because of the steep shore of Howe Sound, the shallower slopes on these cones have been favoured sites for residential construction (e.g., lower Lions Bay village). Alluvial cones and fans constructed prior to full isostatic rebound of the land following deglaciation were uplifted and eroded (Clague et al., 1982a) an example being the uplifted alluvial deposits of Magnesia Creek exposed along the highway above Brunswick just north of Lions Bay.

Channelized debris flows, 'debris torrents', in steep drainages along the east side of Howe Sound have caused costly damage to Highway 99 and various settlements along its route (Jackson et al., 1985). A debris torrent is a moving mass of rock fragments, soil, and mud with very high water content that develops within the confines of a steep channel. A debris torrent may originate as a slide from adjacent hillslopes which enter a steep channel and move downstream, or by the mobilization of debris within a steep channel. As the debris torrent moves downstream, it incorporates organic debris, trees, soil, and channel sediments (sand, gravel, boulders) from the channel, often scouring the channel to bedrock. As the debris torrent loses momentum on a flattening slope, there is deposition of a tangled mass of vegetation debris in a matrix of sediment and fine organic material.

Since completion of the railway and highway in 1958 from Horseshoe Bay to Squamish, there has been record keeping of floods and debris torrents large enough to disrupt road and rail traffic. Debris torrents in the Howe Sound area are associated with heavy precipitation during the autumn and early winter. Thirty-five flood and debris torrent events have occurred in 15 of the 26 creeks between Britannia Beach and Horseshoe Bay. About half the events have been debris torrents, all but one were restricted to 9 creeks south of Brunswick Point (Jackson et al., 1985). This distribution may reflect several factors: the steeper nature of drainages, the occurrence of more erodible metamorphic bedrock in at least parts of drainages, and the more northerly orientation of the mountain front which increases the forced lift of air masses causing more intense rainfall.

The frequency of debris flows is significantly higher on logged slopes versus unlogged slopes. The highest incidence of slope failure occurs several years after logging when root systems of cut trees start to break down decreasing the strength of the slope soils, and before new growth root systems are developed. Clear cuts and associated logging roads occur in the drainages of Harvey and Alberta Creeks. It is likely that a significant amount of the debris in the destructive debris torrent of February 1983 on Alberta Creek was derived from area where a logging road crosses Alberta Creek at the 610 m elevation (Jackson et al., 1985).

LIONS BAY AREA

The village of Lions Bay is built on and adjacent to a steep cone or fan of alluvium deposited by Harvey and Alberta creeks since the glacier retreat. Residential development began in 1957 after the construction of Highway 99 and part of the village has been built on the shallower lower slopes of the fan surface. However, the same depositional processes that have built the alluvial fan put the community at risk. Major debris torrents occurred in both Alberta and Harvey Creeks during the 1930's. The catalyst for the construction of the control structures we see today was an event on February 11, 1983 that followed three days of heavy rain. A debris torrent descended Alberta Creek destroying the highway bridge, several village bridges, and five homes adjacent to the channel. The debris flow moved in a series of surges with flow velocities of 2 to 9 m/sec down Alberta Creek (slope ~16 degrees), transporting a total volume of 20,000m^3 of debris (Thurber Consultants, 1983). Log and boulder tongues were forced out of the channel and into residential neighbourhoods at bends and obstructions in the channel. These tongues froze after a few metres' progress but, nonetheless, caused significant damage.

PROTECTIVE ENGINEERING STRUCTURES

To mitigate debris torrent hazard, structures can be designed to either stop and pond the debris torrent (i.e., dam structure) before entering the vulnerable area, or to allow controlled passage of the debris torrent safely through the area. Examples of such structures occur along Highway 99; these were designed by Thurber Consultants and built by the Department of Highways from 1984 to 1989. An example of a dam and debris catch basin structure is upstream from Lions Bay on Harvey Creek. The catch basins are designed to retain the "design torrent" (the debris torrent with a recurrence interval of 200 years), but allow normal floods to pass without trapping normal sediments. After the capture of a debris torrent, the material is excavated with bulldozer and truck so that the basin does not lose its capacity. The second strategy was used on Alberta Creek where a deep, straight walled channel with necessary clearance for bridges was built so that the torrent can pass through without obstacle. A large submarine storage basin area was dredged at the mouth of Alberta Creek so that debris would not backfill up the channel. The cost of these and other protective measures were: Alberta Creek, $8.6 million; Harvey Creek, $4.4 million; Charles Creek, $3.5 million; and Magnesia Creek, $3.1 million (Thurber Consultants, 1983).

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HYDRODYNAMIC AND SEDIMENTATION MODELLING IN HOWE SOUND, BRITISH COLUMBIA

by

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INTRODUCTION

Water movements and sedimentation in Howe Sound are of considerable interest at present because of the increasing residential and recreational developments there, the reduction of harmful discharges from the two pulp mills in the Sound, and the ongoing fisheries activities. One of the factors entering into the environmental state of Howe Sound is the dynamics of sedimentation because of the ability to bury older, contaminated sediments, and because of the physical-chemical interaction between sediment and pulp mill effluent. As part of the current examination of the Howe Sound environment, this report describes a combined hydrodynamic and sedimentation model of the Sound. The model was used to hindcast the deposition of sediment from a summer freshet of the Squamish River, and could be extended to cover a number of years of sedimentation in the Sound. The motivation for the study was to provide input into assessing the recovery of Howe Sound from its historic high levels of industrialization and associated pollutant loadings. Bottom sediments in Howe Sound have been contaminated by discharge of toxic organic material from the two pulp mills operating at Port Mellon and Woodfibre. These discharges have recently been greatly reduced as a result of upgrades to the mills, and it is expected that the levels of contamination of benthic organisms will decrease as the older contaminated sediments are buried by newer, less contaminated sediment. Thus, the question arises: what is the present rate of accumulation of sediment in Howe Sound? There are other aspects to the sedimentation and pollutant transport question which can be addressed by this modelling approach. For instance, a recent study (McLaren, 1990) established the direction of sediment transport throughout the Sound, based on the change of grain size spectra from station to station over a grid of bottom sediment stations with spacing of 500 m in the cross-channel direction and 1 km in the down-channel direction. The McLaren (1990) approach is somewhat indirect, and provides no indication of the rate of transport. It would be useful to provide an independent calculation of the inferred net currents. The hydrodynamic/sedimentation model could also provide a flow field for the transport of both dissolved and particulate organic material currently discharged by the mills, in order to examine the fate of the present pollutant load.

STUDY AREA

Howe Sound is a coastal fjord located along the British Columbia mainland coast, immediately north of Vancouver, shown in Figure 1 from the perspective of a coupled numerical model consisting of a 2 km resolution model of the Strait of Georgia - Strait of Juan de Fuca system and a 400 m resolution model of Howe Sound. Howe Sound consists of a deep outer basin, with depths up to about 250 m, and an inner basin with similar depths, separated by a sill whose depth is 70 m. The inner basin is a single channel; the outer basin contains several islands and thus assumes a more complicated shape. There are two principal freshwater sources, the Squamish River at the upper end of Howe Sound, and the Fraser River, which enters because of the open connection to the Strait of Georgia. Both of these rivers are also sediment sources to the Sound.

The Sound is well stratified due to the influence of the Squamish and Fraser Rivers. Currents in the Sound are strongly influenced by wind effects, either by the land-sea breezes which are a strong and persistent part of the wind field in the summer months, and by the Squamish winds, arising from outbreaks of Arctic air in the winter. The dynamics of the surface currents driven by the Squamish River discharge, tides, and wind have been described by Buckley (1977). Currents at discrete depths, as determined by moored current meters, have been described by Bell (1975a-d). Bell (1973) also examined historical oceanographic data from 1959 to 1973 to estimate the exchange of deep water in Howe Sound. There has been little other work of an oceanographic basis in the Sound, except for hydrographic surveys carried out by staff and students at UBC (e.g., UBC, 1973), and by Crean and Ages (1972).

Sedimentation in Howe Sound has been described by Syvitski and Macdonald (1982). The Water Survey of Canada maintains a stream flow gauge at the Squamish River at the Mamquam confluence. As well, in 1974 and 1975, water samples were collected from the river and analyzed for suspended sediment concentration and grain size distribution.

In this paper, two hydrodynamic models of Howe Sound are described, differing in their spatial resolution (2 km and 400 m). As well, a sedimentation model is described, which was used to determine the dynamics of the deposition of sediment discharge by the Squamish River. Recommendations are also presented, based on the work described here, which will allow a more complete description of hydrodynamics and sedimentation in the Sound, and their interaction with pollutant fate modelling.

THE HYDRODYNAMIC MODEL

The Howe Sound hydrodynamic model is designated HS8, the first two characters standing for Howe Sound, the character 8 indicating its origin with the GF8 model for the Strait of Georgia (Stronach, 1991). HS8 is a three-dimensional model of Howe Sound, using both the GF8 code and data from GF8 for boundary conditions. Two versions of the model have been developed: a 2 km coarse grid version, and a 400 m fine grid version. The fine grid version consumes considerable computer resources, so only preliminary instantaneous velocity fields will be presented from it. The coarse grid model was developed for the sedimentation study described here. Its rapid speed of execution allowed long-term sedimentation studies to be carried out, and also allowed for testing the implementation of boundary conditions. The code developed for the sediment model can be run in the future using the fine grid model. Both use the same boundary condition data files, and the same wind forcing files, so are interchangeable as far as external forcings are concerned. The fine grid version resolves all significant features of the topography and bathymetry, and will be used for future studies. The interfaces between levels of the HS8 model lie at 5, 10, 20, 30, 60, 90, 150, 250, and 400 m.

BOUNDARY AND INITIAL CONDITIONS

GF8 is run for the entire simulation period, and model variables along the HS8 open boundary are saved every time step. Specifically, the values of surface elevation at the centres of the GF8 grids forming the HS8/GF8 boundary are saved, as well as the components of velocity parallel to the boundary connecting these points, and the component of velocity perpendicular to the boundary, 1/2 grid outside the boundary. As well, the vertical velocity and densities at the elevation points are saved. Subsequently, when HS8 is run, the boundary condition file is read, one timestep at a time. For the coarse grid model, the boundary file points lie exactly on the grid points of HS8, so no spatial interpolation is required. In that sense, HS8 is merely repeating the algebra of the original GF8 run. For the fine grid model, bilinear spatial interpolation is used to establish velocities, densities and elevations at the relevant parts of the boundary openings.

The validity of the boundary condition implementation is shown in Figure 2, which compares the surface current fields calculated by HS8 and by GF8 respectively, both plots representing snapshots after 12 days of simulation. The agreement is very close, but not exact, the reason for the difference being that GF8 contains a narrow grid cell representing Shoal Channel, whereas the HS8 grid does not.

The density fields for both models were obtained by interpolating onto the GF8 grid historical data from Crean and Ages (1972) and from the UBC (1973) data report for the relevant month. This field of densities was then transferred to the HS8 grid. The transfer process was a direct transcription in the case of the coarse grid model. In the case of the fine grid model a small amount of manual adjustment was required because of the different resolution of the two grids. The wind field was obtained by interpolating spatially the observations from AES coastal lighthouses. In Howe Sound itself, the Pam Rock station dominates the wind field.

VALIDATION AND RESULTS OF THE HYDRODYNAMIC MODELLING

Validation of the Howe Sound model can be partially assessed by comparing a typical flow field at low tide, the time of maximum river discharge, (Fig. 3), to a subjective flow field prepared by Buckley (1977) (Fig. 4), which would be dominated by currents at this phase of the tide. The computed flow field shows similar features to the subjective field, which was based on a combination of drogue tracks and examination of aerial photographs of surface sediment patterns. Particularly notable is the jet of water which issues from the Squamish River, moves across to the opposite shore, and then back to the western shore, in both diagrams. The back eddy off Britannia Beach is simulated by the model, as well as the eddy lateral to the issuing jet at the head of Howe Sound. Also noted in the fine grid model was the development of a counterflow immediately under the surface layer in the region around the sill. This feature was noted by Buckley (1977) in the Bell (1975a-d) measurements, and is another form of validation of the model, in a qualitative sense.

THE SEDIMENT MODEL

Sedimentation is of particular concern in Howe Sound because of the role that sediment plays in the fate of trace organic pollutants discharged from the two pulp mills in the Sound, and also because of questions concerning the rate of burial of older contaminated sediment by new sediment. The sediment module in HS8 at present simulates only depositional processes, as there is little resuspension in most of Howe Sound (Mclaren, 1990). The sediment module uses a Monte Carlo approach to describe the fate of sediment discharged by the Squamish River. In this approach, a large number of artificial particles are tracked, with each particle representing a constant mass (several kg) of sediment. Each particle moves according to the three-dimensional velocity field computed by HS8, along with a random motion to simulate turbulent processes, and a settling speed determined by the size of the grains comprising each particle. The model can support simultaneously a number of grain size fractions, each with its own specific settling rate. The daily rate of supply is determined from Water Survey of Canada data.

The sediment model has yet to be verified against observed data, although the rate of accumulation agrees with recent results reported by Syvitski (Carl Amos, pers. comm.). That verification process must await a parallel modelling process for Fraser River sediment, as the flow fields computed so far, as well as observational evidence, indicate significant intrusions of Fraser River water and sediment into Howe Sound.

SEDIMENT SOURCES

The Howe Sound sediment model considered a single source, the Squamish River. Daily flow rates for the Squamish River below the Mamquam were obtained, as well as total suspended solids on a daily basis for 1974 and 1975. These two time series allowed a daily sediment loading, in kg/s, to be computed. In addition, grain size distributions were obtained on 10 occasions in 1973.

Figure 5 plots the average grain size distribution for all samples. The 1975 sediment loading time series was selected for the simulations presented here. The time origin was shifted (Fig. 6), to coincide with the boundary condition data which was available - the sediment peak actually occurred about July 11.

SEDIMENT MOVEMENT

The key aspects of the sediment model are that it is a Monte Carlo simulation, and that the particles which form the sediment are installed at a rate governed by the daily sediment loading. As well, the hourly rate is modulated according to tide height, in the same way that the river flow is modulated by the tide. Thus, when the tide is high, the river flow is shut off, and the sediment supply is also set to zero. At low tide, the river flow is a maximum, and so is the sediment loading. The modulation function was chosen so that over the period of the simulations it had an average value of one, and hence the daily supply of water or sediment was not quantitatively affected by the modulation factor. Each particle released was assigned a grain size, and hence fall velocity, according to the average observed grain size spectrum as follows. When the particle was installed, a random number between zero and one was generated. Its value was compared to the cumulative exceedances assigned to the grain sizes, and a corresponding fall velocity determined. Thus, when a statistically significant number of particles has been installed, their size distribution would approach the observed spectrum.

Once a particle is installed, it is acted on by:

1. Three-dimensional currents calculated by HS8, bilinearly interpolated in x and y, linearly interpolated in z;
2. A random component, governed by the horizontal diffusivity of 100 m*2*/s;
3. A fall velocity calculated from its grain size, using Stokes' Law.

When a particle touched the bottom, it was recorded in a two-dimensional array containing the bottom-deposited particle count, and removed from the array of suspended particles. Computer memory was reclaimed for use by a newly installed particle.

The advection of the particles was complicated by the presence of side walls. A scheme was devised which prevented the particle from drifting through the side wall due to diffusion and also due to small discretization errors in the interpolation scheme for the advective step. This was achieved by treating each particle as a perfectly elastic particle colliding with a solid wall. This becomes a lengthy check because of the possibility of multiple reflections in corners. However, the resulting code reproduced analytic solutions with a high degree of accuracy.

SEDIMENT RESULTS

The model was run for a 69-day period. During the first 45 days, the sediment supply was determined from the observed loadings illustrated in Figure 6. For the last 24 days, the sediment supply was set to zero, for two reasons. First, the actual supply was in fact close to zero. Second, setting the supply to zero would allow a well-defined numerical experiment to be carried out, in that the sinking of the sediment cloud deposited during the first 45 days could be examined, without the complication of additional sediment supply. Figures 7, 8, and 9 illustrate representative stages of the simulation, showing a vertical section of suspended sediment concentration taken along the main channel, from the Strait of Georgia on the left to the head of Howe Sound on the right. The key feature of these diagrams is the three-dimensional plume of sediment, which achieves its maximum concentration at about hour 300 (Fig. 7), and proceeds to settle out over the entire period. Many of the diagrams illustrate the effect of shear in the water column, such as the tongue of lower concentration water between 10 m and 50 m depth at hour 800, in Figure 8. The last diagram in the sequence, Figure 9, illustrates also the deposition on the bottom, shown by filled rectangles along the bottom, whose height is proportional to the thickness of deposited sediment. For scaling, the greatest deposition is 4.3 cm at the head of Howe Sound.

CONCLUSIONS AND RECOMMENDATIONS

This study generated preliminary but believable results, and the bottom deposition rate which was calculated is consistent with observations. The model made very few approximations about the physics involved, and calculated the annual sedimentation in full detail. The feasibility of carrying out sediment and pollutant modelling using a numerical model such as HS8 has been clearly demonstrated. The principal conclusions of this report are:

1. HS8 demonstrated it is capable of providing realistic velocity fields, particularly with the high resolution grid. The velocity fields appeared intuitively correct, and agreed well with the limited amount of available observational data;
2. The feasibility of the Monte Carlo sedimentation approach was also demonstrated. The only verification is the agreement with estimates of bottom sedimentation rates calculated using other methods. However, because the procedure was checked carefully against analytic solutions for simple cases, and because it was not changed during implementation in HS8, it can be concluded that the numerical code expressed exactly the mathematical and conceptual model on which it was based;
3. The specification of the sediment source was inadequate. First, the frequency of sampling was low. Second, it is not known whether the analytical methods used to determine suspended sediment concentration and grain size distribution were sensitive enough to resolve the contribution of the glacial flour which frequently forms part of the Howe Sound sediment supply. As well, the variation in grain size over a season was not readily addressed with the available data. Recommendations for additional work, which will make this sediment model a more useful part of future Howe Sound environmental studies are as follows:

1. The sediment supply should be more precisely determined. This procedure would also be useful for hydrological studies in the Howe Sound watershed.
2. The hydrodynamics should be based on the fine grid model. Lateral differences across each of the main Howe Sound channels could then be resolved.
3. The simulations need to be extended over a number of seasons, to adequately sample the seasonal variations in wind forcing and sediment supply.
4. For other purposes, such as bottom flushing, the model needs to be calibrated over long time periods.
5. The relationship between sediment and trace organic pollutants should be examined in more detail. At present, the model is suitable for calculating the rate of supply of new sediment to the sea floor from the Squamish River. Other questions remain to be addressed, such as the ability of sediment to adsorb organic contaminants, and carry them to the sea floor.

6. The effect of Fraser River sediment should also be investigated. This could readily be done, using GF8 coupled with the sediment model. The results would be calculated at the same resolution as the coarse grid form of HS8, but would allow an estimate of the relative roles of the two sediment sources. The GF8 sediment results could be applied to the HS8 fine grid sediment model if required.

7. For present pollutant loadings, the nature of organic supply should be quantified, the particulate material should be treated as described in this report, and the dissolved material should be treated in a fully three-dimensional transport-diffusive calculation.

8. To improve the hydrodynamic modelling, a mesoscale wind model should be considered. For instance, folklore indicates that Thornbrough Channel is usually much calmer than Montagu Channel, but this is at present not incorporated in the hydrodynamic model.

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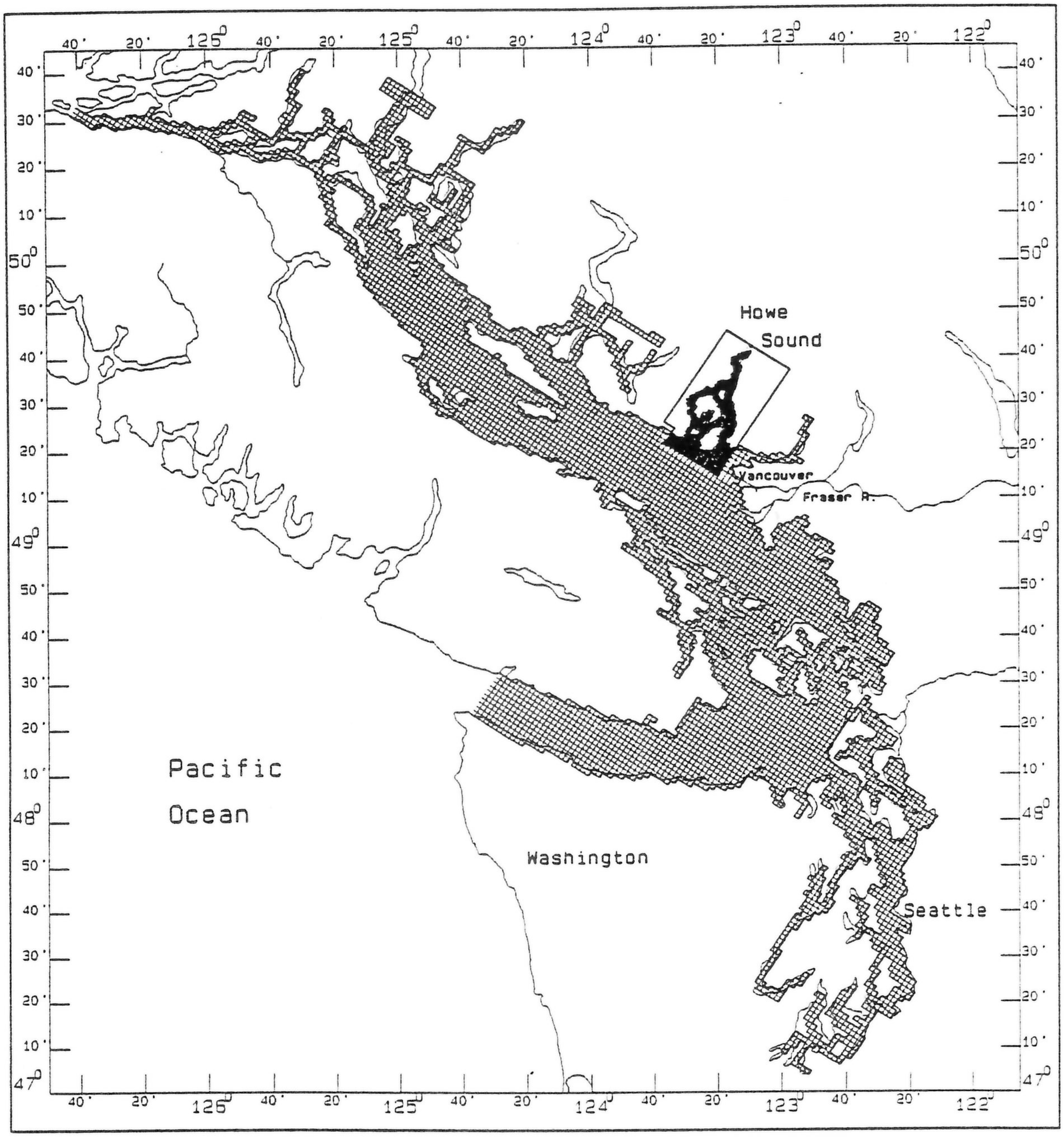

Figure 1. The Straight of Georgia - Strait of Juan de Fuca hydrodynamic model grid (GF8), and the high resolution Howe Sound hydrodynamic model grid.

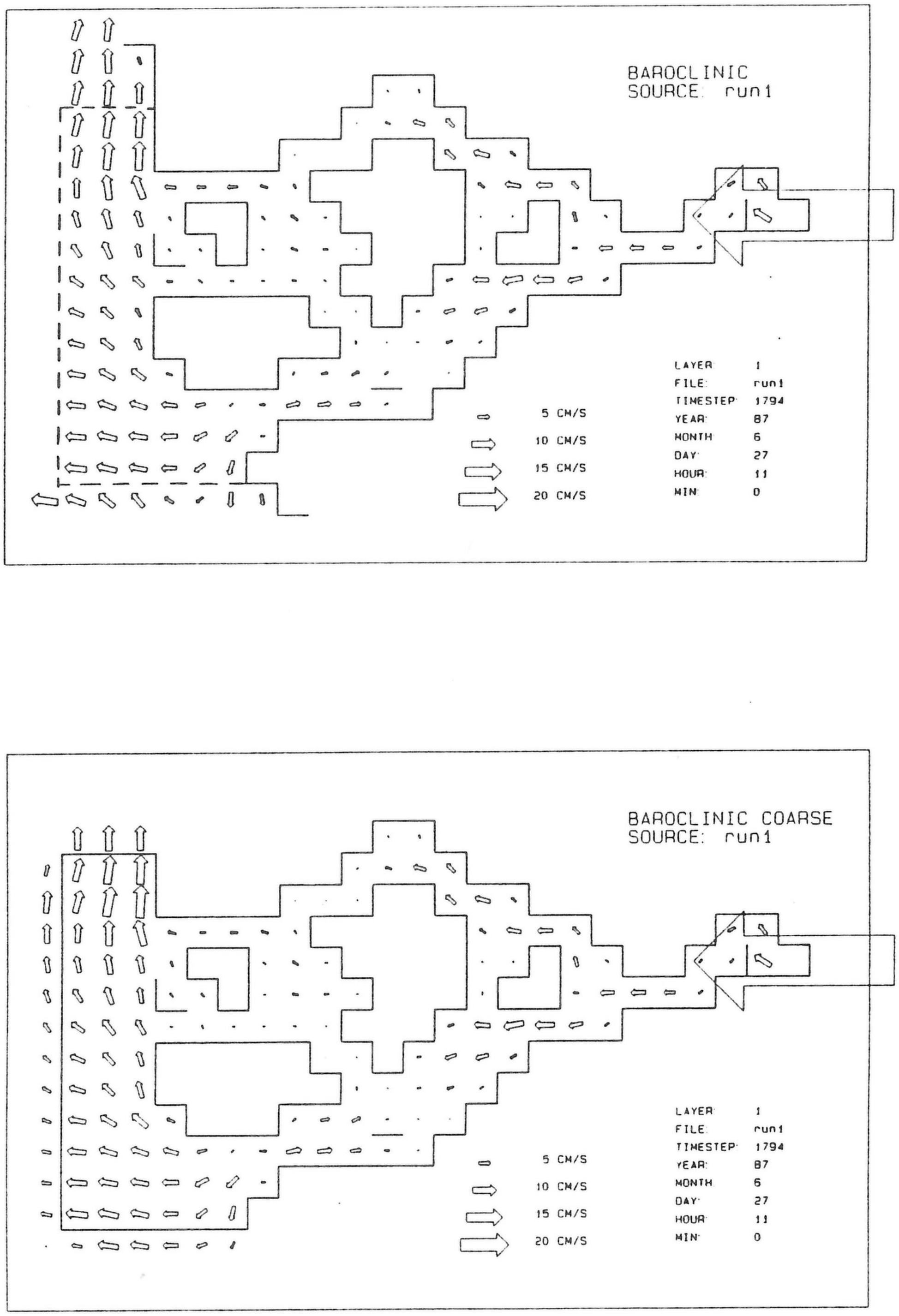

Figure 2. The velocity field after 12 days as computed by the overall model GT8 (top), and by the coarse grid version of the Howe Sound model HS8 (bottom).

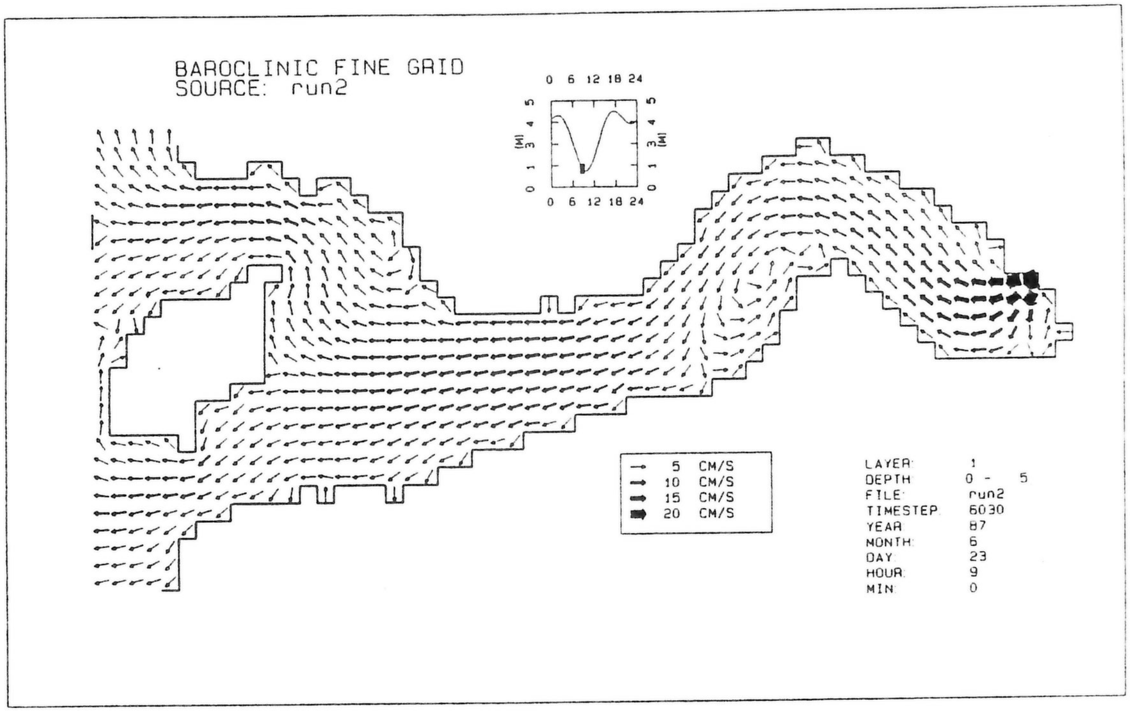

Figure 3. The surface current pattern computed by the fine grid Howe Sound model for upper Howe Sound at about low water.

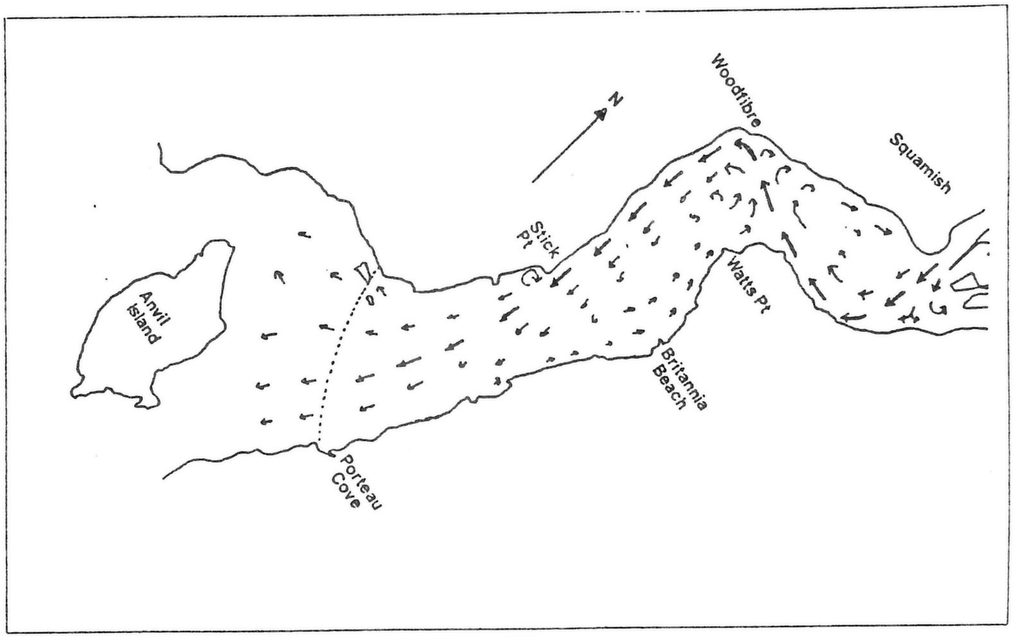

Figure 4. The surface current pattern in upper Howe Sound, as subjectively determined by Buckley (1977).

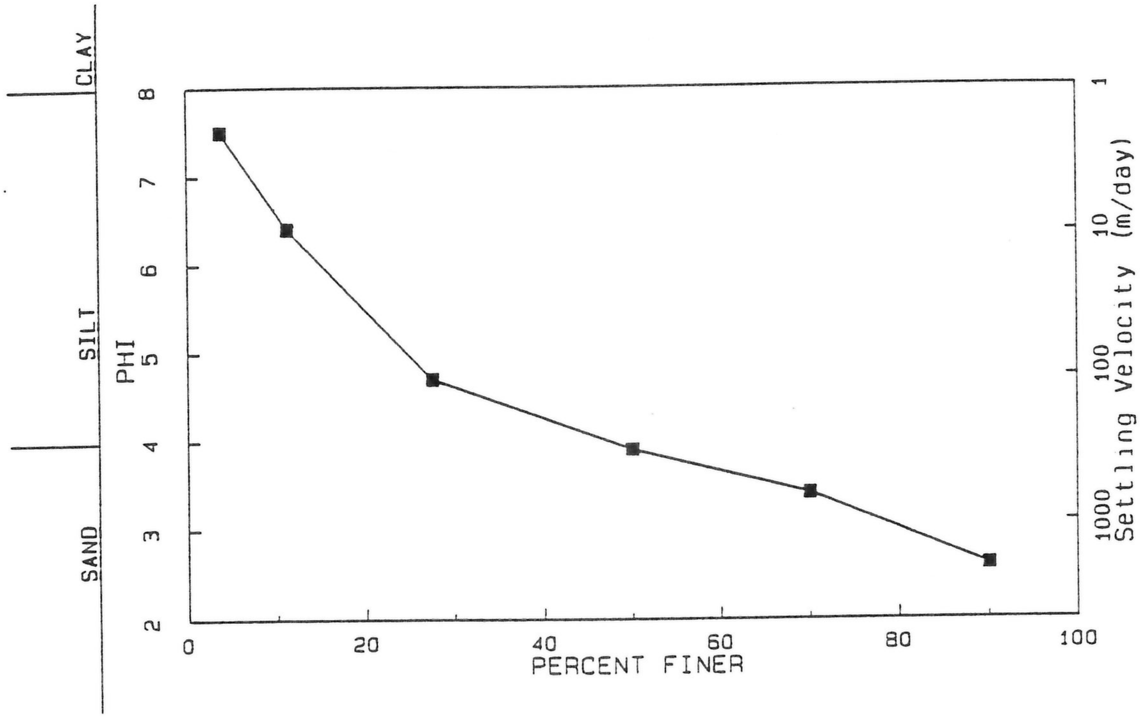

Figure 5. Average grain size distribution for Squamish River sediment samples, 1973. (Source: Water Survey of Canada).

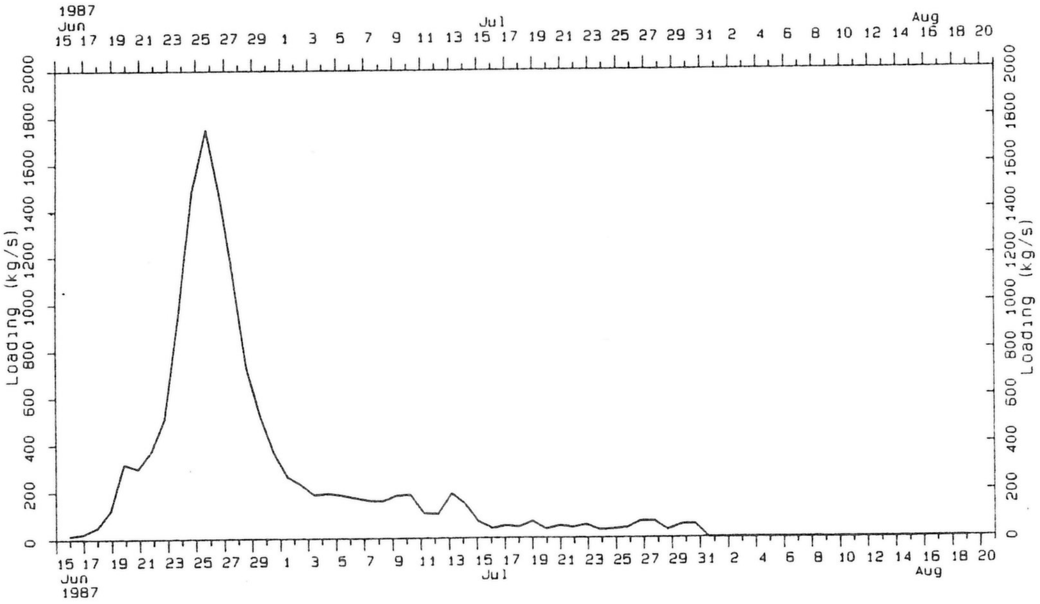

Figure 6. Time series of sediment loading used in the sediment model.

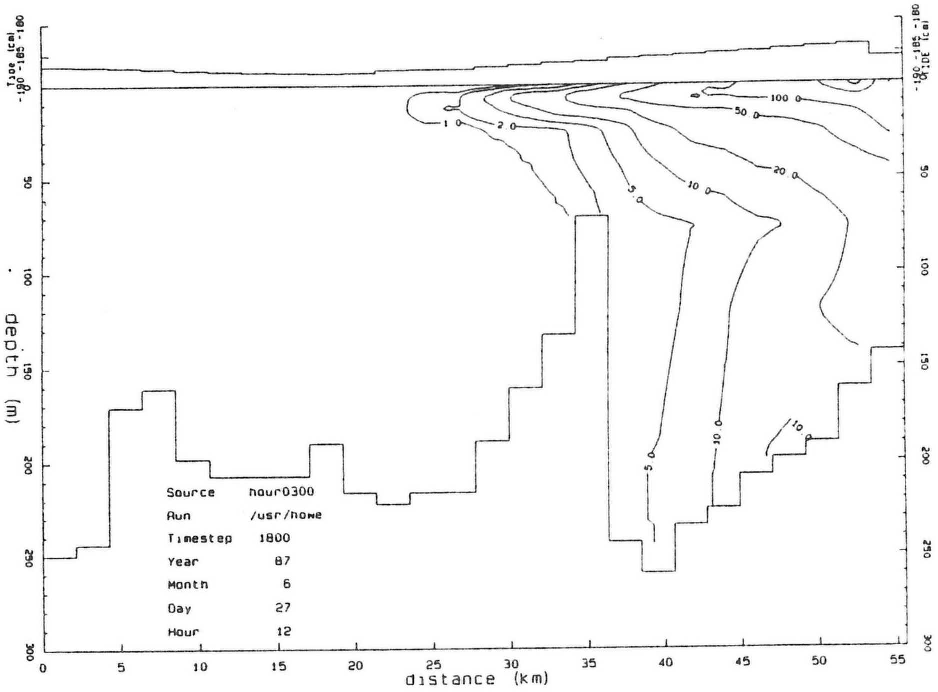

Figure 7. Longitudinal section of suspended sediment concentration computed by HS8. The Strait of Georgia is on the left, the head of Howe Sound on the right: after 300 hours of simulation.

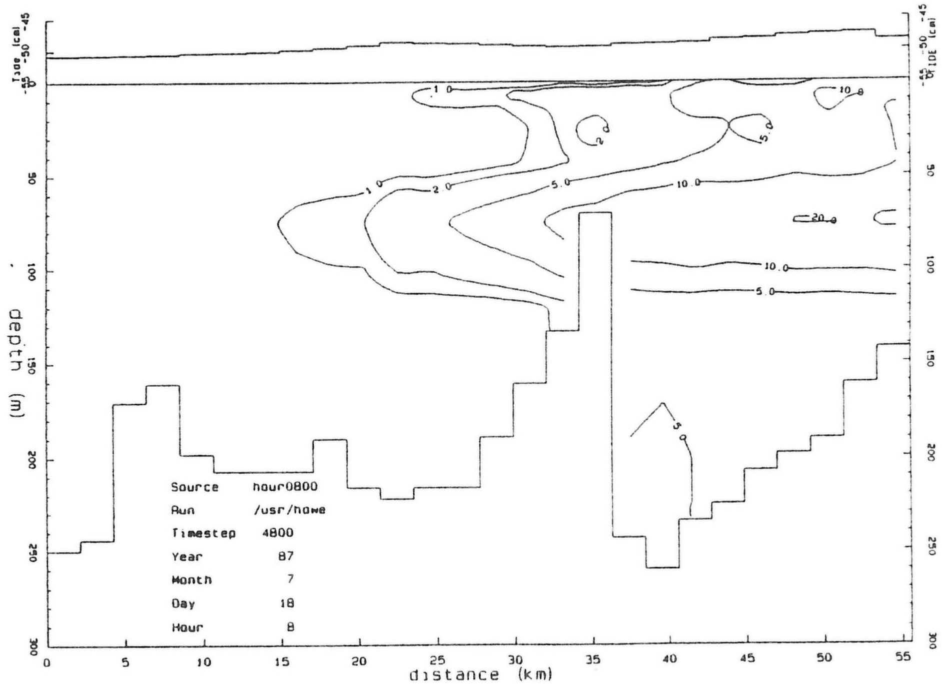

Figure 8. Longitudinal section of suspended sediment concentration computed by HS8. The Strait of Georgia is on the left, the head of Howe Sound on the right: after 800 hours of simulation.

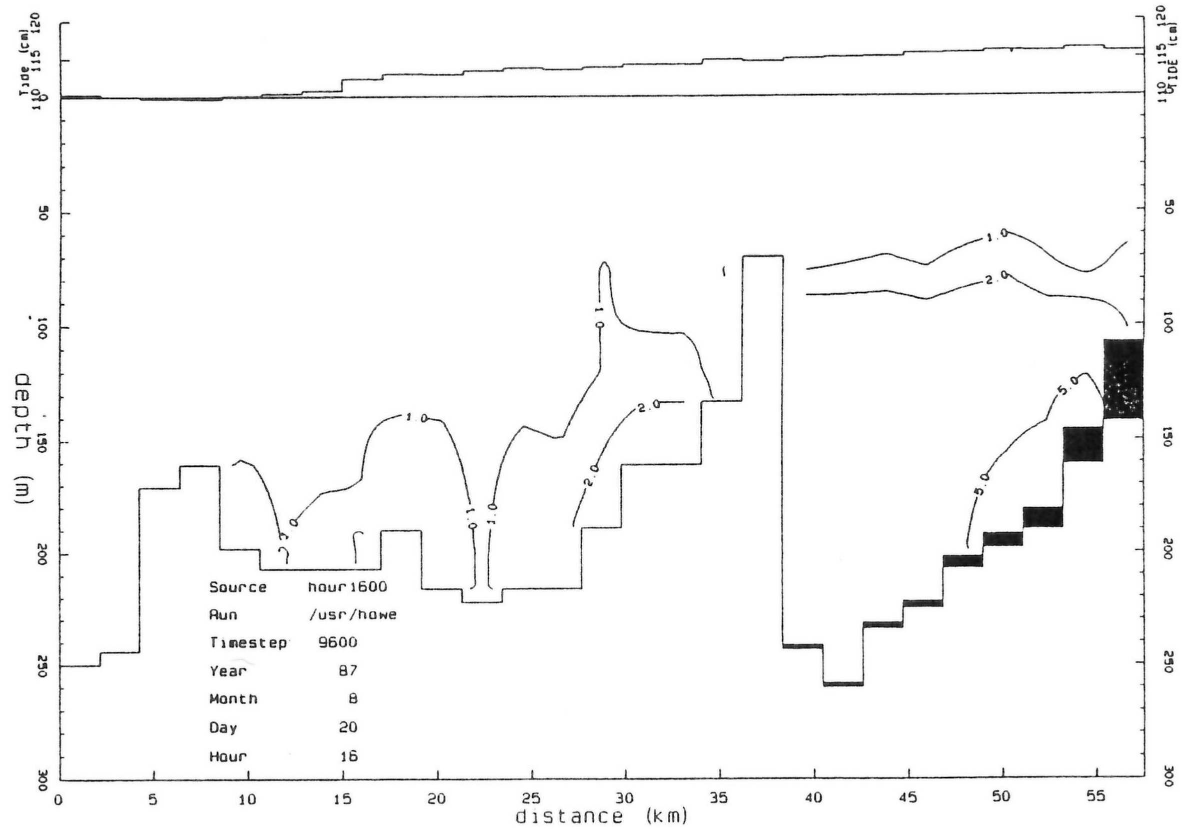

Figure 9. Longitudinal section of suspended sediment concentration computed by HS8. The Strait of Georgia is on the left, the head of Howe Sound on the right: after 1600 hours of simulation. The net accumulation of sediment is shown by the blackened rectangles along the bottom. For scaling, the greatest accumulation, at the head of the Sound, is 4.3 cm.

THE SEDIMENT TRANSPORT REGIME OF HOWE SOUND, BRITISH COLUMBIA: IMPLICATIONS TO THE DISPERSAL OF CONTAMINANTS

by

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ABSTRACT

About 550 bottom grab samples were collected at regular intervals over Howe Sound. These were analyzed for their complete grain-size distributions in order to perform a sediment trend analysis. This is a technique whereby net sediment transport patterns are determined by assessing statistically the relative changes in grain-size distributions along selected sample sequences. The analysis also provides an understanding of the behaviour of the sedimentary environment with respect to erosion, deposition, or dynamic equilibrium.

The study benefitted from an excellent data base and the results showed that the area could be divided into four transport environments; namely Upper Howe Sound (from Squamish to the sill), Ramillies and Montagu Channels (from the sill to Bowyer Island), Thornbrough Channel, and Southern Gambier Island. Upper Howe Sound is dominated by the Squamish River outflow and the derived trends all showed a southward transport indicative of total deposition (i.e., once a particle is deposited, no further transport takes place). As a result, contaminants are deposited at specific locations and may be related to specific sources, a finding that is supported by the distribution of mercury found in the bottom sediments.

The trends in Ramillies and Montagu Channels demonstrated that down-fjord transport continues south of the sill. Here the grain-size is very small (fine silt and clay) and it appears that there is an equal probability for all sizes to be deposited (i.e., size-sorting is no longer applicable). Thus contaminants are unlikely to concentrate at a preferred locality and would tend to be dispersed equally throughout the region. Existing contaminant data support this concept.

Transport in Thornbrough Channel was determined to be northwards with total deposition occurring. Contaminant data show high concentrations both north and south of Port Mellon which are explained by the influence of ebb and flood tidal currents as well as dumping operations that have occurred in the channel immediately adjacent to the mill. Total deposition was also determined for the sediments originating from the streams entering the channel along the south coast of Gambier Island. Because there is no contaminant source associated with this area, it is unlikely that significant levels would be found in this area of the study.

INTRODUCTION

The Howe Sound fishery has been closed due to unacceptable concentrations of polychlorinated dibenzodioxins (PCDDs) and dibenzofurans (PCDFs). These compounds are known to have a high affinity for the organic constituents of abiotic and biotic particles, and therefore they become, through physical, chemical, and biological processes, inextricably linked to the natural sediment regime. As part of a program to determine the behaviour of dioxins and furans in the Howe Sound ecosystem, the Ocean Chemistry group at the Institute of Ocean Sciences supported a study to determine the role of sediment transport on their distribution in the bottom sediments. The principal purpose of this study, therefore, is to establish the probable sediment transport pathways and to assess those areas in the Sound particularly susceptible to contaminant build-up or dispersal.

METHODS

THEORY

The technique to determine the existing sediment transport regime utilizes the relative changes in grain-size distributions of the bottom sediments. The derived patterns of transport are, in effect, an integration of all processes responsible for the transport and deposition of bottom sediments over the period of time represented by the actual samples. Details of the theory are contained in McLaren and Bowles (1985); however, the approach is summarized here.

Suppose two sediment samples (D_1 and D_2) are taken sequentially in a known transport direction (for example, from a river bed where D_1 is the up-current sample and D_2 is the down-current sample). The theory shows that the sediment distribution of D_2 may become finer (Case B) or coarser (Case C) than D_1; if it becomes finer, the skewness of the distribution must become more negative. Conversely, if D_2 is coarser than D_1, the skewness must become more positive. The sorting will become better (i.e., the value for variance will become less) for both Case B and C (Fig. 1). If either of these two trends is observed, we can infer that sediment transport is occurring from D_1 to D_2. If the trend is different from the two acceptable trends (e.g., if D_2 is finer, better sorted, and more positively skewed than D_1), the trend is unacceptable and we cannot suppose that transport between the two samples has taken place.

In the above example, where we are already sure of the transport direction, $D_2(s)$ can be related to $D_1(s)$ by a function $X(s)$ where 's' is the grain size. The distribution of $X(s)$ may be determined by:

$$X(s) = D_2(s)/D_1(s)$$

$X(s)$ provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular grain size being eroded, transported, and deposited from D_1 to D_2.

INTERPRETATION OF THE X-DISTRIBUTION

Empirical examination of X-distributions from a large number of different environments has shown that four basic shapes are most common when compared to the D_1 and D_2 distributions (Fig. 2). These are as follows:

(1) Dynamic Equilibrium (Fig. 2A): The shape of the X-distribution closely resembles the D_1 and D_2 distributions. The relative probability of grains being transported, therefore, is a similar distribution to the actual deposits. This suggests that for every probability of finding a particular grain in the deposit, there is an equal probability that it will be transported and redeposited (i.e., there is a grain by grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium.

(2) Net Accretion (Fig. 2B): The shapes of the three distributions are similar, but the mode of X is finer than the modes of D_1 and D_2. Sediment must fine in the direction of transport; however, more fine grains are deposited along the transport path than are eroded, with the result that the bed, though mobile, is accreting.

(3) Net Erosion (Fig. 2C): Again the shapes of the three distributions are similar, but the mode of X is coarser than the D_1 and D_2 modes. Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing net erosion.

(4) Total Deposition: (Fig. 2D): Regardless of the shapes of D_1 and D_2, the X-distribution more or less increases monotonically over the complete size range of the deposits. Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a "rain" of sediment that fines with distance from source. Once deposited, there is no further transport.

INTERPRETATION OF A TREND

In reality, progressive changes in grain-size distributions as shown in Figure 1 are seldom observed in a sequence of samples, even when the transport direction is clearly known. This is due to complicating factors such as variation in the grain-size distributions of the source material, local and temporal variability in the X(s) function, and a variety of sediment sampling difficulties (i.e., sample does not adequately describe the deposit; it is taken too deeply; not deep enough, etc.).

Initially, a trend is easily determined using a statistical approach whereby, instead of searching for "perfect" changes in a sample sequence, all possible pairs contained in the sequence are assessed for possible transport direction. When one of the trends exceeds random probability within the sample sequence, we infer the direction of transport and calculate X(s). The precise statistical technique is described more fully in McLaren and Bowles (1985).

Despite the initial use of a statistical test, various other qualitative assessments must be made in the final acceptance or rejection of a trend. Included is an evaluation of R^2, a multiple correlation coefficient defining the relationship between the mean, sorting, and skewness in the sample sequence. If a given sample sequence follows a transport path perfectly, the three grain-size descriptors will contain a relationship as defined in Figure 1. R^2 will, therefore, approach 1.0 (i.e., the sediments are perfectly "transport-related"). A low R^2 may occur, even when a trend is statistically acceptable for the following reasons: (i) sediments on a presumed transport path are, in reality, from different facies, and valid trend statistics occurred accidently; (ii) the sediments are from a single facies, but the sequence chosen deviates from the actual transport path, and (iii) extraneous sediments have been introduced into the natural transport regime, as in the case of dredged material disposal. R^2, therefore, is assessed qualitatively, and when low, statistically accepted trends must be treated with considerable caution.

To analyze for sediment transport directions over 2-dimensions, a grid of samples is required. Each sample is analyzed for its complete grain-size distribution and these are entered into a micro-computer equipped with appropriate software to calculate statistically acceptable trends for all sample sequences and the corresponding transport (X(s)) functions. Most importantly, a final interpretation of the sediment pathways is accepted only when the patterns of transport form a "coherent" whole over the entire area of sampling.

FIELD METHODS AND DATA BASE

Sample Collection

The findings described in this paper are the result of two separate projects. In the first, samples were collected with a Van Veen grab between January 4 and January 12, 1990. Sampling was carried out from the M.V. *Beatrice* (IOS Cruise 90-01) and the area covered extended from Squamish south to Lat. 49°30′ (immediately south of Port Mellon and Anvil Island). The sampling strategy was based on a grid with spacing of 500 m across the channel (fjord) width and 1 km spacing down the channels. Positioning was achieved using radar bearings.

A sub-sample of the top 10-15 cm of each grab was collected for grain-size determination. In addition, about every third grab was further sub-sampled for later chemical analysis. A total of 312 stations were visited from which 293 samples were collected and analyzed for their full grain-size distributions (no samples could be obtained at 19 stations due to the steepness of the fjord sides or an excessive covering of bark over log booming areas). A report using these data was prepared and submitted to Ocean Chemistry in September 1990 (GeoSea Consulting, 1990).

The second project continued from the first with an identical sampling strategy. Sample coverage was extended farther south to Lat. 45° 25′. A further 227 samples were obtained between Dec. 3 and Dec. 17, 1990. For the interpretation of the sediment trends, however, the new data were integrated with the previous samples and a second report prepared (GeoSea Consulting, 1991). The sample locations for both studies are shown in Figure 3.

Grain-size Analysis

The samples were all analyzed using a standardized method developed by GeoSea Consulting. This combines measurements on a Malvern 2600L laser particle sizer with data obtained from dry sieving the gravel fraction where necessary. It provides a consistent method of analysis which allows large numbers of samples to be analyzed. Because a sediment trend analysis looks at relative changes in the grain-size distributions, it is of prime importance to have a constant method of analysis. All samples were well mixed prior to analysis in order to obtain a representative sub-sample. A series of tests on a muddy sand showed excellent reproducibility of results.

The Malvern instrument employs lenses of different focal lengths to look at portions of the total range of grain sizes. Frequently, two measurements were required; one to cover the sand fraction and the other for the silts and clays. The separate distributions and the sieve data were then "merged" together using an algorithm to reproportion the weight percents into a single, complete distribution. This was accomplished with software developed by GeoSea Consulting and the merged data provides the data base used in the sediment trend analysis. The full grain-size distributions are contained on diskettes in an ASCII file (HOWE.DAT and HOWSOUTH.DAT) and are available from the authors on request.

PHYSICAL SETTING

Howe Sound is a fjord exhibiting a typical U-shaped submarine valley. In the area of the study, its width is about 3.5 km and it originates in the north at the Squamish delta. Water depths increase rapidly to about 220 m near Woodfibre (Fig. 3), and then more gradually to nearly 300 m at the base of the sill 17 km to the south. The water depth over the sill is in places less than 50 m; it is composed of morainic materials and marks the maximum ice advance of the Fraser glaciation (11,300 years B.P.)(Mathews et al., 1970). Immediately south of the sill, the fjord divides into a number of channels separated by Anvil, Gambier, and Bowen Islands, each with an average depth of 230 m.

The Squamish River, which drains 3,600 km^2 of the southern coast mountains, yields about 1.5 x 10^6 m^3/y of sediment into Howe Sound and appears to be the dominant influence on the circulation of surface waters in the Sound (Hickin, 1989). The present Squamish delta is prograding down-fjord at an average rate of 3.86 m^3/y. In the Sound itself, the bottom is covered by a layer of 50-150 m of Holocene sediments that overlie thick deposits of Pleistocene sediment (Syvitski and MacDonald, 1982). According to Hickin (1989), the rate of sedimentation decreases exponentially down the fjord with an average annual accumulation of 0.004 m/y near Britannia Beach and 0.0002 m/y at the foot of the sill.

In addition to the transport and deposition of sediments by the "normal" circulation of the fjord waters, considerable transfer of materials is achieved by catastrophic mass movements down the Squamish delta front and sides of the Sound. Prior and Bornhold (1984), using sub-bottom profiling and side scan sonar surveys have shown a complex bottom morphology consisting of numerous elongate chutes which incise the delta slope to water depths of 200 m. At their downslope ends, these chutes terminate in debris fans and associated features such as closely spaced arcuate scarps and large allochthonous sediment blocks that have moved across the fjord floor as a result of load-related sliding.

The oceanography of the Sound has received much attention and excellent literature reviews are contained in Syvitski and MacDonald (1982) and Hickin (1989). The fjord is contained in a macrotidal environment (range 5.5 m); however, tidal oscillations contribute little to residual currents and their influence decreases with depth (Pickard, 1961). More important to generating residual flow are the freshwater discharge of the Squamish River and katabatic winds, the latter being generated over the hinterland ice fields to produce high velocity outflow winds. These result in strong up-inlet and stronger down-inlet forces causing both short-term residual velocities in the surface waters and deep water exchanges at the sill (Buckley, 1977).

Current measurements show that velocities throughout the water column are usually lower that 0.8 m/s. Buckley (1977) and Buckley and Pond (1976) described a surface-layer outflow and a return flow in the waters immediately below. A mean down-inlet flow was observed in the deeper waters below about 130 m.

At present Howe Sound supports two pulp and paper mills at Port Mellon and Woodfibre, as well as a chlor-alkali plant at Squamish. The latter was a source for mercury in the sediments, the distribution of which is described in Thompson et al., (1980). Much of the fjord bottom in the vicinity of the two mills is covered with bark mulch, and effluent from the manufacture of pulp and paper is considered to be a source of dioxins.

PRESENT PATTERNS OF SEDIMENTATION

For the sediment trend analysis, numerous sequences of samples were tested for preferred transport directions. For the first part (northern portion) of the study, 25 lines of samples produced a coherent pattern of transport. In the second part (southern portion) samples from both studies were used to obtain an interpretation over the whole region. The findings of both studies were compatible with each other, thus providing mutual support for their interpretation. The appropriate maps of sample lines and their individual trend statistics are provided in the two reports (GeoSea 1990 and 1991) but, for the sake of brevity, are not included here. Figure 4 illustrates the derived transport pathways, and the findings of the sediment trend analysis are discussed according to specific regions as follows:

(1) Upper Howe Sound

The lines of samples used in the trend analysis for this region originated at the Squamish delta and terminated at the base of the sill. With the exception of one line immediately adjacent to the eastern shoreline, all the trends produced Case B transport in a down-fjord direction, and an X-distribution signifying total deposition (Table 1 and Fig. 5). The trend statistics were exceptionally high with a mean R^2 value of 0.86 ± 0.10. However the two lines closest to the fjord sides were the weakest, probably the result of local sediment sources derived from the steep surrounding walls.

(2) Ramillies Channel

Ten sample sequences were used to determine the transport trends from the base of the sill, through Ramillies Channel to the northern part of Queen Charlotte Channel. The direction for all the lines was south, although there appears to be some indication that transport is diverted in and out of the channel separating Gambier Island from Bowen Island (Fig. 4). The distinguishing feature of these lines compared to the Upper Howe Sound lines is that virtually all the trends are Case C. Furthermore, the derived X-distribution is essentially horizontal (Fig. 6), a shape that is undefined according to Figure 2. The average R^2 value for this region is significantly lower than that of Upper Howe Sound (0.69 ± 0.27; Table 1).

(3) Montagu Channel

Similar to Ramillies Channel, the sample sequences for this area also originate at the base of the sill and continue southwards as far as Bowyer Island. The trends are identical to those in Ramillies Channel, the statistics showing Case C transport as well as an identical (undefined) X-distribution (Fig. 7). The R^2 value, however, is considerably higher with a value much the same as Upper Howe Sound (0.88±0.06; Table 1).

(4) Thornbrough Channel

Transport in Thornbrough Channel originates at the south end near Langdale and continues northwards and eastwards to join with Ramillies Channel (Fig. 4). All the sample sequences produced an X-distribution indicative of total deposition (Fig. 8). The R^2 values, however, were the lowest found in the complete study area (0.40±0.19; Table 1).

(5) Southern Gambier Island

The southern end of Gambier Island is composed of three bays that open into a single large bay (unnamed). A small river enters each of the small bays. Excellent trends were determined for lines of samples originating near the river mouths and entering the large bay. All lines showed Case B transport indicative of total deposition (Fig. 9). Similar to Upper Howe Sound and Montagu Channel, the average R^2 value was extremely high (0.88±0.07; Table 1).

DISCUSSION

GENERAL TRANSPORT PATTERNS

The derived transport patterns in Upper Howe Sound (Fig. 4) agree well with known surface currents which are dominated by the outflow of the Squamish River (Buckley, 1977) as well as with currents in deep water (>150 m) (Bell, 1975). Two minor discrepancies exist: surface drogue studies by Buckley (1977) show the presence of a clockwise gyre between Squamish and Woodfibre and a counterclockwise gyre in the vicinity of Britannia Beach. Neither gyre could be detected in the trend analysis suggesting that outflowing bottom currents may be negating the effects of the surface circulation at these locations.

Down-fjord transport appears to dominate the greater part of Howe Sound at least as far as Bowyer Island. However, the X-distribution which so clearly defines an environment of total deposition between Squamish and the sill, changes in Ramillies and Montagu Channels. South of the sill, the X-distribution is essentially horizontal which has not previously been observed. The modal size for sediments north of the sill (6.5 phi) is a full phi size coarser than those farther south (7.5 phi). The horizontal X-distribution suggests that, for the very fine sizes of particles remaining in transport beyond the sill, there is an equal probability of all sizes to be deposited. In other words, the particles are now too small to be deposited on the basis of a size sorting. Only along the sides of the fjord where there is an input of larger sized materials can the more typical X-distributions be observed (Fig. 4).

Disagreement in the transport paths occurs in Thornbrough Channel where Syvitski and MacDonald (1982) have shown a Squamish River-dominated west and southwest transport. The sediment trends, on the other hand, indicate an opposite direction in which sediment is transported in a clockwise direction around Gambier Island. The interpretation by Syvitski and MacDonald is based primarily on the patterns of mica, nickel, and copper contained in the sediment, all of which show protrusions of high concentrations from the north into Thornbrough Channel. Published current data for this area do not exist.

There are two principal failings in the arguments used by Syvitsky and MacDonald. First, in their map of mean grain size, they show the sediments becoming coarser towards the southern end of Thornbrough Channel. For this to occur in the direction of transport, a high energy regime is required, a situation which is most unlikely at the bottom of a fjord more than 200 m deep. Second, the trends are based on very few samples (8 in Thornbrough Channel) and the mineralogy content appears to be related much more to grain size than to transport direction. In favour of the findings of the trend analysis is that eight separate lines of samples all produced exceptionally good transport paths with no ambiguities. Furthermore, the fining sequence of total deposition is completely acceptable in the deep water, fjord environment.

The exceptionally low R^2 values observed in Thornbrough Channel (Table 1) are attributed to a dumpsite adjacent to Port Mellon. It is interesting to note that R^2 for Ramillies Channel is also low compared to the other environments. This may be explained by an input of Thornbrough Channel sediments mixing with the Ramillies Channel transport regime. The latter is dominated by the Squamish River and even a small input from Thornbrough Channel would have the effect of introducing an extraneous sediment, and thus lowering the R^2 value. The sediments on the Montagu Channel side have no such mixture of sediments from a different source; hence, the R^2 value is significantly higher.

The south side of Gambier Island is characterized by three bays, each associated with a small river. Similar to Upper Howe Sound, this environment is dominated by alluvial sediments which are totally deposited in the main channel. Samples taken in the middle of the northern end of Collingwood Channel could not be related to any transport paths. They may be the result of:

(1) Given greater surface areas and more sites available for adsorption, contaminants have a greater association with fine sediment (silt and clay) than with coarse sediment (sand).

(2) Dynamic Equilibrium (Fig 2A): When sediments are in dynamic equilibrium, there is no relationship between the contaminant loading and distance along the transport path.

(3) Net Accretion (Fig. 2B): In environments undergoing net accretion there is a general, linear increase of contaminant loadings along the transport path.

(4) Net Erosion (Fig. 2C): Contaminant loadings decrease rapidly along the transport path.

(5) Total deposition: (Fig. 2D): The highest contaminant loadings are associated with environments of total deposition.

The trend analysis in this study indicates that the area can be divided into four transport environments. These are:

(i) Upper Howe Sound - total deposition; high R^2 value.
(ii) Ramillies and Montagu Channels - undefined, horizontal X-distribution; low R^2 in Ramillies Channel, high R^2 in Montagu Channel.
(iii) Thornbrough Channel - total deposition; very low R^2 value.
(iv) Southern Gambier Island - total deposition; high R^2 value.

According to the above concepts, contaminant levels should be highest in the environments of total deposition (i.e., Upper Howe Sound, Thornbrough Channel, and Southern Gambier Island). Data for mercury in the sediments of the northern part of Upper Howe Sound (Thompson et al., 1980) showed highest concentrations in the centre of the fjord about 2 km south of Woodfibre. Beyond this point concentrations decreased. A repeat survey four years later showed no change in concentrations, lending support to the interpretation that the environment is one of total deposition. Once mercury-contaminated sediment is deposited, no further transport takes place.

The location of the high concentration of mercury coincides with the "start" of the finest sediment in Upper Howe Sound. Grain-size steadily decreases from Squamish to about the 225 m water depth beyond which there is negligible change in size to the foot of the sill (Fig. 10). This suggests that mercury is associated with the finest sediment and the preferred location for its deposition is the result of proximity to source rather than to a build-up along an accreting sediment transport path. The decline of mercury in sediments farther south indicates that there must be a dilution effect by uncontaminated sediments entering the fjord from the innumerable small streams running down either side.

A second explanation is that the rate of sediment accretion near Woodfibre is small compared to that towards the sill, a concept that appears unlikely given the dominance of the Squamish River and its associated prograding delta. Hickin (1989) suggested a formula to predict the annual sedimentation rate down the length of the fjord. It is a decreasing log function and provides a sedimentation rate of 1.2 cm/y at the location of the high mercury concentration. Given that much of the mercury effluent was reduced in 1970, and the high concentration was found about 7 cm below relatively uncontaminated sediment 6 years later, this sedimentation rate appears to be quite reasonable.

By analogy, contaminants found in the sediments of Thornbrough Channel should also be "source-related". It would be expected, therefore, that highest concentrations should be found north and east of the Port Mellon pulp and paper plant (i.e., in the direction of net sediment transport). In a study by Hatfield Consultants Ltd., the highest concentrations of tetrachloroguaiacol and tetrachlorocatecol were located just northeast of the plant near the north end of Woolridge Island (Dr. Wayne Dwernychuk, Hatfield Consultants, pers. comm., 1991). However, their data show concentrations decreasing on either side of this "high" to both the southern and northern ends of the channel, an observation also made by researchers at IOS (Ocean Chemistry).

There are two explanations for these findings and neither is likely to be exclusive of the other. First, there is a dumpsite in the middle of the channel immediately adjacent to Port Mellon. The low R^2 values in Thornbrough Channel attest to the effects of dumped material affecting the natural transport regime. If dumped material is contaminated, then transport of material at the time of dumping would be affected by the flood and ebb tidal regime. Dumping and total deposition could occur in both ebb and flood conditions giving rise to the observed concentrations decreasing in both directions.

The second also suggests that ebb and flood currents are dispersing contaminated particles despite the fact that flood-directed transport is favoured. Unlike the Woodfibre site where the influence of the Squamish River is unidirectional and apparently overrides the tidal influence, Thornbrough Channel is entirely tidally dominated. In an environment of total deposition, particles may be deposited at both slack high and low water periods giving rise to decreasing contamination on either side of the source.

The bays and adjacent channel on the south side of Gambier Island are also in an environment of total deposition; however, there is no contaminant source associated with these sediments and they are unlikely to contain concentrations of any significance.

The remainder of the study area (Ramillies and Montagu Channels) are characterized by the "horizontal", undefined X-distribution. If, as discussed above, such a distribution represents no further size sorting of the sediments in transport, it is unlikely that contaminants would have any favoured location for their deposition. Rather, particles containing contaminants would be deposited with equal probability throughout the area. The Hatfield data strongly suggest that this is the case. Contaminant values from sites encompassing the sill, Ramillies, and Montagu Channels all show low and equal concentrations.

SUMMARY AND CONCLUSIONS

(1) A sediment trend analysis was performed on about 550 grain-size distributions taken from the bottom deposits of Howe Sound. The technique enabled patterns of net sediment transport to be determined, as well as the depositional behaviour of the sediments.

(2) The trends indicate that the transport regime from Squamish to Bowyer Island is driven largely by the inflowing Squamish River (i.e., in a southerly direction). From Squamish to the sill, the derived X-distributions are typical of total deposition. Thus, sediments tend to fine in the down-fjord direction and, once deposited, undergo no further transport. South of the sill, however, the X-distributions are horizontal, a shape never previously observed. It is suggested that the horizontal X-distribution signifies deposition of extremely fine material that is no longer sorted according to the size of particle (i.e., there is an equal probability of all sizes to be deposited).

(3) Sediments in Thornbrough Channel show transport in a northerly direction indicating a clockwise regime around Gambier Island. As in Upper Howe Sound, the X-distribution is one of total deposition. Very low R^2 values are explained by a dumpsite in the middle of the Channel adjacent to Port Mellon. Total deposition of sediments is also observed in the bays along the south side of Gambier Island.

(4) Data for mercury levels in the sediments of Upper Howe Sound agree well with the concept of total deposition. Repeat surveys showed the same levels and the amount of relatively clean sediment overlying mercury-contaminated sediment supports a published deposition rate of about 1.2 cm/y near Woodfibre (Hickin, 1989).

(5) In Thornbrough Channel, highest levels of contaminants are found immediately northeast of the pulp and paper plant which is consistent with the derived transport regime. Unlike Upper Howe Sound, which is dominated by the unidirectional Squamish River influence, Thornbrough Channel appears to have a strong tidal component responsible for transporting and depositing contaminated particles. As a result, levels of contaminants decrease in both directions away from Port Mellon. Disposal operations adjacent to Port Mellon, which would occur at any stage of the tide, may also contribute to the southward dispersal of contaminants.

(6) Given that particles are not deposited according to size in Ramillies and Montagu Channels, it is unlikely that contaminants could become concentrated at a particular locality, or be related to a specific source; rather they will be dispersed more or less equally throughout the area. Existing contaminant data support this concept.

(7) The total deposition of sediments occurring on the south side of Gambier Island have no association with a contaminant source and are, therefore, unlikely to show significant contamination levels.

ACKNOWLEDGMENTS

Special thanks are extended to Norman Crewe (IOS), Sarah Blenkey (GeoSea) and the crews of the CSS *Vector* and MV *Beatrice* for field support. Richard Powys (GeoSea) undertook all the sample analyses, and Jerry Horel (Sea Turtle Systems) was responsible for meshing the data of the two study phases.

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Table 1. Summary of the sediment transport environments in Howe Sound.

Environment	No. of Sample Lines	Mean R^2 values	Interpretation of X-distribution
Upper Howe Sound	7	0.86 ± 0.10	Total deposition (Fig. 5)
Ramillies Channel	10	0.69 ± 0.27	Horizontal X-distribution (Fig. 6)
Montagu Channel	8	0.88 ± 0.06	Horizontal X-distribution (Fig. 7)
Thornbrough Channel	8	0.40 ± 0.19	Total deposition (Fig. 7)
South Gambier Island	10	0.88 ± 0.07	Total deposition (Fig. 9)

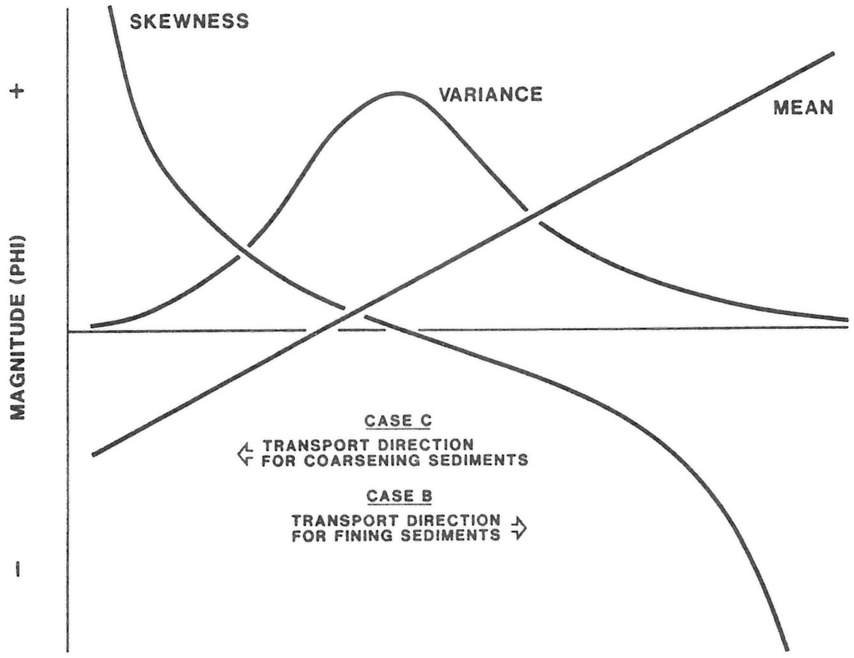

Figure 1. Summary of the changes in grain size measures (phi scale) that may occur in a given direction of transport. The X-axis is distance along the transport path.

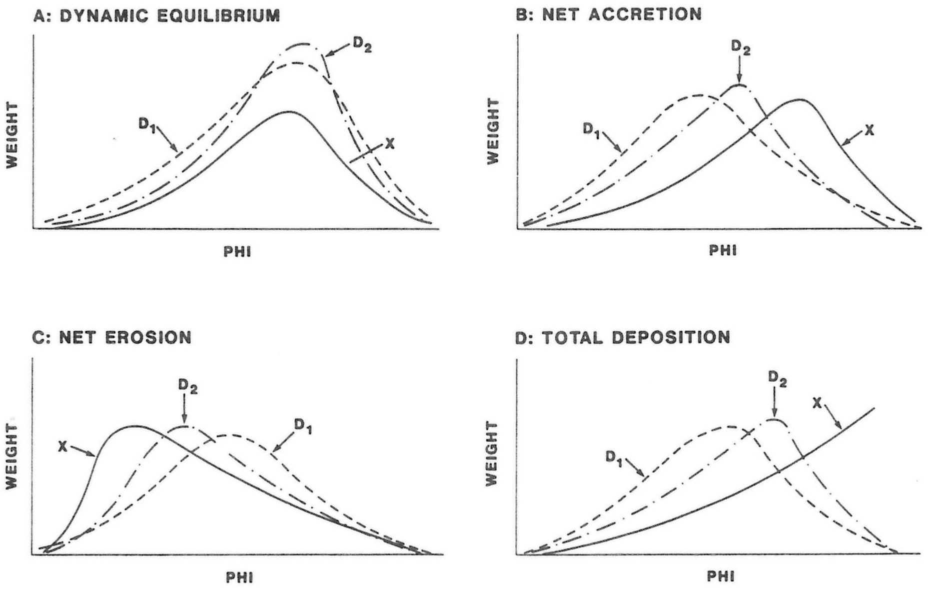

Figure 2. Summary of the interpretations given to the shapes of X-distributions relative to the D^1 and D^2 distributions.

Figure 3. Location map and sediment sample sites.

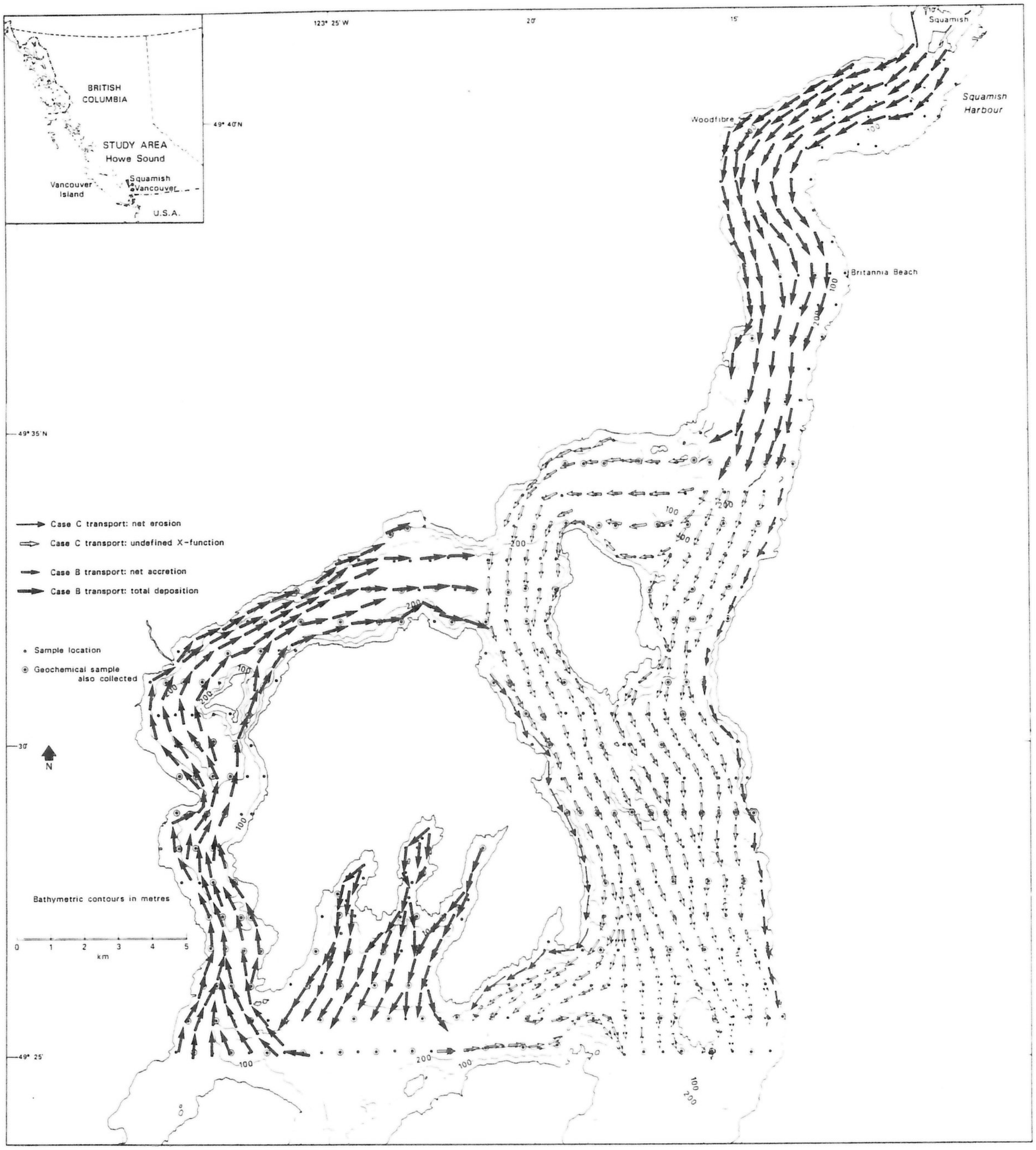

Figure 4. Net sediment transport pathways in Howe Sound.

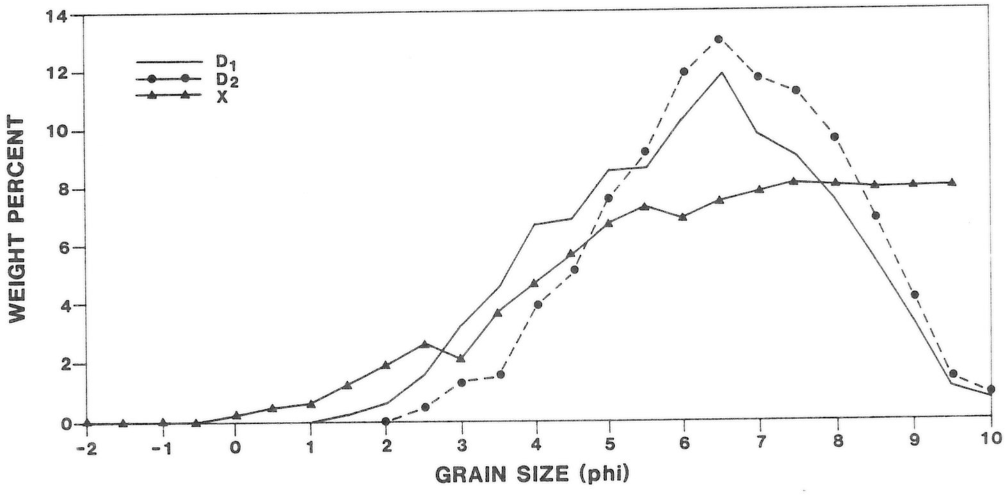

Figure 5. Typical D1, D2, and X-distributions for Upper Howe Sound signifies total deposition (compare with Fig. 2D).

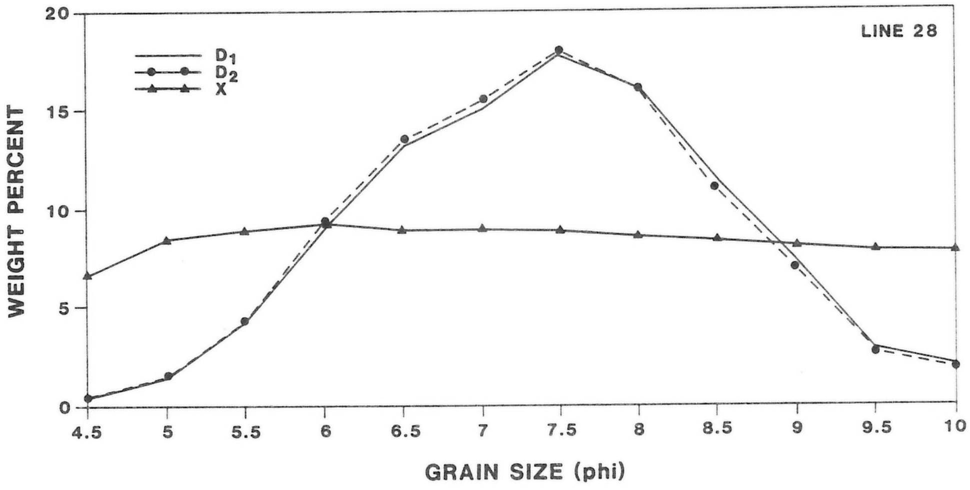

Figure 6. Typical D1, D2, and X-distributions for Ramillies Channel illustrating the horizontal X-curve. This shape is undefined according to Figure 2.

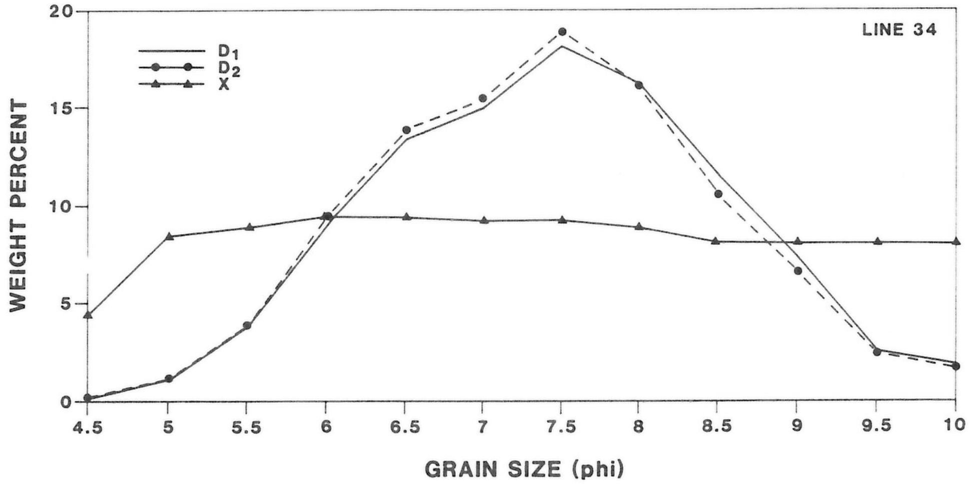

Figure 7. Typical D1, D2, and X-distributions for Montagu Channel showing an undefined X-curve identical to that found in Ramillies Channel (see Fig. 6).

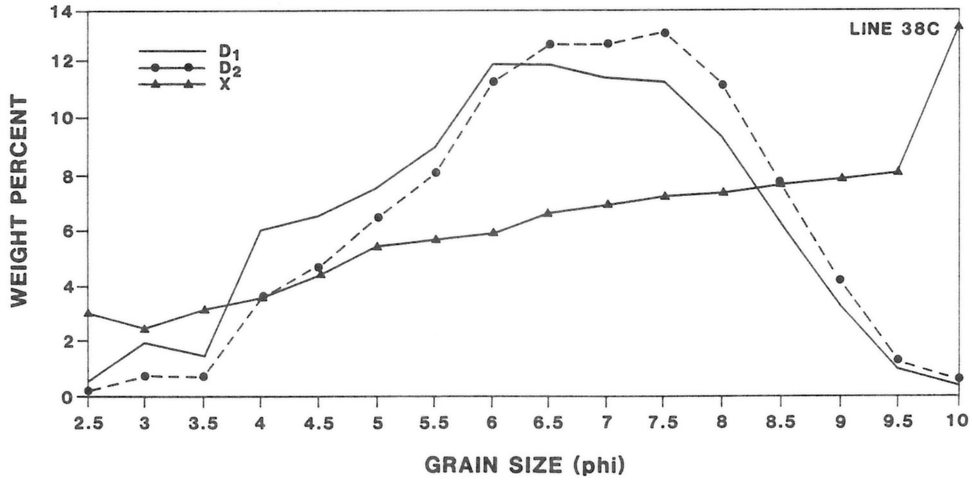

Figure 8. Typical D1, D2, and X-distributions for Thornbrough Channel indicating an environment of total deposition (compare the X-distribution with Fig. 2D).

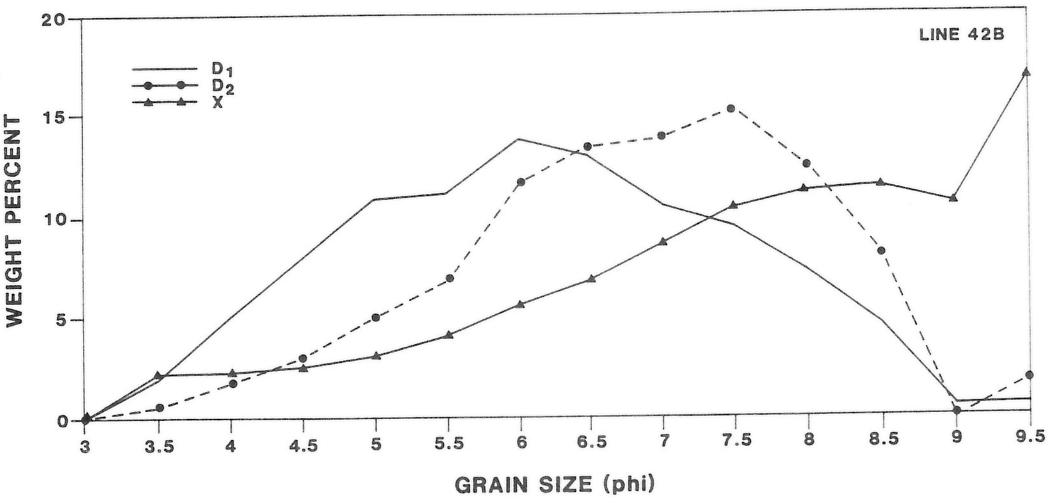

Figure 9. Typical D1, D2, and X-distributions for Southern Gambier Island indicating an environment of total deposition (compare the X-distribution with Fig. 2D).

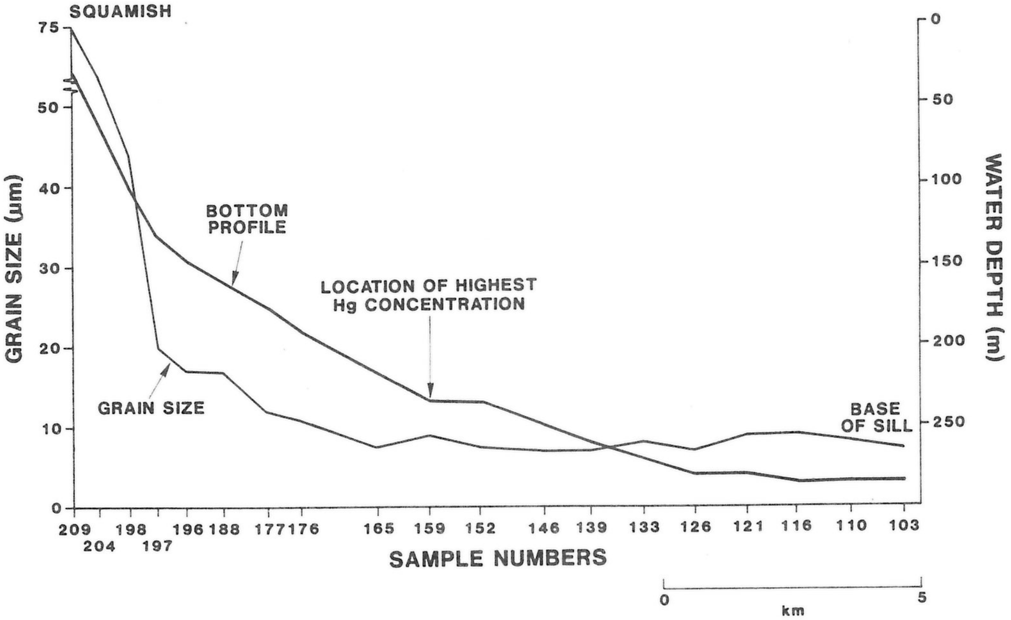

Figure 10. Longitudinal profile and mean grain size of Upper Howe Sound.

SPATIAL AND TEMPORAL DISTRIBUTIONS OF DIOXINS IN SUBTIDAL SEDIMENTS FROM HOWE SOUND, B.C.

by

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ABSTRACT

Howe Sound, a fjord system contiguous with the Strait of Georgia, has two bleached kraft mills at Woodfibre on the upper basin and at Port Mellon on Thornbrough Channel. Subtidal surface sediments were collected at mid-channel at varying distances from both mill sites to look for trends in the PCDD and PCDF distributions. Sediment cores were collected and age-dated to examine the historical records of these compounds as well as those of PAHs, PCBs, and other selected organics and metals. In surface sediments, the concentrations of PCDDs and PCDFs, excepting O8CDD, generally diminished with distance from the mill sites. In cores, 2,3,7,8-T4CDF, the P5CDDs, and the H6CDDs were found to exhibit elevated concentrations dating from about the time of the introduction of chlorine bleaching of pulp. The O8CDD concentrations, however, were found to have been elevated for a period of time before that. These results are consistent with a time-varying, mixed input of mill and combustion derived dioxins and furans.

INTRODUCTION

In a Dioxin Workshop held at IOS on July 19, 1989, and attended by Pacific Region Department of Fisheries and Oceans research and operations personnel, there was agreement that the two related key questions regarding the Howe Sound and Prince Rupert fisheries closures were:

1. How long will the fish remain inedible due to TCDD and TCDF concentrations?
2. How long will the sediments remain a potential source of these compounds to biota?

To begin to answer these questions a multifaceted research strategy was begun by researchers at the Institute of Ocean Sciences of the Department of Fisheries and Oceans with the primary focus on Howe Sound (Fig. 1.). One facet of the work was to estimate the spatial extent in sediments of pulp mill-generated dioxins and furans. A second facet was to develop a predictive model for burial of the dioxins and furans in subtidal sediments. Key to this model development, it was felt, would be the use of sediment cores to determine the historical variation of concentrations of these and other contaminants, such as mercury and polycyclic aromatic hydrocarbons, which were known to have increased in the environment and then decreased because of public pressure and government regulation. This paper presents evidence of the historical record and spatial distribution in surface sediments of the octachlorodibenzodioxin (O8CDD) and 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-T4CDF).

METHODS

SAMPLING

Surface sediment samples were collected in Howe Sound from the M.V. *Beatrice* between January 4 and 12, 1990, on December 16 and 17, 1990, and from the C.S.S. *Vector* between December 3 and 7, 1990. A Van Veen grab was deployed from the M.V. *Beatrice* and a Smith-McIntyre grab from the C.S.S. *Vector*. A box corer (0.6 m^2 area) with stainless steel liner was used from the C.S.S. *Vector* to obtain core samples. The cores were segmented at 1 cm intervals to 10 cm and then at 2 cm intervals. Precleaned stainless steel sampling tools were used and samples for PCDD and PCDF analyses were transferred to precleaned mason jars with Teflon-lined lids. Samples for chemical analysis were immediately frozen and kept frozen prior to analysis.

ANALYSIS

Lead-210 determinations for age-dating of the cores were done under contract by Flett Research Ltd. The method of Eakins and Morrison (1978) was used. Age-dating followed the procedures described in Macdonald et al. (1991). PCDD and PCDF analyses were performed as outlined in Figure 2 under contract by Zenon Environmental Laboratories Ltd. (B.C. Lab.).

Sample Extraction

About 20 g of accurately weighed wet sediment and anhydrous Na_2SO_4 were ground with a mortar and pestle until the mixture was free flowing. A surrogate standard solution containing 2,3,7,8-$[^{13}C_{12}]$T4CDF (2 ng), 2,3,7,8-$[^{13}C_{12}]$T4CDD (2 ng), 1,2,3,7,8-$[^{13}C_{12}]$P5CDD (2 ng), 1,2,3,6,7,8-$[^{13}C_{12}]$H6CDD (4 ng), 1,2,3,4,6,7,8-$[^{13}C_{12}]$H7CDD (4 ng), and $[^{13}C_{12}]$O8CDD (6 ng) was added to the sample in a soxhlet thimble. The sample was soxhlet extracted overnight with CH_2Cl_2 (400 ml). The extract was rotary evaporated to near dryness, its solvent displaced with hexane and then treated with acid-activated copper filings to remove sulfur.

Chromatographic Separation

Gel permeation chromatography using an Autoprep 1002A (Analytical Biochemistry Laboratories) separated high molecular weight (lipid) compounds from the analytes. Further purification was achieved by chromatography on columns of carbon/celite and acidic biosil over alumina. The analyte fraction was transferred to a toluene solution containing the chromatography recovery standard 1,2,3,4-$[^{13}C_{12}]$TCDD.

Measurement

Gas-chromatographic separation was achieved with a 60 m DB-5 fused silica column (0.25 mm i.d.) using helium carrier gas and temperature programming: 100 °C for 1 min, 20 C°/min to 200 °C, then 3 C°/min to 250 °C, and hold for 30 min.

GC/Low Resolution(LR) MS determinations were performed on all samples using a Hewlett Packard 5890 GC with a 5970 mass selective detector (resolution 800, 1 scan/sec). Quantification ions, confirmation ions (2) and chlorobiphenyl interference ions were monitored. Measurement criteria included: peak maxima for quantification and confirmation ions within 2 scan units of expected, and conforming to the retention time limits as defined by the window standards; m/z within +/- 0.5 amu for labeled and unlabeled standards; quantification and confirming peak area ion ratios within 20% of theoretical values; satisfactory separation of 2,3,7,8-T4CDD from 1,2,3,7-T4CDD and 1,2,3,8-T4CDD.

Linearity of the GC/LRMS was determined from a 5-point calibration in the range 0.01 to 0.5 ng/ul. Single point calibrations were done at least every 8 hours. Relative Response Factors (RRFs) were calculated as the mean from the 5-point calibrations provided that the standard deviation (s) was less than 20% of the mean. The RRFs from the single point calibrations had to be within 20% of the mean from the 5-point calibrations. GC/High Resolution(HR)MS was used to confirm the analyses by GC/LRMS. The machine was operated according EPA Method 1613.

Blanks, spiked blanks, and replicate sample determinations were run at a rate of about one for every 10 samples. Detection limits (3 s) were determined from actual samples and blanks and were corrected for surrogate recovery.

RESULTS

The concentration profiles of O8CDD in Core A from Howe Sound (Fig. 3) and in Core C from Ballenas Basin (Fig. 4) were very similar. Both showed a subsurface maximum which dated at about 1970. The concentrations decreased up to the present time, but had not yet decreased to concentrations found for the period prior to the early 1950's. The O8CDD profile in Core B from Thornbrough Channel in Howe Sound (Fig. 5) was distinctly different from the other two in demonstrating no, or a perhaps a modest, maximum in the post-1970 period. The period of rapid increase in O8CDD for this core was very similar to the other two. The concentration profiles (not shown) of unsupported lead-210, by which the strata in the cores were dated, established that Cores A and C were unmixed by biota in the upper layers whereas Core B was mixed to a depth of about 8 cm.

The concentration profiles of 2,3,7,8-T4CDF in Core A and Core C were similar to each other, but differed significantly from those of O8CDD in the same cores. There was an increase in the 2,3,7,8-T4CDF concentration up to the present, beginning much later in time than for O8CDD. Core B showed a similar increase to Cores A and C in 2,3,7,8-T4CDF concentration, apparently beginning sometime in the 1960's and maximizing in the post-1970 period.

The concentration of O8CDD in surface sediments (Fig. 6) showed no general correlation with proximity to the pulp mills at Port Mellon and Woodfibre. Some of the concentrations in samples from Ramillies and Montagu channels and the lower basin were as high as those in the vicinity of the mills. One very high value was obtained for a sample from Thornbrough Channel at a site some distance from Port Mellon. Only the O8CDD and the H7CDDs, however, were anomalously high in this sample. Confirmation of this result with other samples from the area is required.

The concentration of 2,3,7,8-T4CDF in surface sediments (Fig. 7) showed a strong correlation with proximity to the pulp mills. The highest concentration in the upper basin was obtained at a station just south of Woodfibre and near the western shore. In the middle of the basin at the same latitude and north of Woodfibre, the values were low. Aside from the sediment concentrations in the lowest part of the upper basin, Montagu Channel and the lower basin, these values were the lowest of all. The concentration of T4CDF was found to obtain its maximum values in Thornbrough Channel. Interestingly, the site of the highest concentration was further south of the nearest stations to Port Mellon. Also, the concentrations in sediments to the south of Port Mellon were found to be somewhat higher than those in sediments to the east.

DISCUSSION

From these results we may infer that the sources of 2,3,7,8-T4CDD and O8CDD are different. The fairly uniform distribution of O8CDD in the Sound indicates that its source is diffuse or multifold and its dispersal primarily through the atmosphere. The one very high value obtained in a sample from Thornbrough Channel may indicate a local major combustion source. More samples must be analyzed from the area to confirm this result, which may also have resulted from sampling or analytical contamination. The 2,3,7,8-T4CDF is directly linked to the pulp mills by the local maxima and gradient away from them. In the cores, the presence of a subsurface maximum in the O8CDD profiles corresponding to about 1970 compares well with results from cores obtained by others in eastern Canada, eastern U.S.A., and Europe. The decrease following this maximum is attributable to the use of emission controls on combustion in cars, incinerators, and thermoelectric plants; the increase after World War II, to the production and subsequent incineration of organochlorine-based chemicals and products (Hites, 1990). The lack of a distinct subsurface maximum for O8CDD in Core B can be explained by the role of organisms living in the surface layers in mixing the sediment to a depth of about 8 cm as determined by the lead-210 results. The maximum for 2,3,7,8-T4CDF is more distinct and may be related to the change from using two near surface effluent diffusers to using a single deep water diffuser made by Howe Sound Pulp and Paper in 1983. Since that time less effluent material may have been transported to the core site. Also, more recent changes in the bleaching process may be contributing to the apparent decrease in 2,3,7,8-T4CDF. A sediment mixing and deposition model that has been developed at IOS predicts well the observed distribution of O8CDD in Core B using a source function derived from the other two non-mixed cores. The detailed development and results of this model for Howe Sound are the subject of a paper in preparation. For the site of Core B the model predicts that the furans and dioxins from the mill will have a half life of about a decade at the sediment surface. The half life at the sites of little or no bioturbation will, of course, be much shorter. At these sites without benthic organisms, however, there is little or no potential for uptake into the food chain.

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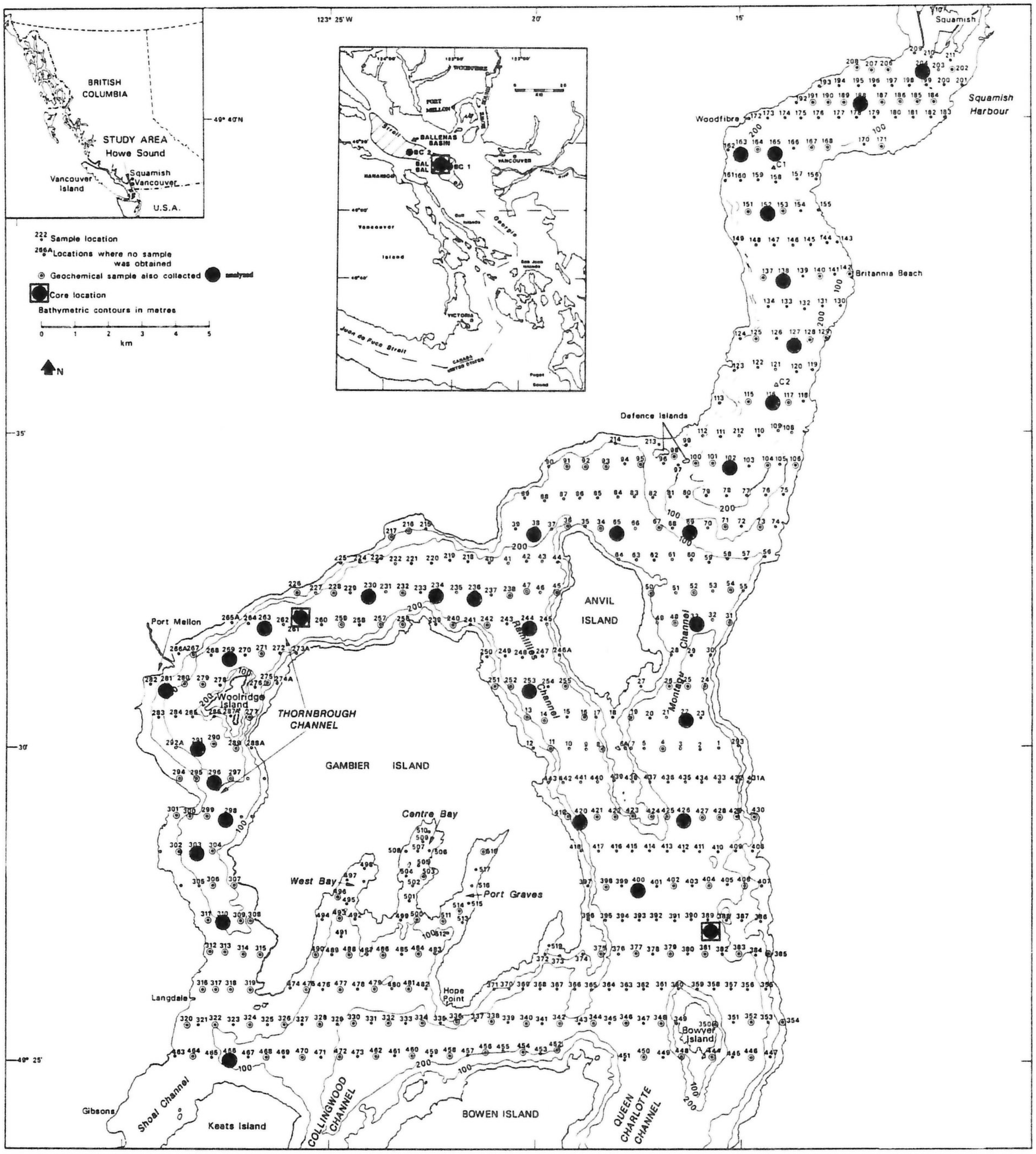

Figure 1. Map of sampling sites in Howe Sound and Ballenas Basin.

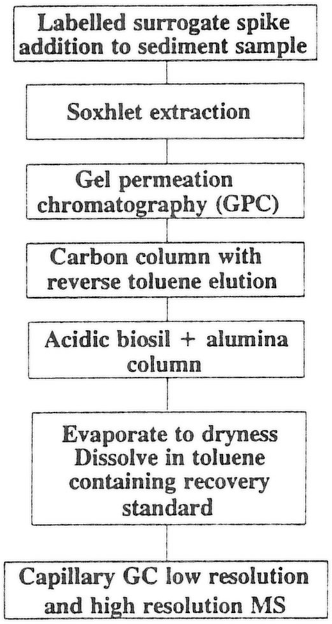

Figure 2. Flow chart for the analysis of polychlorinated dibenzodioxins and dibenzofurans in subtidal sediments.

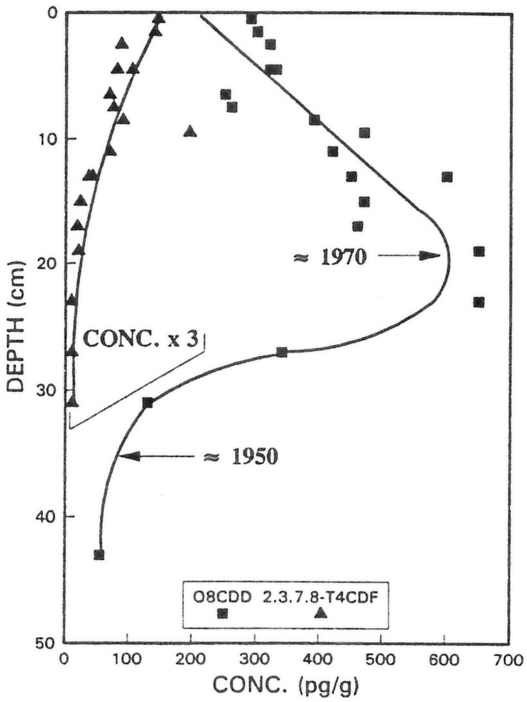

Figure 3. Depth profiles of 2,3,7,8-T4CDF and 08CDD in sediment Core A obtained in Howe Sound near Lions Bay.

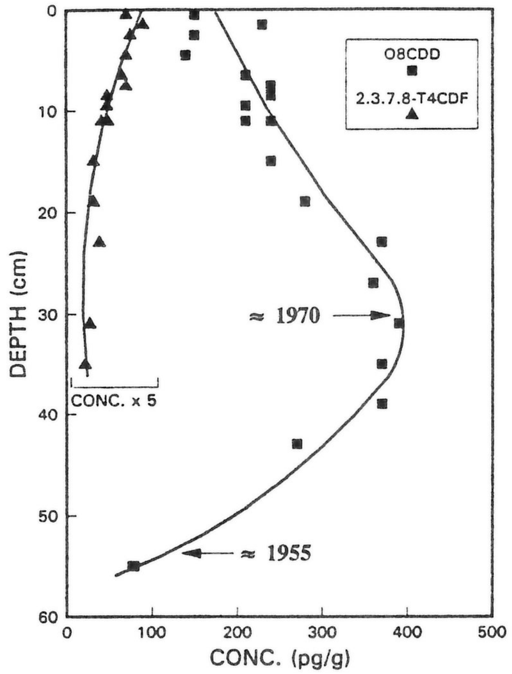

Figure 4. Depth profiles of 2,3,7,8-T4CDF and O8CDD in sediment Core C obtained in Ballenas Basin of Georgia Strait.

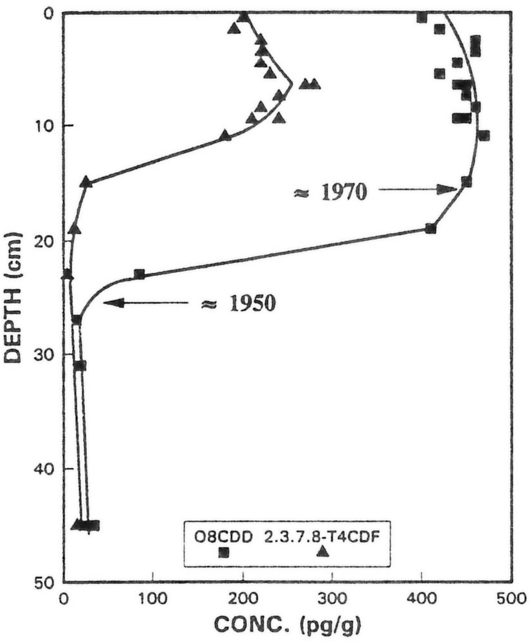

Figure 5. Depth profiles of 2,3,7,8-T4CDF and O8CDD in sediment Core B obtained in Howe Sound near Port Mellon.

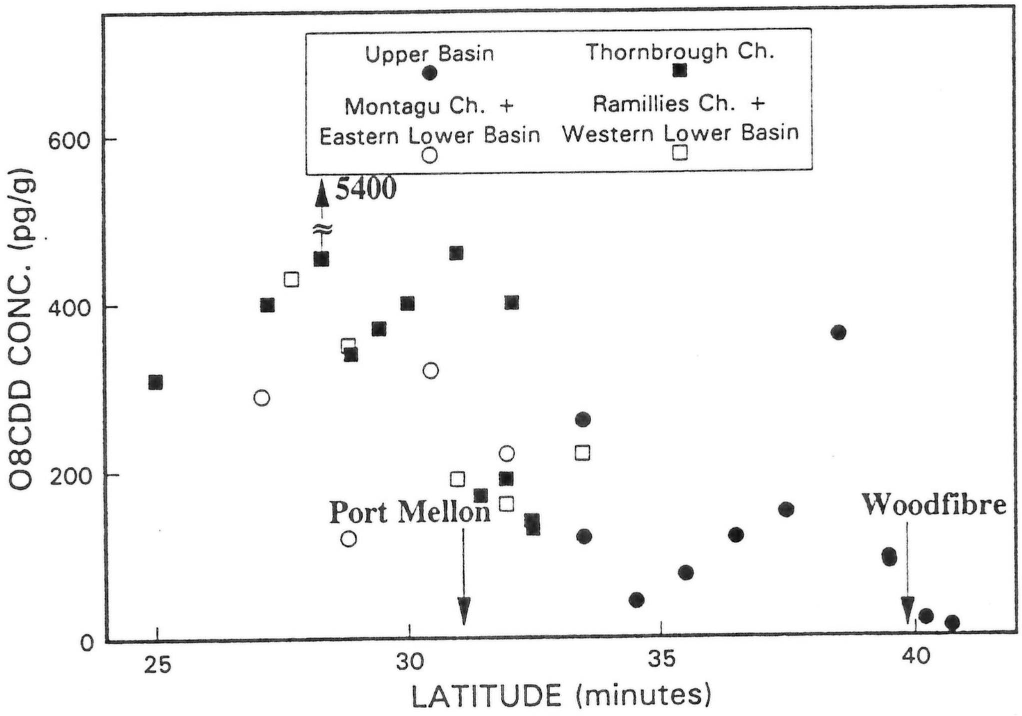

Figure 6. Concentration of O8CDD in Howe Sound surface sediments.

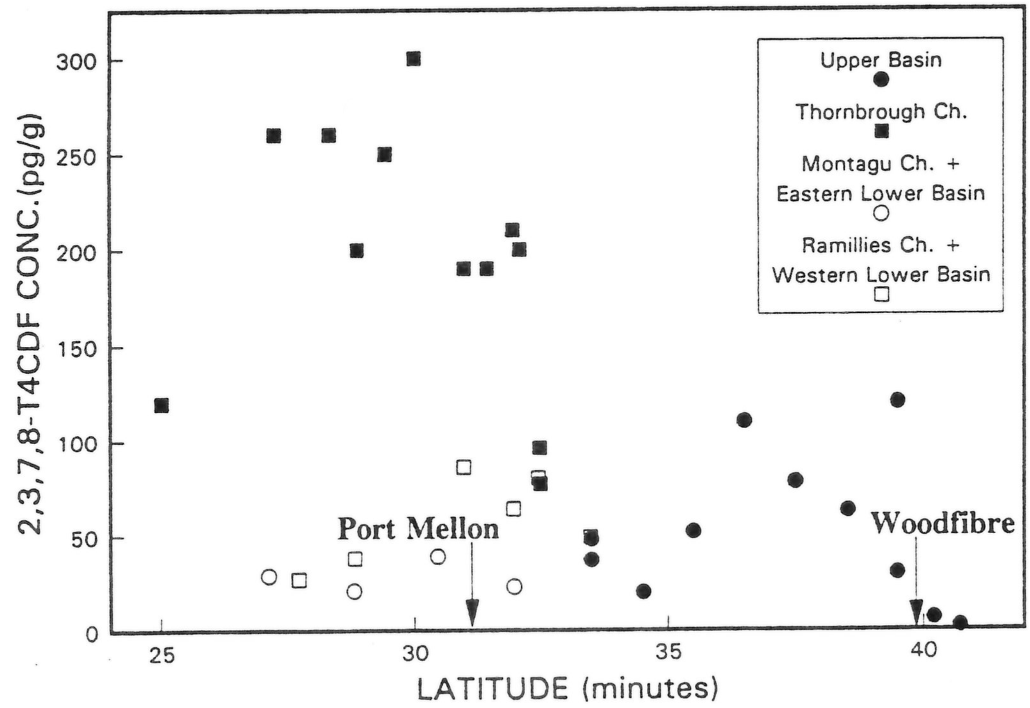

Figure 7. Concentrations of 2,3,7,8-T4CDF in Howe Sound surface sediments.

GEOCHEMICAL BEHAVIOUR OF A BURIED MARINE MINE TAILINGS DEPOSIT HOWE SOUND, BRITISH COLUMBIA

by

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ABSTRACT

One hundred surface sediment samples and two 30 cm cores were collected in 1987 and 1988 from Howe Sound, British Columbia, a deep (~280 m) fjord with a restricted inner basin into which mine tailings rich in Cu, Zn and Pb had been discharged for 75 years. The samples were analyzed for an extensive suite of major and minor elements, including organic C and N. In addition, nutrient and dissolved trace metal concentrations in pore waters were examined in order to assess the geochemical reactivity of the metals contained within the buried tailings deposit.

The solid-phase data suggest that the inner basin sediments are dominated by Squamish River-derived plagioclases, while the outer basin is characterized more by sediments from Georgia Strait, which are discernible in the Cr signal. Although Cu, Zn and Pb are still enriched in sediments near the old tailings outfall, 13 years of natural sedimentation since cessation of tailings deposition has resulted in reduced metal levels throughout much of the rest of the inlet. Profiles of these metals with depth show that the tailings deposit proper is buried by ~14 cm of natural sediment in the deep central portion of the inner basin.

Porewater analysis of the two cores revealed that the redoxcline occurs at approximately 2-3 cm depth in the inner basin, and at 6-8 cm in the outer basin. Cu and Zn are enriched in surficial pore waters of both basins, but decrease rapidly within the top 2-3 cm, suggestive of active removal by some mechanism, possibly authigenic sulphide precipitation. Dissolved Pb levels are extremely low throughout both cores (1-3 nmol/L) and show no surface enrichment. These data suggest that the reducing environment which develops at shallow sediment depths is inhibiting the remobilization of potentially labile metals in the tailings.

INTRODUCTION

Traditionally the disposal of mine tailings has been governed by simple economics: since it generates no revenue, the practice has been to do it as cheaply and as quickly as possible. In some cases, disposal of tailings into a nearby body of water has been used as a convenient and economic alternative to land-based disposal, without much consideration given to the environmental consequences. However, there is a growing consensus that in certain cases, subaqueous deposition of mine wastes may actually be preferable to land disposal (Waldichuk, 1978). Some of the fjords on the west coast of British Columbia (an area characterized by heavy rainfall, high seismicity, and high local relief) have been considered as acceptable receiving environments for metal-rich mine wastes from nearby mines (Caldwell and Welsh, 1982), despite some evidence that obliteration of the benthic habitat and release of dissolved metals into the overlying waters may be undesirable consequences of such action.

In an attempt to broaden our understanding of this subject, we have recently examined the submerged tailings deposit from a mine that had been abandoned for fifteen years prior to collection of our samples in 1987-88. The Anaconda Mine, located at Britannia Beach in Howe Sound, British Columbia (Fig. 1), had for seventy-five years discharged copper- and zinc-rich tailings into the upper basin of the fjord via an outfall located just below the low-tide mark.

Subsequent slumping and winnowing carried much of these unstable sediments into the deep, flat portion of the basin, and an earlier study indicated that they may also have been dispersed beyond the sill into the outer basin (Thompson and Paton, 1976).

Although the mine has been closed since 1974, the waters in Britannia Bay have since been found to contain elevated levels of dissolved copper and zinc (van Aggelen and Moore, 1986), and fish and invertebrates living in the area have relatively high concentrations of these metals within their tissues (Goyette, 1975; van Aggelen and Moore 1986). Faunal assemblages are also considerably reduced in the inner basin (McDaniel et al., 1978; Levings and McDaniel, 1980), although this may be influenced by intermittently low O_2 concentrations in bottom water. It has been suggested that the buried tailings deposit may be a source of the high metal levels in the deep waters (Thompson and Paton, 1978).

Detailed analysis of both solid and dissolved (porewater) phases is essential if the flux of materials into or out of sediments or tailings is to be discussed. Using this approach, the submerged tailings deposit in Rupert Inlet on Vancouver Island has been shown to release dissolved copper and molybdenum to the overlying waters of the inlet, although the dissolved copper efflux is much smaller than that from many natural sediments (Pedersen, 1985). In contrast, tailings deposits in Buttle Lake, British Columbia, and Anderson Lake, Manitoba, appear to be sinks for dissolved zinc in the overlying water, rather than sources (Pedersen, 1983; Pedersen et al., 1991a and b).

In order to assess the current geochemical state of the Britannia tailings deposit, a two-stage study was therefore initiated in April 1987 to 1) determine the areal extent of the tailings and the degree to which they are being covered or diluted by natural sediments, and 2) to assess the contribution of dissolved trace metals (specifically copper, zinc, manganese, iron, and lead) from the tailings deposit to the overlying waters.

To that end, an extensive geochemical analysis was performed on a suite of 100 surface sediment (0-2 cm) samples (see Figs. 1a & b). The major elements Si, Al, Ti, K, Na, Ca, Fe, Mg, and P, minor elements Rb, Ba, Sr, Co, Cr, Ni, V, Y, Mn, Cu, Pb, Zn and Zr, and organic C and N were determined in the solid phase. In addition, a core was taken from each of the two basins (see Fig. 2) and analyzed for the above elements in the solid phase, and for interstitial water concentrations of diagenetic indicator species such as SO_4^{2-}, PO_4^{3-}, NH_3, alkalinity, Fe^{2+}, and Mn^{2+}. Finally the concentrations of the trace metals Cu, Zn and Pb in porewater were determined in order to assess the contribution, if any, of these metals to the overlying waters. The analytical methods are detailed in (Drysdale, 1990).

THE PHYSICAL SETTING

Howe Sound is the first inlet north of Vancouver on the mainland of southwestern British Columbia (Fig. 1a). The south end of the Sound connects with the Strait of Georgia from which Fraser River water enters, and at the northern end, the Squamish River is the principal fresh water source. The two basins are separated by a sill which rises over 200 m from the fjord floor to within 70 m of the water surface (Fig. 2). Both inner and outer basins are characterized by steep walls and flat bottoms.

The northernmost section of Howe Sound, called the Britannia Basin (maximum depth 285 m), is bounded at the seaward end by the steep-sided sill and at the head by the more gradually-sloped Squamish Delta. One effect of the sill is to prevent the continuous renewal of deep water in the upper basin, resulting in occasional hypoxia in the bottom waters.

RESULTS AND DISCUSSION

SOLID SEDIMENT ANALYSIS

The organic carbon (C_{org}) concentration in these sediments averages less than 3% over most of the Sound (Fig. 3a). This relative paucity of organic matter largely reflects dilution by the riverine lithogenous fraction rather than low absolute organic inputs. Exceptions are areas dominated by pulp mill waste in the westernmost channel and the far northwest corner of the upper basin, and a shelf area near the sill dominated by plant debris from nearby Potlatch Creek.

The C/N ratio is useful for determining the origin of organic material within sediments: terrigenous plant material typically exhibits C/N weight ratios from ~20 to as high as 200 (Emerson and Hedges, 1988), while marine organic matter has a C/N ratio of about 6 (Borodowskiy, 1965). The generally high C/N values over most of the region (Fig. 3b) reflect the predominance of terrigenous plant material in the Sound; only sediments from the large channel near the mouth have C/N ratios which approach that of marine plankton.

In the outer basin core, the organic carbon content decreases linearly from ~1.75% at the surface to ~1% at 30 cm depth, which may reflect decomposition of organic material over time in addition to a time varying input (Fig. 4a). The overall C_{org} content of the inner basin is lower due to dilution by rapidly-accumulating Squamish River sediments. Both the C_{org} and C/N ratio profiles for the inner basin vary with depth, reflecting variable inputs of inorganic sediments and changes in relative proportions of terrestrial and marine organic material. The higher C/N ratios in the inner basin indicate that the organic material in these sediments is predominantly of terrestrial origin.

The major and minor element distributions in Howe Sound surface sediments support earlier work by Syvitski and MacDonald (1982) and show that sedimentation patterns are dominated by input from three primary sources: the Fraser River/Georgia Strait waters which enter Howe Sound at the south end, and which are visible in the distributions of several major and minor elements, including Cr (Fig. 5b); the Squamish River which enters the upper fjord portion of Howe Sound at the north end, and whose sediments, rich in plagioclase feldspars, are depicted by the Ca and Na distributions (e.g., Fig. 5a); and the tailings from the Britannia Mine, which are still discernible in the trace metal (Cu, Zn, Pb, Ba, and Fe) distributions in the upper basin and portions of the lower basin.

The areal distributions of copper and zinc (Figs. 6a, 6b, 7a, & 7b) indicate that the tailings have been considerably dispersed from their place of origin. However, concentrations are extremely high (>300 ppm) only very near the site of the old mine outfall. Comparison of these distributions with those of Thompson and Paton (1976) indicates that the tailings have been diluted by recent sedimentation. Cu concentrations approach normal background levels (80 ppm) in most of the outer basin. Sediments surrounding Gambier Island appear to have some secondary, though probably unrelated, enrichment in Zn and Pb. Further study is needed to determine the source of metals in this area.

In both cores, high copper and zinc levels were encountered at 14 cm below the sediment surface (Figs. 8a & 8b); this depth is interpreted to be the top of the tailings deposit. The Ba, Pb, and Fe profiles all show similar increases at 14 cm (data not shown), reflecting the relatively high contents of barite, galena, and pyrite associated with the Britannia ore.

PORE WATER ANALYSES

Studies of the chemistry of pore waters yield significant insight into the diagenetic environment within sediments. Early diagenesis is driven by bacterially-catalyzed oxidation of organic matter, during which a number of components are remobilized from the solid phase and released as solutes to the surrounding water. When this occurs at the sediment surface, the oxidation products are released directly to the overlying water. Below the surface, they accumulate in pore water and may migrate upward or downward along concentration gradients until they encounter other conditions under which they may precipitate or dissolve.

During the progressive diagenetic degradation of organic matter, manganese oxyhydroxides become the preferred oxidant after O_2 and NO_3^- have been depleted. Utilization of these phases results in the addition of MN^{2+} to pore water as the oxyhydroxides are reduced. In the Howe Sound cores, upward concavity in the pore water manganese profiles (Fig. 9) indicates that Mn^{2+} is being produced at depths as shallow as 2-3 cm. Thus the sedimentary redoxcline must be located at approximately this level. The profiles suggest that the redox boundary is slightly shallower in the inner basin, which may reflect the characteristically lower O_2 content in bottom waters north of the sill. The depletion of manganese at depth in both cores can be attributed to the precipitation of an authigenic manganese carbonate phase, which is a common phenomenon in reducing marine sediments (Shimmield and Pedersen, 1990). Dissolved pore water sulphate data (Drysdale, 1990) indicate that sulphate reduction occurs to a limited extent at shallow depths in both basins, which is consistent with the interstitial manganese distribution. However, dissolved sulphide is virtually absent, indicating active near-surface precipitation of authigenic iron sulphide phases (Drysdale, 1990).

Concentrations of Cu in the surface pore waters (Figs. 10a and b.) of both cores are similar in magnitude to those in pristine coastal, hemipelagic or pelagic sediments (e.g., Klinkhammer, 1980; Emerson et al., 1984; Heggie et al., 1986, 1987). Indeed, assuming that the profiles presented here are representative, the benthic copper efflux in the inner basin of Howe Sound is about half that observed in the tailings-free outer basin.

The Zn distributions also suggest release of Zn^{2+} from surface sediments due to dissolution of some phase (likely opal or organic matter) and subsequent removal at depth by precipitation of zinc sulphide or coprecipitation with iron sulphide. These data indicate that zinc must be diffusing both upward into the overlying water and downward to be fixed at shallow depths in the sediments. Note that Zn^{2+} in the topmost sample in the outer basin core is substantially higher than that at the inner basin site, even though the solid-phase Zn content is higher in the latter. This suggests that the tailings may not be the source of the labile zinc.

There is little variation with depth in the generally low dissolved Pb concentrations in either core; thus it is unlikely that Pb associated with the tailings is mobile in these deposits.

The dissolved metals profiles suggest clearly that the tailings buried below the oxic zone in Howe Sound are not undergoing active diagenesis with respect to Cu, Pb, and Zn.

SUMMARY AND CONCLUSIONS

Although other researchers have determined abnormally high levels of copper and zinc in the surface and bottom waters of the inner basin of Howe Sound, the diagenetic environment of the tailings-rich sediments defined by this study indicates that there is little likelihood that the buried tailings deposit is substantially contributing to this excess. In both basins active bacterial decomposition of organic matter renders the sediments anoxic within centimetres of the sediment surface. In these reducing conditions, dissolution of trace metals is inhibited; any metal cations in pore waters are likely removed by sulphide precipitation or adsorption onto particulates.

It should be noted, however, that these cores represent only the deep, flat, relatively undisturbed portions of the two basins. The geochemical environment may be quite different in shallower, more oxygenated areas of the Sound, or where tailings material is regularly resuspended by subsurface currents. Further study is recommended to explore the reactivity of metals in these areas. In addition, more work is needed to define both the spatial variability of the Zn release to pore water at the interface, and the specific reason for this enrichment.

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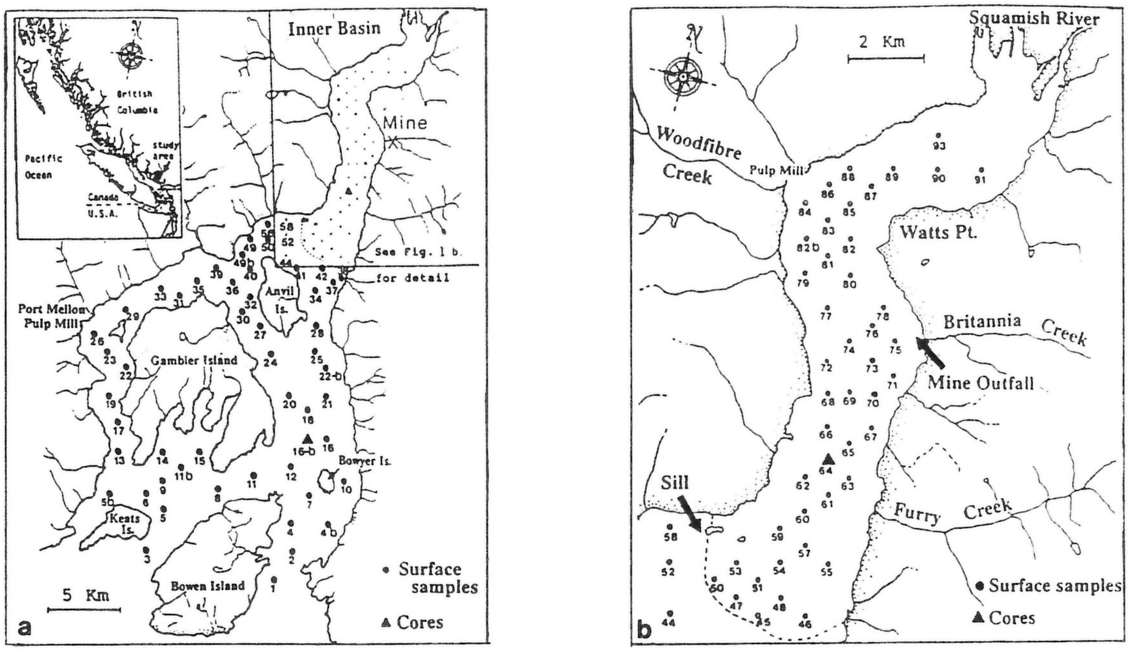


Figure 1a & b. Locations of surface sediment (●) and core samples (▲), Howe Sound, B.C.

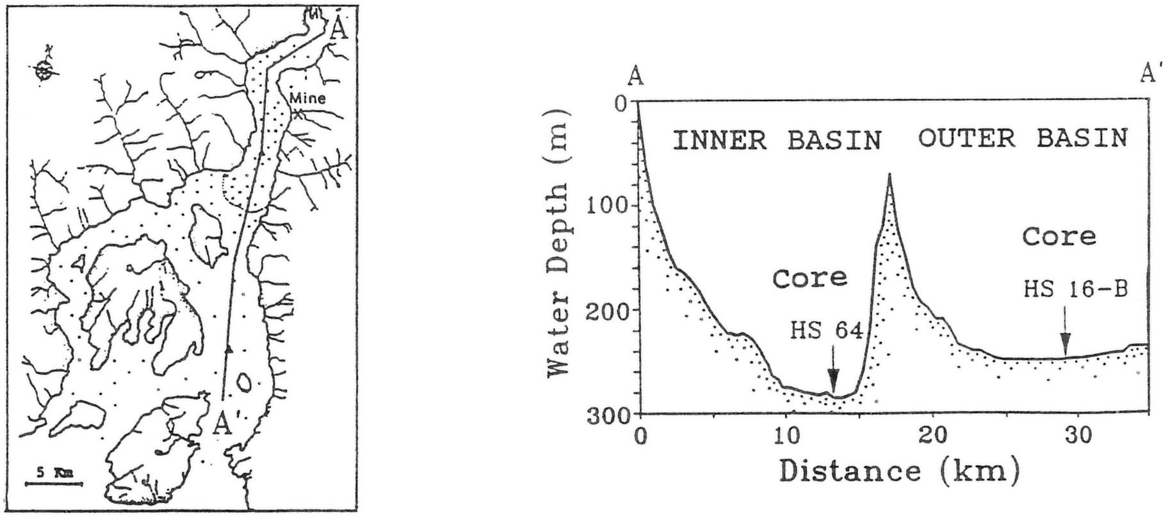


Figure 2. Longitudinal section of Howe Sound from Squamish (A) to Bowen Island (A'), showing core locations. The vertical scale is greatly exaggerated.

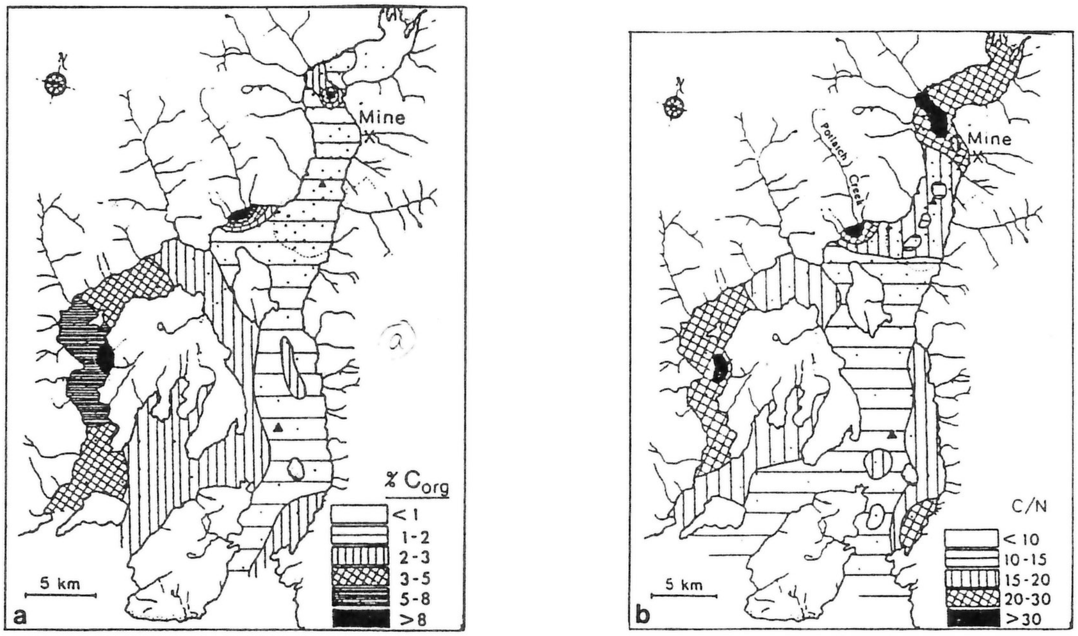


Figure 3a & b. Distribution of organic carbon and C/N ratios in surface sediments in Howe Sound.

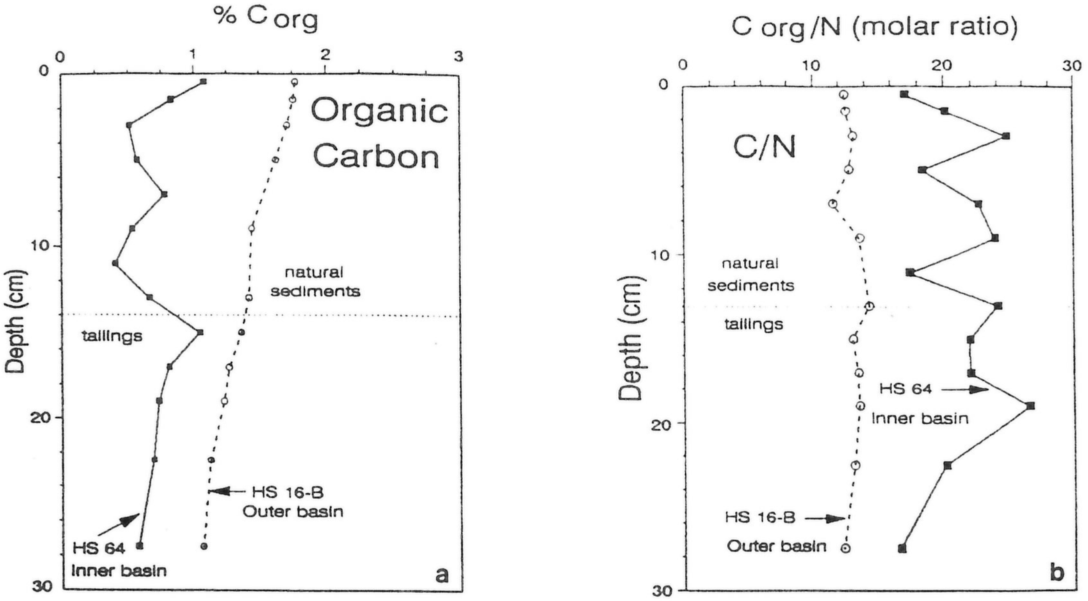


Figure 4a & b. Organic carbon and C/N ratio with depth in two Howe Sound cores. Locations are marked by the solid triangles in Fig. 3.

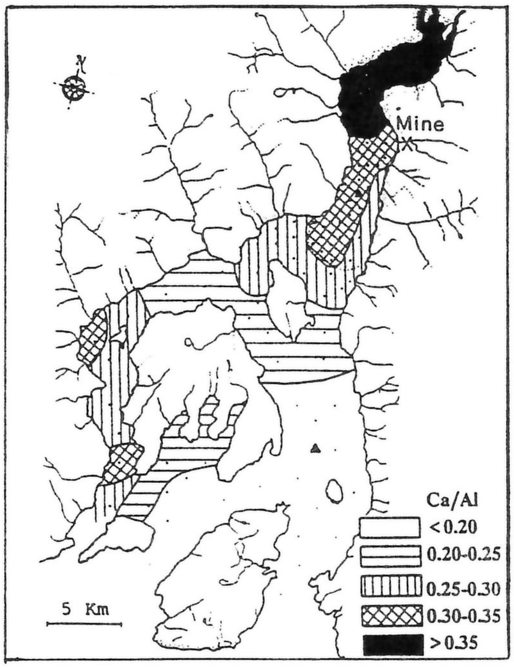


Figure 5a. Ca/Al ratios in Howe Sound surface sediments. The Na/Al distribution (corrected for sea-salt) is very similar.

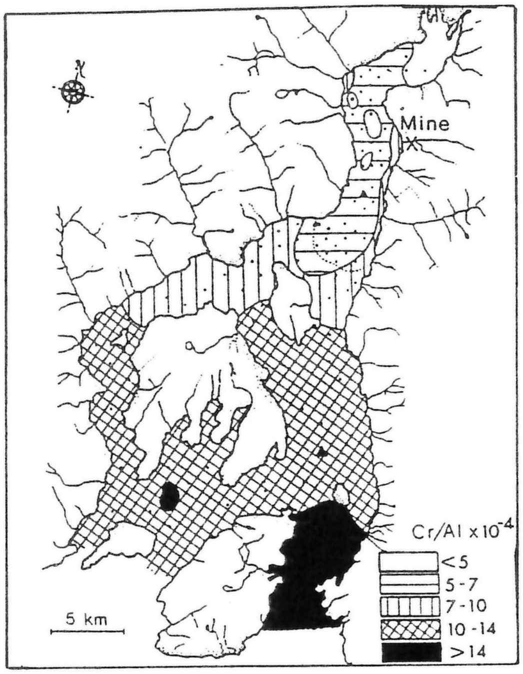


Figure 5b. Cr/Al ratios in Howe Sound surface sediments.

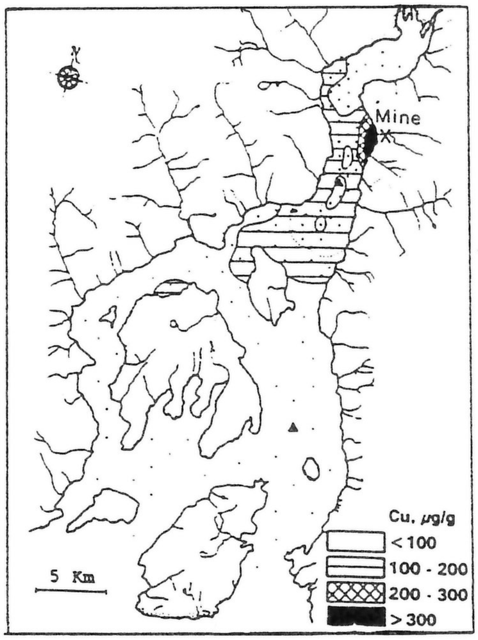


Figure 6a. Copper concentrations in Howe Sound surface sediments.

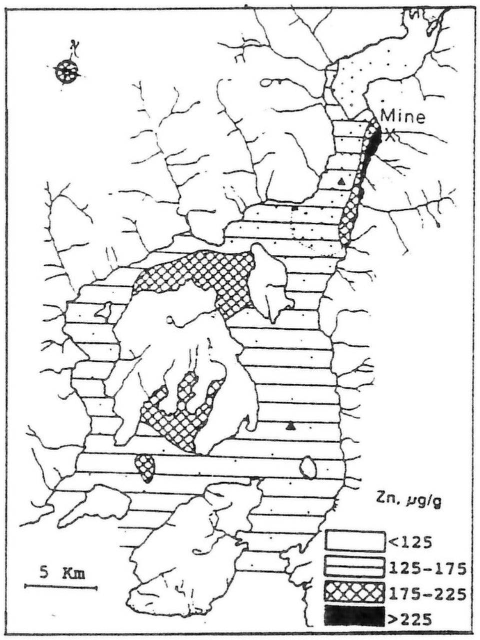


Figure 6b. Zinc concentrations in Howe Sound surface sediments.

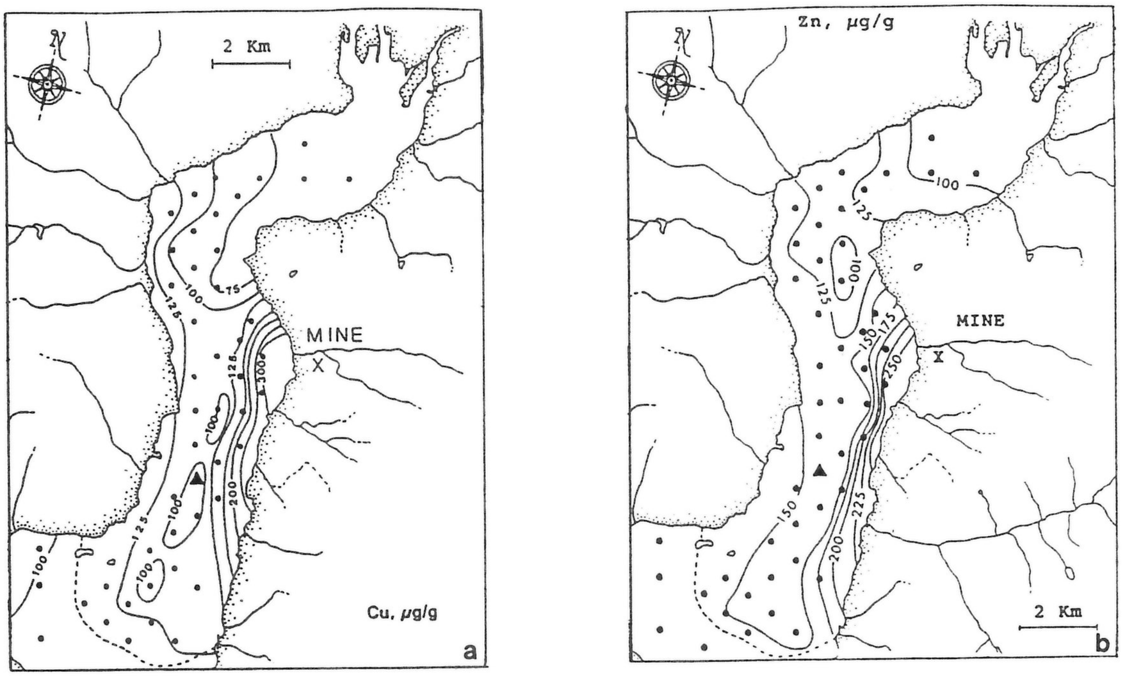


Figure 7a & 7b. Detail of inner basin of Howe Sound showing copper and zinc concentrations in surface sediments.

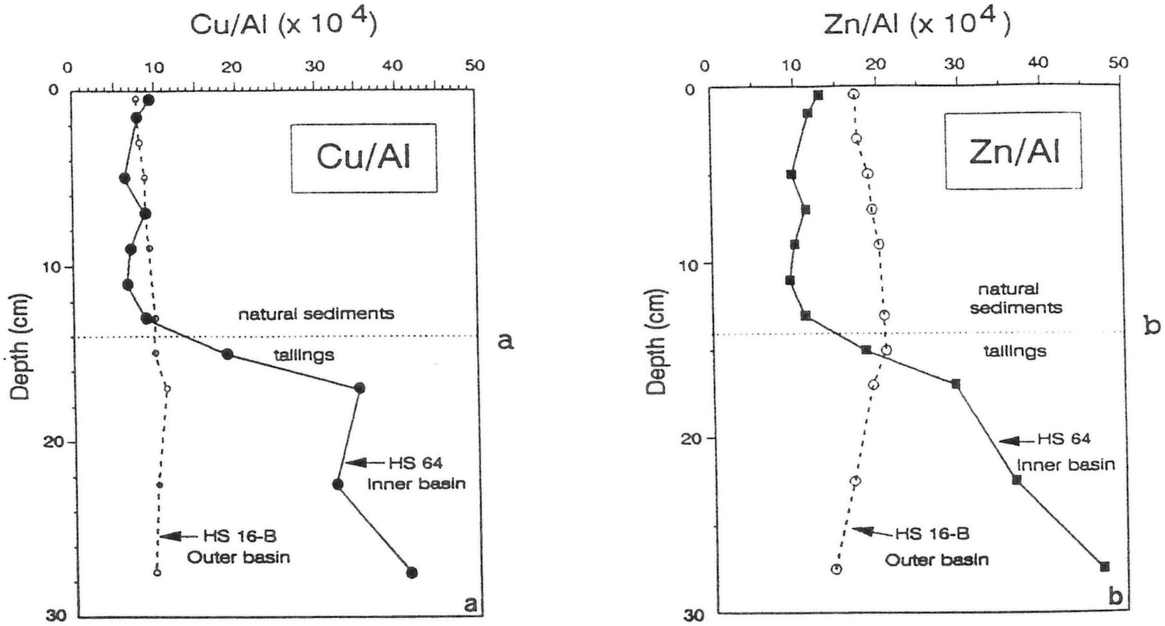


Figure 8a & 8b. Cu/Al and Zn/Al ratios with depth in two Howe Sound sediment cores.

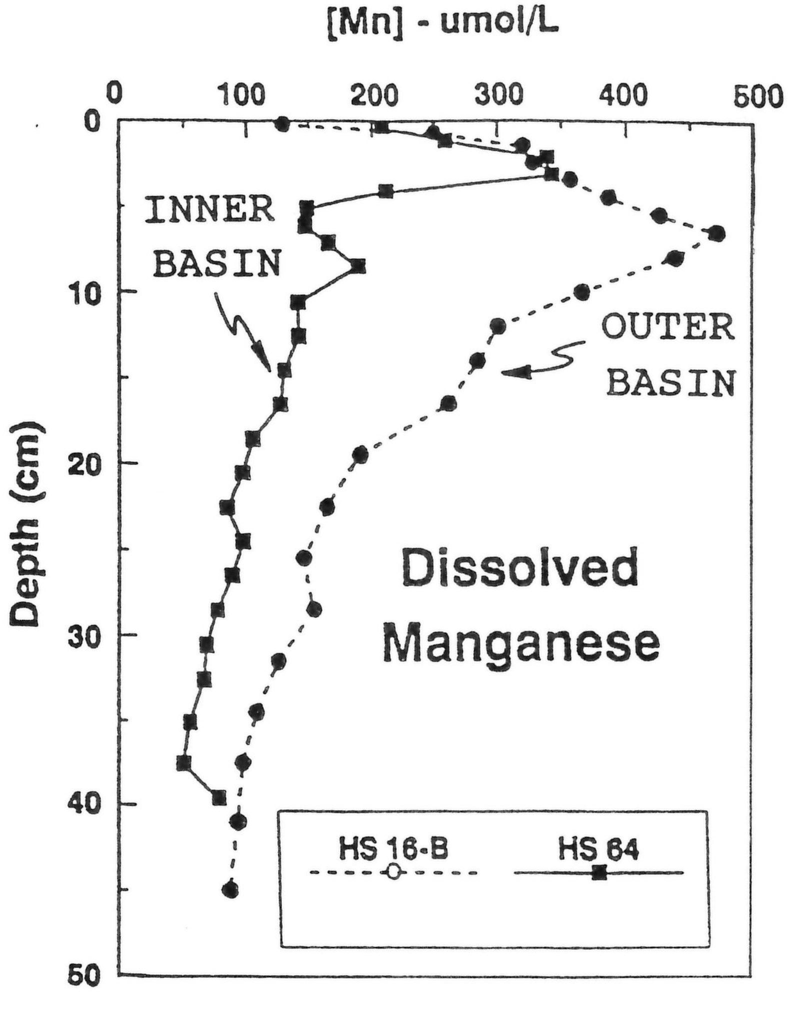
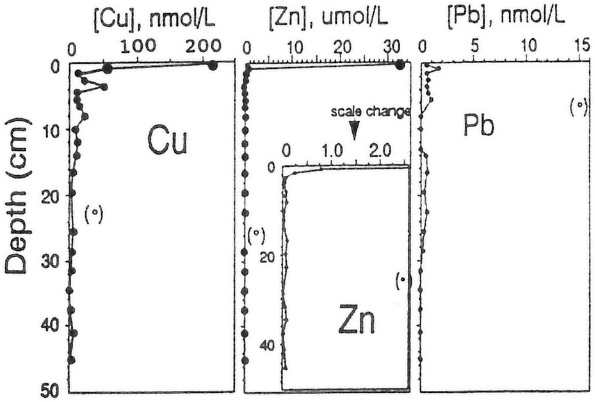
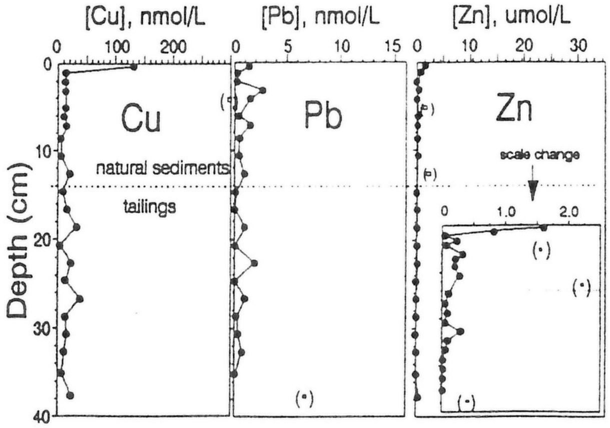


Figure 9. Dissolved manganese in porewaters in two Howe Sound sediment cores.



a

HS 16-B OUTER BASIN



b

HS 64 INNER BASIN

Figure 10. Dissolved copper, zinc and lead in porewaters in two Howe Sound sediment cores. Points marked by parentheses are thought to be contaminated.

OVERVIEW OF THE MARINE ECOSYSTEM OF HOWE SOUND

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INTRODUCTION

Howe Sound has been the subject of several planning studies during the past two decades: The Burrard Inlet - Howe Sound Area Planning Study by Environment Canada in 1973, a Howe Sound Overview Study by the B.C. Environment and Land Use Committee Secretariat in 1980 and a federal-provincial Squamish Estuary Management Plan, completed in 1982. These planning initiatives have been supported by numerous scientific environmental studies. This overview summarizes some of the key physical and biological features of Howe Sound as they relate to functioning of the marine ecosystem.

Marine ecosystems, like other ecosystems, are complex and defy simple categorization. The scientific community has standard measures for health of lower levels of biological organization such as organisms, of populations, and of communities, but not for ecosystems. Attributes of ecosystems include resilience, resistance, stability, carbon cycling, energy cycling, carbohydrate production, diversity of niches and of species filling them, and relations between trophic levels. "Unhealthy" marine ecosystems are characterized by smaller and less specialized, more opportunistic species; excessive or unduly limited primary production; reduced diversity of niches and of species; wild fluctuations in populations; and rapid change in functional relationships between trophic levels.

"Health" of marine ecosystems, therefore, means the state of the system in relation to other, possible ecosystem states, some of which may be undesirable. "Health" of marine ecosystems implies not only scientific parameters, but cultural ones: we want the marine environment to produce abundant resources, to be aesthetically pleasing, to be "fishable" and "swimmable".

While we don't have any standard measures for health of marine ecosystems, we can identify processes leading to ecosystem state changes, and we can detect when structural changes have occurred. This paper reviews some of the physical and biological features of Howe Sound against this theoretical background of ecosystem health, and draws some conclusions about the state of the Howe Sound ecosystem. The purpose is to provide an ecological context for the presentations that follow, some of which will elaborate on these points in more detail.

OCEANOGRAPHY

The upper Howe Sound basin (Fig. 1) is a true fjord, approximately 290 metres at the deepest point, bounded by the Squamish River estuary to the north and a shallow sill (61 m) near Anvil Island to the southwest (Fig. 2). The sill inhibits regular flushing of the upper basin. The waters of the upper basin are strongly influenced by salinity, temperature and current changes associated with freshwater input. A pronounced stratification occurs during freshet of the Squamish River (May to September) and extensive silt loading and turbidity result. Progressive density differences between water outside and inside the sill, which entrains lower-density freshwater from the Squamish River (Fig. 3), cause periodic renewal of bottom water in the inner basin.

PRIMARY PRODUCTIVITY

Plant biomass is produced in two principal areas: production by phytoplankton in the euphotic zone of the surface waters of the Sound (Fig. 4), and production by marsh plants in the Squamish River estuary.

Throughout upper Howe Sound, the impact of turbidity from the Squamish River reduces primary productivity during freshet (Stockner and Cliff, 1976; Figure 5). Turbidity from the Fraser River plume also intrudes into the outer basin. However, the light attenuation properties of bleached kraft pulp mill effluent (BKME) were shown to be the major cause of reduced phytoplankton productivity near Woodfibre (Stockner et al., 1975). Under certain conditions, nutrient enrichment from the effluent can enhance productivity if light conditions are suitable (Stockner and Costella, 1976). Announced new federal and provincial effluent regulations will reduce these impacts.

The Squamish estuary is a detrital-based community, with considerable production of plant biomass by rooted emergents providing a carbohydrate base for detritivores, which in turn nourish secondary consumers, and so on (Figure 6; Hoos and Vold, 1974). Salmon and steelhead rear in the estuary and migrate up the river, providing seasonal fare for eagles and other scavengers and predators. The Squamish estuary has been extensively restructured by training dikes, dredging, filling, and other industrial activities (Fig. 6). These have reduced freshwater-saltwater mixing with consequent effects on marsh vegetation, and altered sediment deposition patterns. Extensive use of intertidal areas for log storage has further reduced productivity. Although these effects are probably permanent, implementation of the Squamish Estuary Management Plan could help prevent further habitat loss and degradation (Deans, 1992).

DISSOLVED OXYGEN

Surface dissolved oxygen (DO) is strongly influenced by the Squamish River flow. The stratification created during freshet aids in dilution and dispersion of effluent discharged at the surface. The effects of tides, winds, and currents also lessen the impact of BKME. Poor flushing and exchange because of restricted subsurface flow over the sill can result in a progressively hypoxic environment. Renewal occurs approximately every three years (Giovando, 1972; Bell, 1973). Extremely low DO (< 1.0 mg/L) is typical of the deep basin in between renewal events.

BENTHIC COMMUNITIES

Shallow subtidal epibenthic communities in the upper basin include brachiopods, nudibranchs, numerous crab species, shrimp, tubeworms, anemones, sea cucumbers, etc., typical of sheltered, west coast inlets (McDaniel, 1973). Trawls in deeper water have produced prawns, ratfish, walleye pollock, several sole species, eelpouts, deepsea smelt, prickleback, sculpin, Pacific cod, northern lampfish and various shark species, numerous bivalve and gastropod molluscs, polychaete annelids, echinoderms and an ascidian chordate (Harbo and Birtwell, 1978; Levings, 1980; Levings and McDaniel, 1980; McDaniel et al., 1978). Halibut are no longer fished in the Sound, and lingcod have declined to the point that severe restrictions on the recreational fishery have become necessary.

The presence of pulp mill fibre beds at Woodfibre and, to a lesser extent at Thornbrough Channel, locally reduces or eliminates infaunal communities (McGreer, 1984). The size of the fibre beds is probably stable; improved suspended solids control at the mills, commensurate with announced new federal and provincial effluent regulations, may permit some recovery. Benthic biota were also scarce or absent on the old mine tailings from the abandoned mine at Britannia Beach (Goyette, 1975; Goyette and Ferguson, 1985). Recolonization does occur, but may be inhibited by the periodic hypoxia of deeper waters.

INTERTIDAL COMMUNITIES

The usual mix of nemerteans, oligochaetes, chironomid larvae, amphipods, isopods, barnacles, crabs, snails, clams, mussels, oysters, urchins, sea stars, etc. occurs in intertidal communities except near the two pulp mills (Levings and McDaniel, 1976) and other modified shorelines, such as wharves and marinas.

Approximately 40% of the shoreline of the Sound has been leased for log booming and other industrial uses, and this area has not changed for the past decade. Bacterial contamination from municipal (Gibsons) and domestic sources has closed a number of areas to oyster and clam harvesting.

PELAGIC COMMUNITIES

Primary production by phytoplankton was discussed above. This carbohydrate source supports an abundant and diverse zooplankton community, which in turn supports resources such as salmon, shrimp, and prawns. The Sound, however, has changed a lot in the last century. The Howe Sound Whaling Company found productive hunting for humpback whales during the mid-1800's; however, that species was extirpated from the Strait of Georgia area by 1908. Anecdotal information suggests that killer whales enter the Sound much less frequently than previously. After the commercial salmon fishery in Howe Sound was closed in 1971 because of mercury contamination, it was later re-opened for recreational fishing only; commercial fishing remains closed for "conservation purposes", meaning that the populations no longer support commercial fishing. Chinook, the largest and most desirable species for sportsmen, remain at critically low levels. A major herring spawning area in the Squamish estuary has been eliminated by industrial use. On the other hand, seal and sea lion populations are known to be stable or increasing in the area, and cormorant populations have made a major comeback in recent decades (Vermeer et al., 1989).

INDUSTRIAL IMPACTS

Biological communities (intertidal and subtidal) are greatly modified near the two pulp mills, and on tailings deposits from a mine, which has been closed for many years, at Britannia.

Mussels and oysters have increasing levels of heavy metals (especially copper) with proximity to the Britannia mine (Figs. 8 & 9; Goyette, 1975). Mercury from the chlor-alkali plant occurred at high enough levels to force closure of some fisheries during the early 1970's until more stringent regulations brought these levels down. Figure 10 shows the levels in sediments at the time of the fisheries closure; Figure 11 shows more recent (1984) mercury levels in sediments near the plant, a legacy of past abuse that will remain for many years.

More recently, dioxins and furans have been found in fish, crustacean shellfish, and waterfowl, indicating uptake through the food chain. More research is needed to determine if these contaminants have had any influence on the complex marine ecosystems of the Sound. The sources of dioxins and furans have largely been eliminated commensurate with announced new federal regulations, but will be a feature of the benthic environments for many years or decades.

Tributyl tin (TBT) compounds used as anti-fouling paints on boat hulls have been implicated in effects on oysters and marine gastropods elsewhere in B.C., and these probably occurred in Howe Sound as well, although no data are available. TBT has now been eliminated for most marine uses and restricted for use on large ships. Figure 12 shows a summary of pollution and shoreline impacts.

CONCLUSIONS

Overall, the Sound can be characterized has having some natural limitations on productivity, owing to the natural turbidity in surface waters, the naturally hypoxic and occasionally anoxic deep waters of the inner basin, and the steep rocky shorelines. Productivity has been further reduced by restructuring and industrial use of the Squamish estuary, and by habitat damage near the two pulp mills and the abandoned mine. However, the remaining productivity of the Squamish estuary, and the areas of good habitat and well-oxygenated waters near the outer Sound support well-developed, productive and stable biological communities. It is not known if industrial contaminants have had any impact on the complex marine ecosystem.

Processes have been detected in Howe Sound that may lead, or may have already led, to ecosystem state changes. These include limitations on primary productivity in the Squamish River estuary, uptake of contaminants (mercury, dioxins) and biomagnification in successive trophic levels (cormorants, waterfowl), and over-harvesting of whales and fish. The loss or significant declines in the largest representatives of several communities - humpback whales and chinook salmon from pelagic communities, halibut and lingcod from benthic communities - fits the classic ecosystem theory that size of organisms declines in degraded environments.

It seems clear that, while the Sound remains a productive and diverse marine environment, it has changed to a less desirable state. The known processes that could lead to further ecosystem state changes have largely been arrested: mercury contamination has been controlled, dioxins have virtually been eliminated from pulp mill effluents, further alienation of shoreline development throughout the Sound and industrial development in the Squamish estuary have been restricted, and fishing is now more carefully managed. The prognosis is for continued stability of the Howe Sound ecosystem in a reduced state of desirability, and perhaps some recovery as contaminants are gradually eliminated by long-term ecological processes and as salmon stocks are enhanced.

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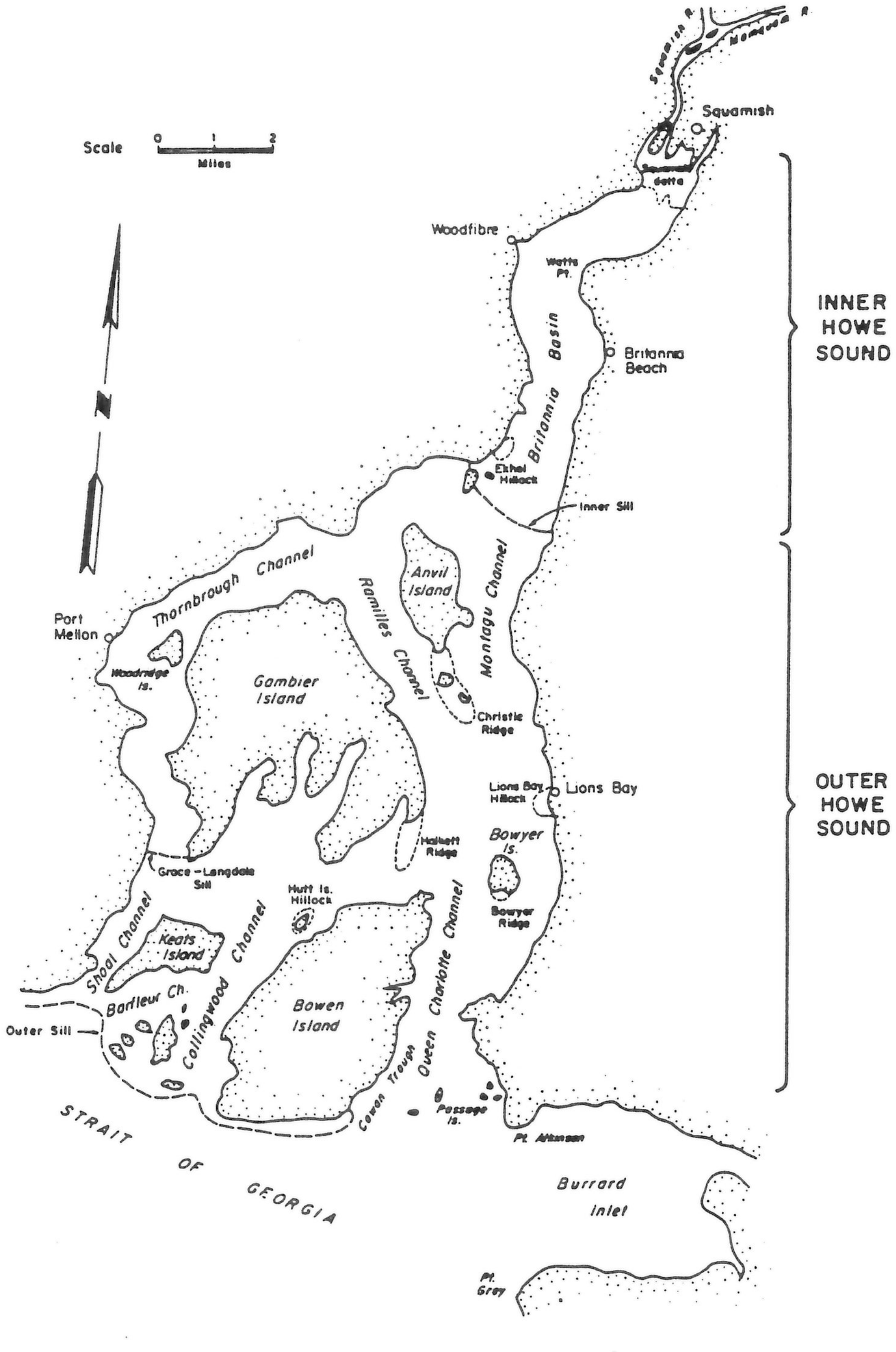

Figure 1. Diagramatic representation of some major geological features of Howe Sound. (after St. John, 1972 in Hoos and Vold, 1975).

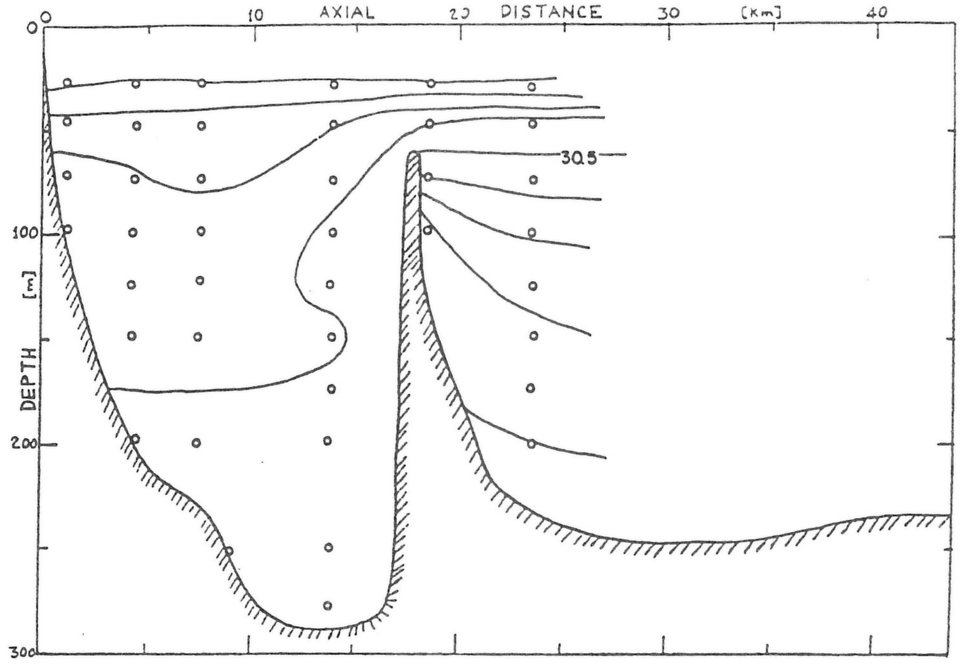

Figure 2. Salinity isopleths in (°/oo) Howe Sound. Dots indicate sample depths. From Bell, 1973.

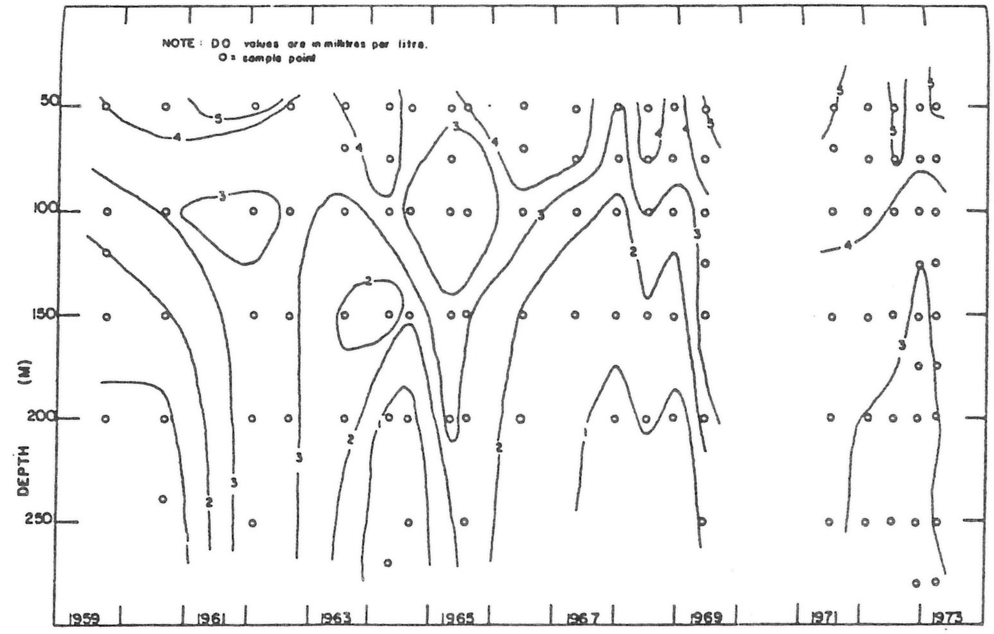

Figure 3. Dissolved oxygen isopleth (ml/L) in the inner basin of Howe Sound. Dots indicate sample depths. From Bell, 1973.

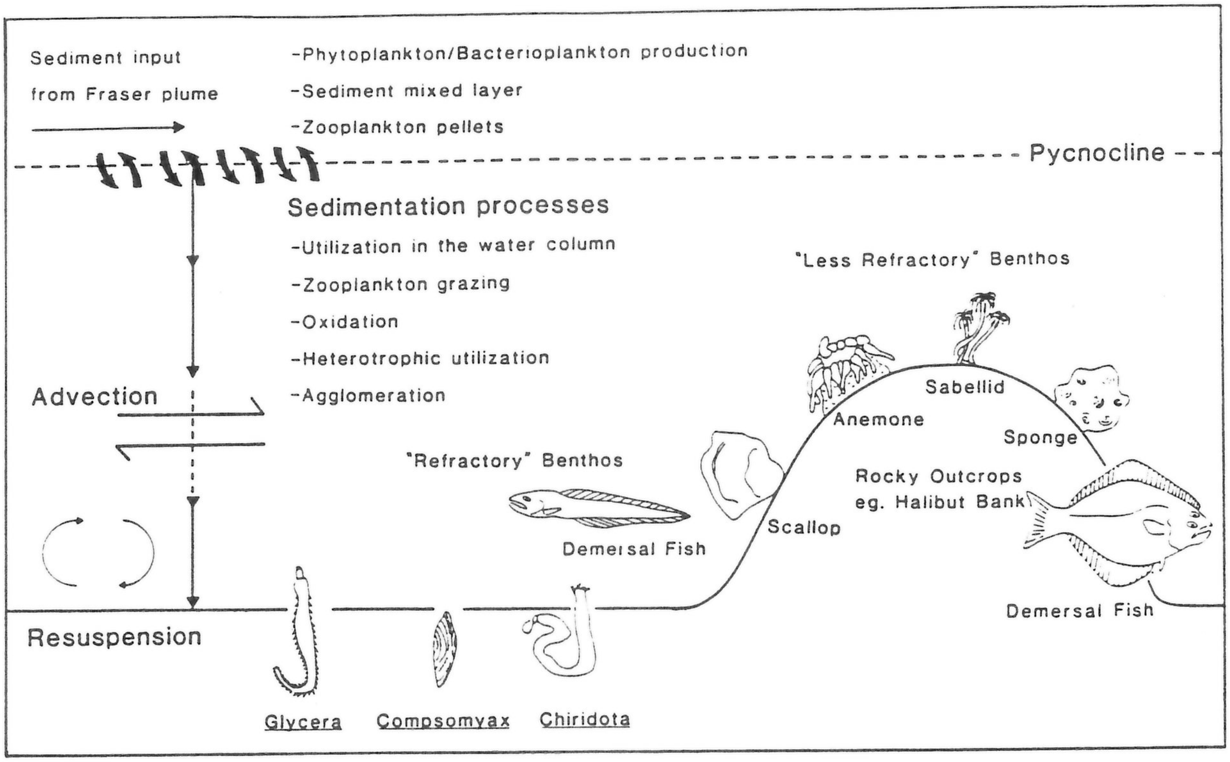

Figure 4. Physical processes involved in benthic - pelagic coupling and fauna in the major basins of the Strait of Georgia. From Levings et al., 1983.

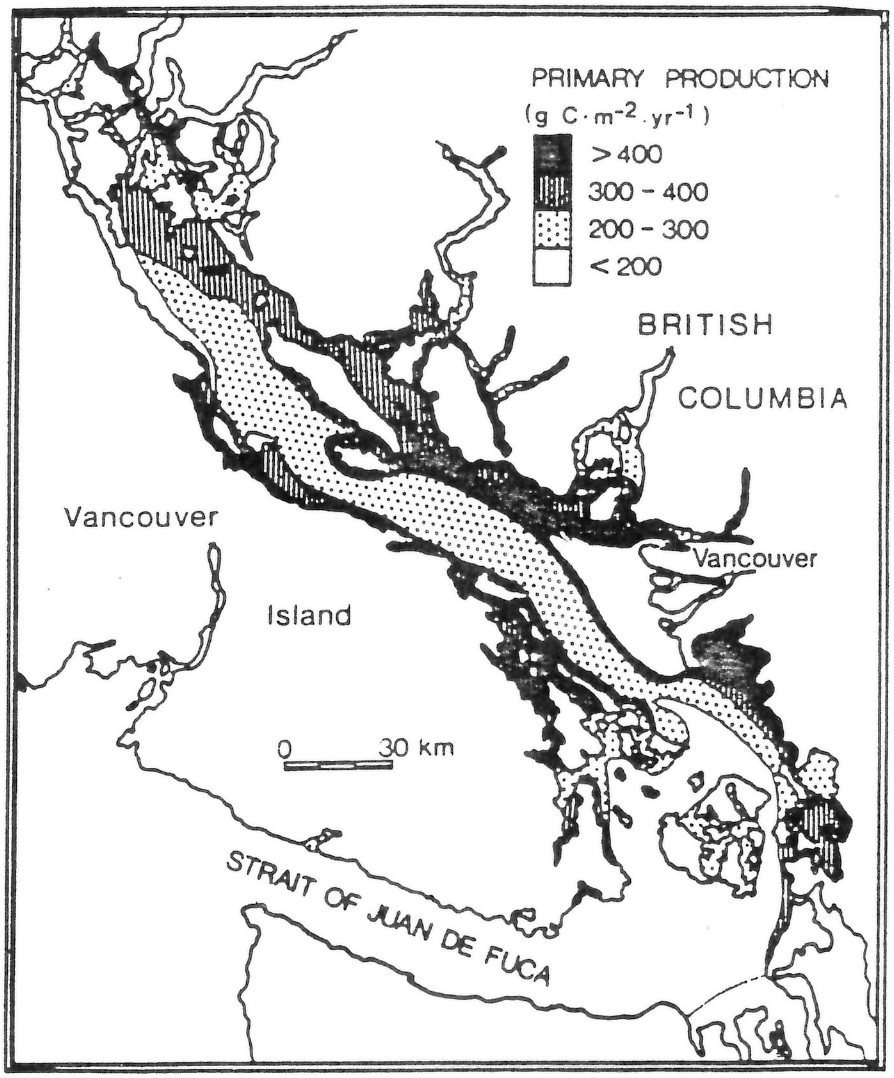

Figure 5. Primary productivity in the Strait of Georgia and adjacent inlets. From Stockner et al., 1979.

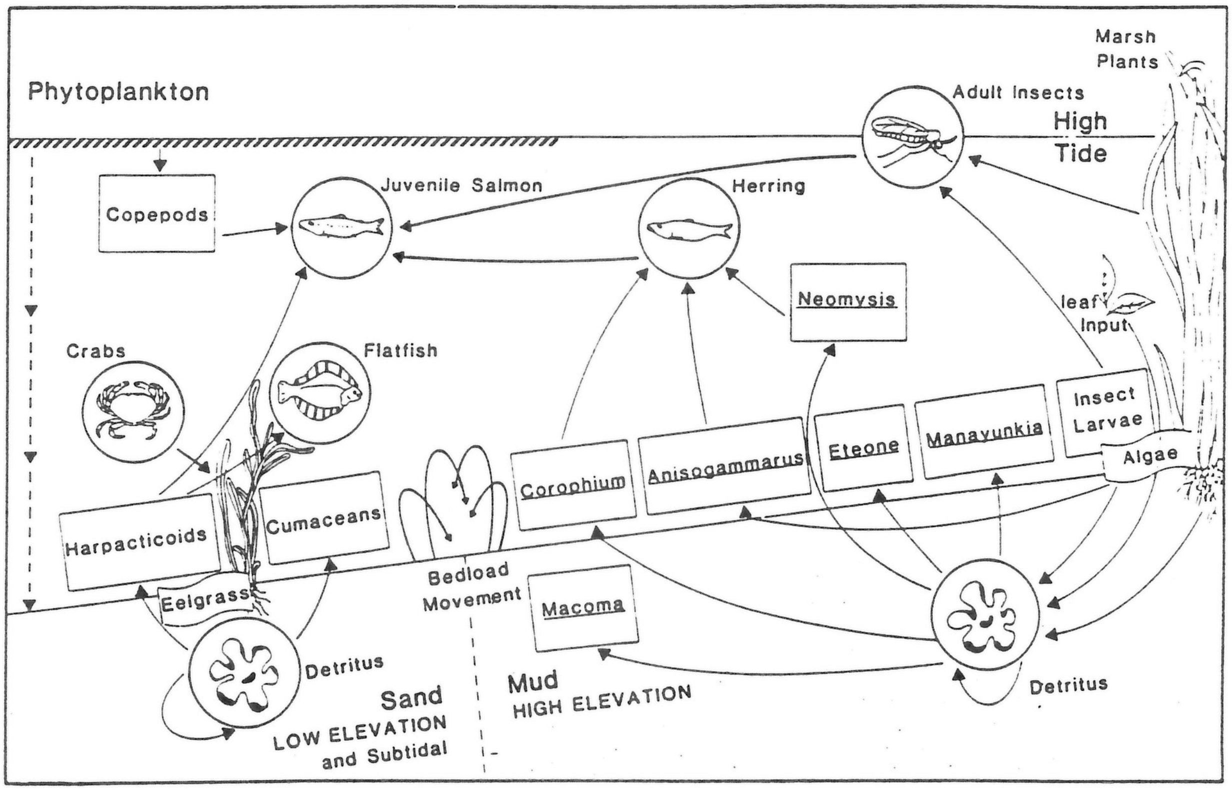

Figure 6. Food webs and important processes relating trophic levels at an idealized estuary or foreshore habitat. Strait of Georgia. From Levings et al., 1983.

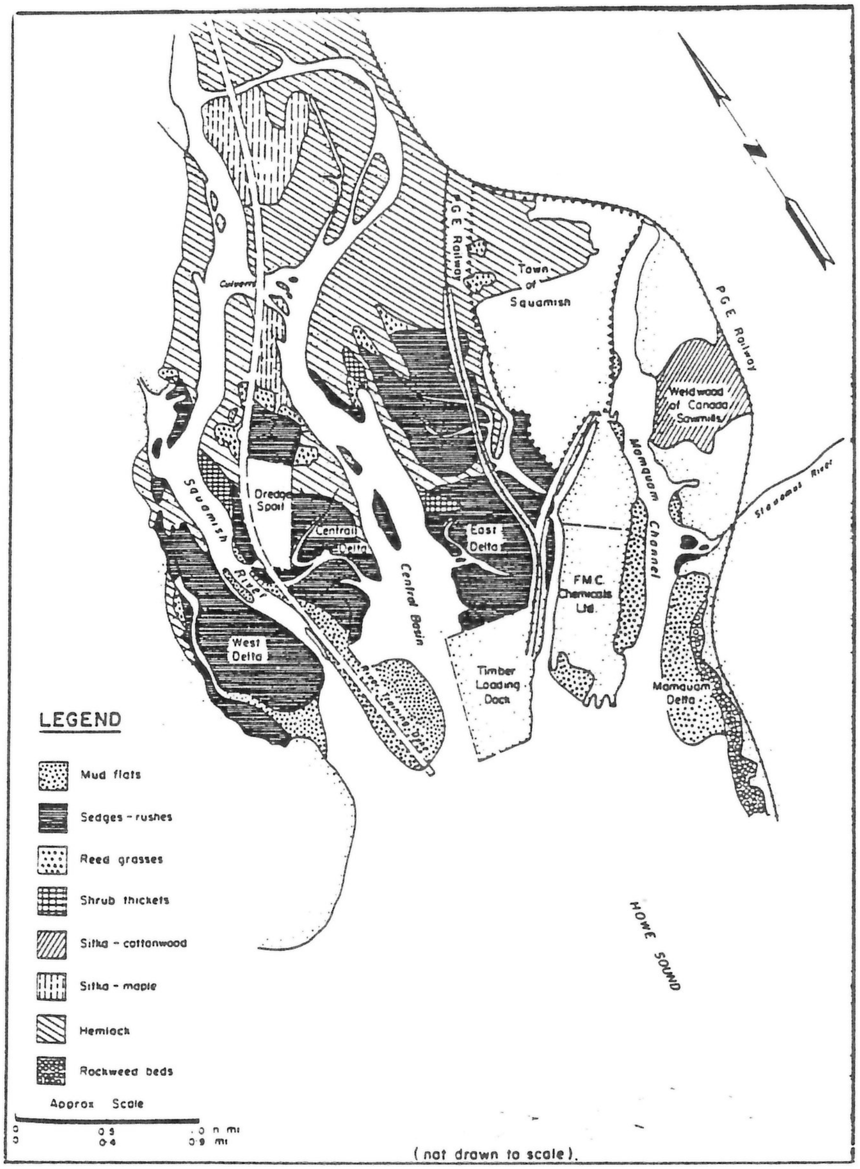

Figure 7. Diagrammatic representation of some major vegetation zones of the Squamish River delta (after Paish et al., 1972) (not drawn to scale). From Hoos and Vold, 1975.

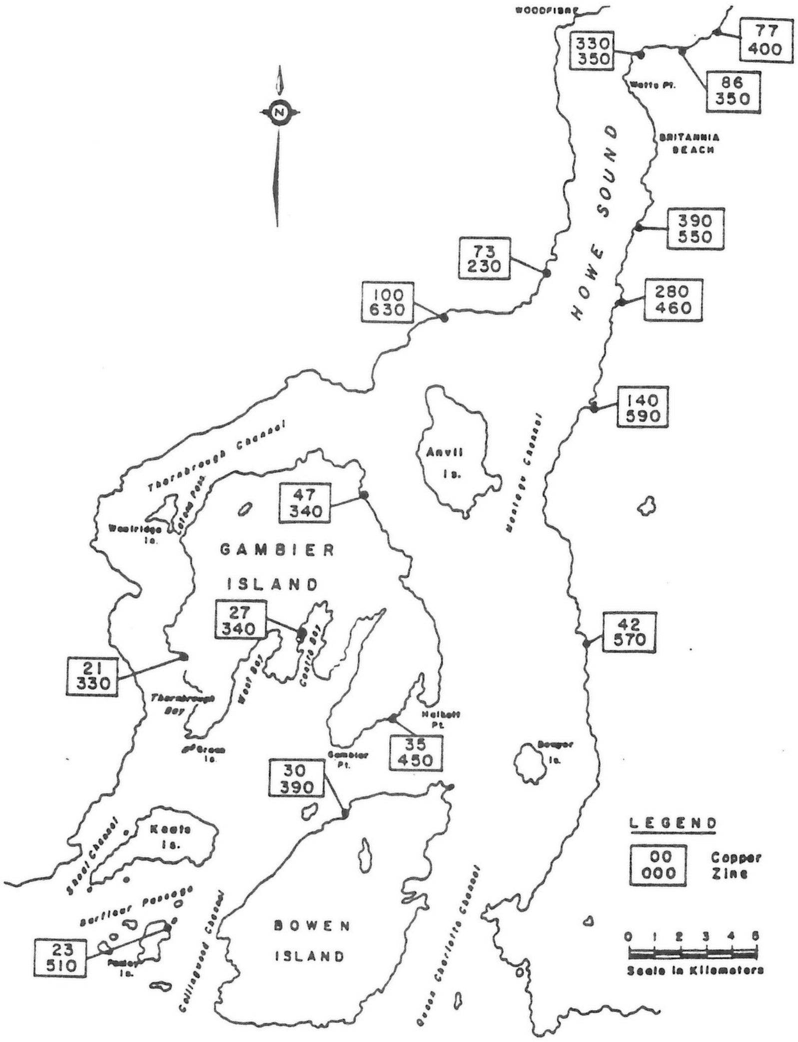

Figure 8. Mean copper and zinc concentrations in mussels (Mytilius edulis) in mg/kg, dry weight - Howe Sound, June 1974. From Goyette, 1975.

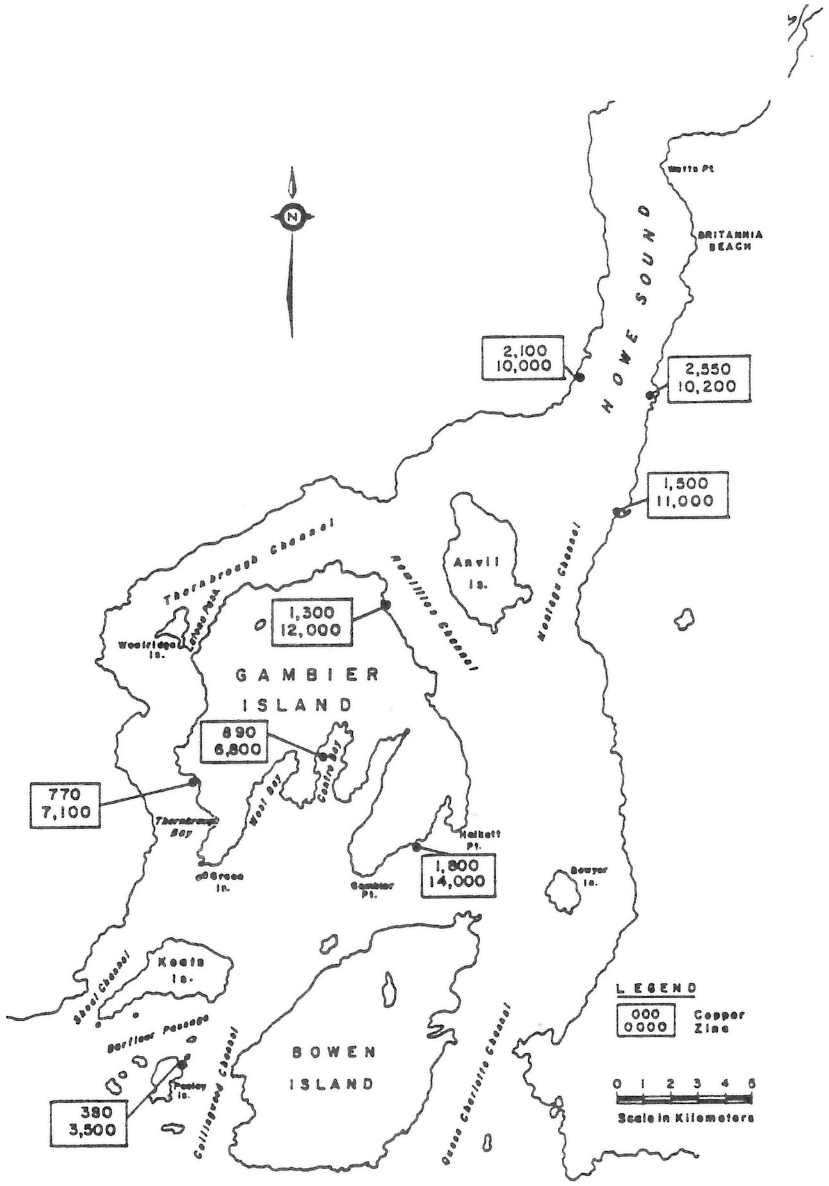

Figure 9. Mean copper and zinc concentrations in oysters (Crassostrea gigas) in mg/kg, dry weight - Howe Sound, June 1975. From Goyette, 1975.

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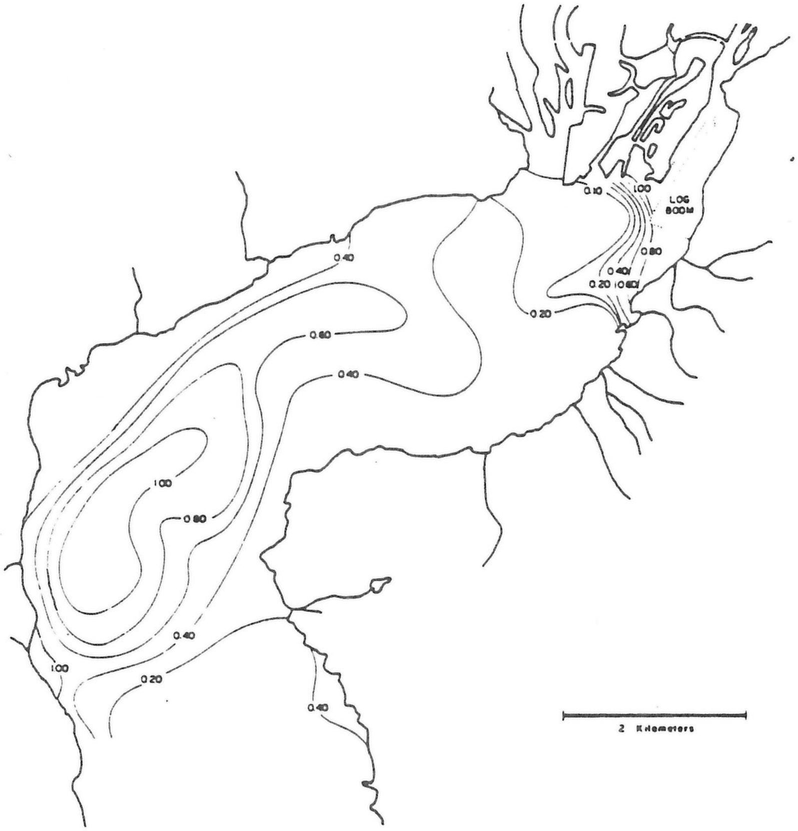

Figure 10. Contour diagram of mercury concentrations (µg/g dry weight). From Thompson and McComas, 1973.

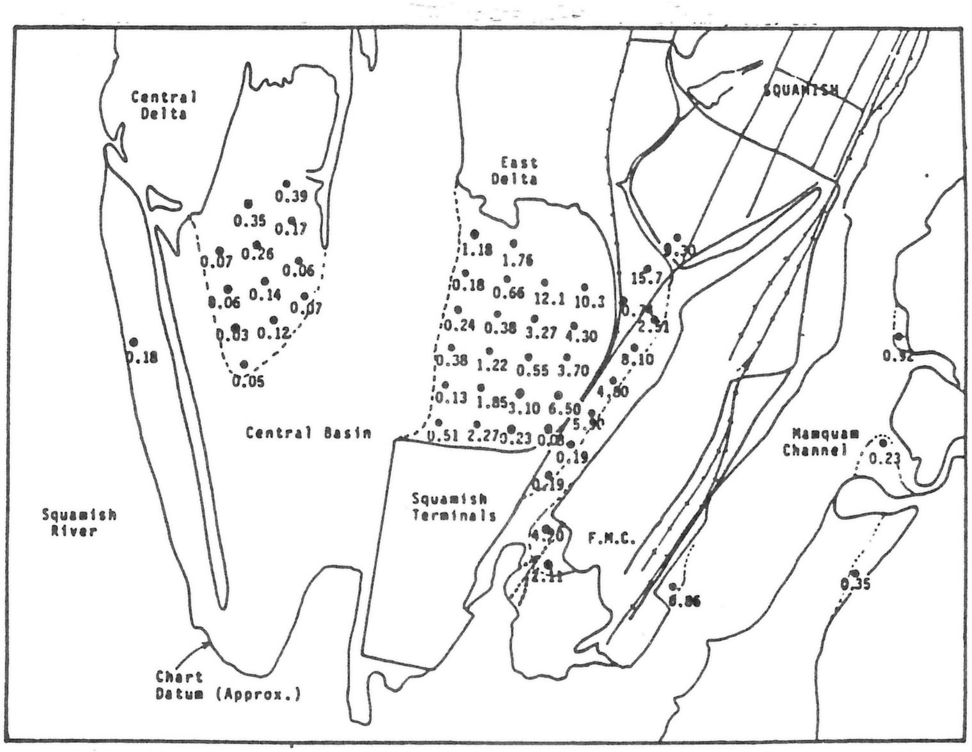

Figure 11. Mercury concentrations in Squamish Estuary, 1984. From Moody and Moody, 1985.

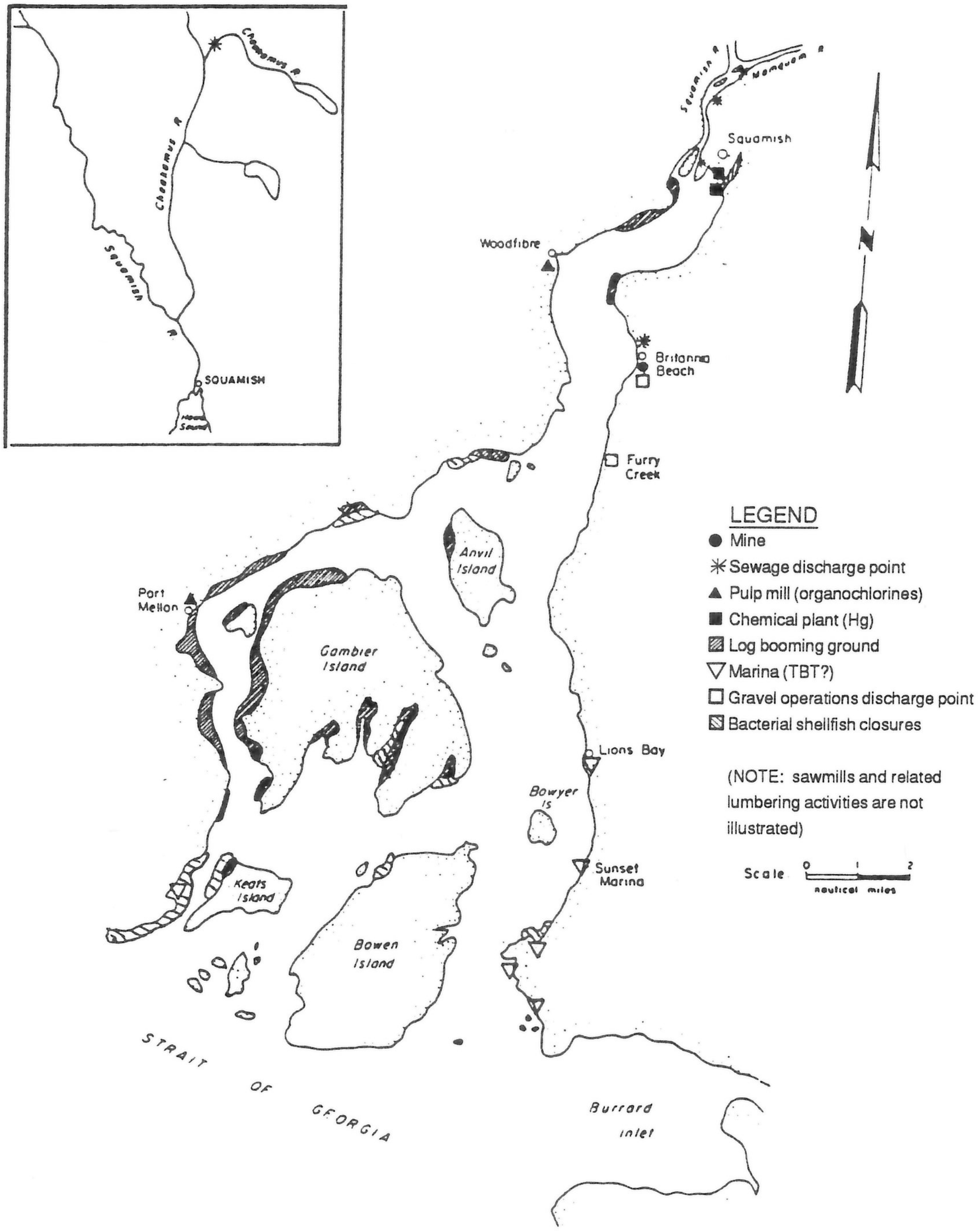

Figure 12. Major sources of pollutants for the Squamish River estuary and Howe Sound. (after McDaniel, 1973).

WASTEWATER DISCHARGES TO HOWE SOUND AND THEIR APPARENT SIGNIFICANCE

by

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INTRODUCTION

The B.C. Ministry of Environment is setting water quality objectives in priority water basins in the Province. One of those priority water basins currently being assessed is Howe Sound. Water quality objectives are numerical concentrations of water quality variables measured in the water column, sediments, or biota, which protect designated water uses in the water body. In order to propose water quality objectives, a water quality assessment is prepared which evaluates factors such as oceanography, current water uses, wastewater discharges, and ambient water quality. This paper provides an overview of the factors which are considered in the process.

THE SETTING

Howe Sound is immediately north of Burrard Inlet, north from a line between Point Atkinson and Gower Point at the south, to the mouth of the Squamish River at the north. It is 43 km long, actually consisting of two basins. The southern basin, south of Defense Islands, is about 3.5 km wide, and extends 26 km southward through a series of islands. The northern basin is fjord-like, with high cliffs, the Squamish River at its north, and a sill at its south.

Howe Sound experiences a moderate maritime climate with cool, moderately dry summers and wet, moderately cold winters. The Squamish Valley which intrudes into the interior of British Columbia can affect Howe Sound by allowing extremely cold air from the Interior to sweep periodically into the Sound, resulting in very cold temperatures and strong winds. These "Squamishes" can be sudden and violent.

Glaciers formed the two major sills in Howe Sound. The more northern sill extends between Porteau Cove and Defense Islands, and rises to within 35 m of the surface. This causes stagnation of the deep waters north from the sill. The second sill is at the southern end of Howe Sound, and this sill rises only to within 60 m of the surface, allowing better deep water exchange. In addition, there is a smaller sill between Gambier Island and the mainland, with a minimum water depth of 30 m.

Water depths on average are 240 m in the southern basin and 275 m in the northern basin. Both basins are flat bottomed by coastal standards with mid-channel reliefs of only a few metres (Thompson, 1981). Near the islands and the mainland shores the bottom is much more rugged. There is a fairly steep bottom slope seaward from the Squamish River, with river sediments advancing the delta front as much as 7 m/year (Thompson, 1981).

DRAINAGE, TIDES, AND FLUSHING

Fresh snowmelt water draining into Howe Sound comes from a number of creeks and rivers in the adjacent Coastal Mountains. By far, the largest is the Squamish River, which drains an area of 2,330 km^2, and has a mean annual flow of 238 m^3/s (Inland Waters Directorate, 1989). Others include the Rainy River at Port Mellon, with an average annual flow of 8.7 m^3/s, and the Stawamus River at Squamish, with an average annual flow of 3.63 m^3/s. There are incomplete or no flow records for the other creeks.

Tides in Howe Sound are predominantly semi-diurnal, with little difference in tide height throughout the Sound. The mean high tide is 3.1 m at Point Atkinson and Squamish, and 3.2 m at Gibsons (Canadian Hydrologic Service, 1984). The large tides range from 5.0 metres at Point Atkinson, 5.1 m at Squamish, and 5.2 m at Gibsons (Canadian Hydrologic Service, 1984).

Freshwater input from the Squamish River drives estuarine circulation (Canadian Hydrologic Service, 1984). There is a net seaward flow of brackish water in a relatively shallow-surface layer of about 10 m. A slow inward drift at depth compensates for the loss of salt water at the surface (Thompson, 1981). Currents in the top 3 m are uniform with depth; however, there is cross-channel variation in seaward surface currents in the northern basin.

Winds over the northern basin can cause considerable variation in the general circulation patterns, usually at velocities greater than 10 m/s. Winds from the south can actually reverse the surface circulation pattern, especially at times of low runoff. Down-inlet current speeds can be from 0.25 to 0.5 m^3/s, while up-channel velocities can reach 0.25 m^3/s with southerly winds in excess of 15 m/s.

SALINITY and TEMPERATURE

The salinity of surface waters is lower (down to $^\circ/_{oo}$) than that of deeper water (typically close to $30^\circ/_{oo}$) due to fresh water at the surface from local runoff with a lack of vertical mixing (Buckley and Pond, 1976).

The water is generally well mixed at a station 5 km north from the inner sill with salinity values of about $30^\circ/_{oo}$. Salinity in the southern basin is typically slightly higher than in the northern basin, due to the blocking effect of the sill between the two basins (Thompson, 1981).

Howe Sound surface water temperatures are cooled by the Squamish River, which has summer temperatures of only about 10°C (Thompson, 1981). In winter they can drop to 5°C (Thompson, 1981). Temperatures below the surface water are 8 - 10°C throughout the year, with only minor modifications in the outer basin caused by incursions of warmer water from the Strait of Georgia (Thompson, 1981). The surface water lens varies in thickness from 0.5 to 2 m. The temperature 5 km north from the inner sill at 3 depths was generally well-mixed with temperature about 8° throughout the water column.

DISSOLVED OXYGEN

Dissolved oxygen concentrations located between the inner sill and the Squamish River are typically about 6 to 10 mg/L in the top 50 m, declining to less than 1 mg/L at depths greater than 100 m (Waldichuk, unpublished). Below sill depth in the inner basin, an overflow of more oxygen-rich water from the outer basin provides an approximately biannual re-freshening of the deeper waters. Such overflow events are triggered by a combination of strong Squamish winds and abnormally high river discharge produced by heavy rainfall or sudden thaw at higher elevations (Thompson, 1981).

About 5 km north from the inner sill the water in the Sound is generally well mixed, although low oxygen concentrations are often observed at depths greater than 150 m.

WATER USES

Recreation (fishing, boating), marine shipping, and waste discharges are obvious water uses in Howe Sound. Recently, public attention has heightened with respect to dioxin and furan discharges from the Howe Sound pulp and paper mills, and their effects on the crab fishery.

Environment and Land Use Secretariat (1980) outlined the recreational use of Howe Sound. The Sound provides a major protected boating area accessible to Greater Vancouver residents. There are many marinas, yacht clubs, public wharfs, provincial parks, and recreational areas along the Sound. Commercial salmon fishing was closed in 1963 to preserve Howe Sound for recreational fishing and is closed to sports salmon fishing annually in various periods. The ling cod fishery is closed from November 15 to April 30 annually.

The crab fishery of the entire Howe Sound area is closed to commercial fishing (at the time of writing), while sports fishermen can only crab in an area south from Anvil and Gambier islands and east from Gambier and Keats islands. In these areas, sport fishermen are advised not to eat the hepatopancreas from the crabs. Shrimp and prawns can not be taken by sport or commercial fishermen in an area north and east from Anvil Island, nor west from Gambier or Keats islands. These closures are due to dioxin and furan contamination.

The fisheries resources of Howe Sound are valuable. The area supports large populations of chum, coho, and pink salmon.

Virtually the entire escapement of salmon is bound for spawning in the Squamish River or its tributaries, as shown below (Farwell et al., 1987; G. Serbic, DFO Pacific Biological Station, pers. comm., July 2, 1991).

AVERAGE	CHINOOK	CHUM	COHO	PINK	SOCKEYE
1951-1960	16,925	66,968	32,443	160,955(A)	NO RECORD
1961-1970	18,713	46,743	21,378	251,065(A)	NO RECORD
1971-1980	6,348	133,175	27,136	42,700(A)	192
1981-1990	1,883	107,836	8,378	4,120(A)	61

(A): an average of odd years.

These data illustrate a dramatic decline in average escapements of salmon to Howe Sound rivers in the last decade. The decline in the population of chum salmon returning to the Squamish River is even worse than the data portray, since escapements for the last three years of record (1987, 1988, 1989) were 18,270, 12,000, and 25,000 per year, respectively. For all the species of salmon, the number of fish returning to spawn since 1986 has been less than the average for the nine-year period ending in 1989.

The following species return to non-Squamish rivers: a few chinook salmon spawn in McNab Creek; chum salmon spawn in Archie, Avalon, Centre, Dakota, Eagle Harbour, Langdale, Long Bay, Mannion, McNab, McNair, Nelson, Ouillet, Potlatch, Williamson, Whispering, and West Bay creeks, and to the Rainy River; coho salmon spawn in Dakota, Eagle Harbour, Mannion, McNab, McNair, Ouillet, Terminal, Williamson, and Whispering creeks, and to the Rainy River; and pink salmon in Rainy River and McNab Creek (Farwell et. al., 1987).

The Rainy, Squamish, and Mamquam rivers are major steelhead rivers. Some searun cutthroat trout are present in the Howe Sound area. Ling cod, rock cod, and dogfish are present throughout Thornbrough Channel, with rock cod and flatfish present in upper Howe Sound. Small numbers of herring spawn areas exist, west from Keats Island and southeast from Gambier Island. A third spawning area near Squamish in the Mamquam Blind Channel was ruined by log booming. Herring are not fished in the area.

The value of the commercial fishery in 1988 (latest available data) was $115,851 for shrimp (53,619 kg), $197,922 for prawn (23,482 kg) and $25,921 for crab (6,299 kg).

WASTE WATER DISCHARGES

A number of small discharges of treated domestic wastewater from various establishments to Howe Sound are allowed under Waste Management permits. Many are associated with summer camps or cottages, discharging either to tile fields located near Howe Sound, or directly into Howe Sound through submerged outfalls. In addition, many small discharges from homes and cottages to septic fields are regulated by the Health Act and do not require Waste Management permits. Permitted domestic discharges are listed below:

DISCHARGES TO TILE FIELDS

Gambier Island Sea Ranch Strata Corporation operates a residential condominium development on Gambier Island. The wastewater is treated in septic tanks prior to disposal in four tile fields. Waste Management permit PE 5301 allows the discharge of a maximum of 75 m^3/day of treated effluent.

Farwest Developments and the Sunshine Coast Regional District will discharge wastewater from a proposed 40-lot subdivision located at Langdale on the west shores of Howe Sound. The domestic sewage is to be treated to secondary standards prior to discharge. Waste Management permit PE 6209 allows the discharge of 54.6 m^3/day of treated effluent.

A restaurant/campsite complex located 4.8 km south from Squamish near the ferry dock to Woodfibre discharges treated wastewater. Waste Management permit PE 3801 allows the discharge of 32 m^3/day of domestic sewage from a package aeration plant.

Porteau Cove Provincial Park, south of Britannia Beach on Howe Sound, has 33 campsites, three common toilet buildings, and a sani-station. The wastewater from each of these sources is settled in separate septic tanks prior to discharge to about 490 m of tile, located about 100 m from the Howe Sound shoreline, and about 5 m above the high tide level. Waste Management permit PE 6239 allows the discharge of 29 m^3/day.

Van Mor Holdings Ltd. own a luxury dwelling at the north end of Bowen Island. Filter backwash water from a swimming pool and hot tubs is discharged to a seepage pit located at the high water level. Waste Management permit PE 6273 allows the discharge of a maximum 5 m^3/day to the pit.

The Camp Fircom Society of the United Church of Canada Bible camp discharges wastewater from a two bedroom cabin under Permit 3755. The sewage is settled in a septic tank and discharged to a field 55 m from Fircom Bay.

None of these discharges to tile fields would likely affect the water quality of Howe Sound.

SMALL-VOLUME DISCHARGES TO HOWE SOUND

Copper Beach Estates, near the old Britannia Mine Site, operates a septic tank which serves the area. Flows from the septic tank are discharged into the acid mine drainage pipe along Britannia Creek. The acid mine drainage pipe extends into Howe Sound for a distance of about 170 m to a depth of about 55 m. Permit PE 1989 allows the discharge of up to 205 m^3/day.

The B.C. Ferry Corporation discharges treated domestic wastewater from its Langdale Terminal. The wastewater is provided secondary treatment with a rotating biological contactor, and is discharged through a submerged outfall 6.1 m below the low water level. Waste Management permit PE 3357 allows the discharge of up to 42 m^3/day of effluent with maximum concentrations of 45 mg/L of BOD5 and 60 mg/L suspended solids.

Wastewater from The Daybreak Bible Camp on Anvil Island is settled in a septic tank and discharged through a marine outfall about 15 m from the low water mark at a depth of about 6 m. Waste Management permit PE 2784 allows the discharge of 20.5 m^3/day.

The Camp Fircom Society of the United Church of Canada operates a bible camp on Gambier Island. The wastewater is in a septic tank which discharges into Haklett Bay, 61 m from the shore at 4.6 m below the low water mark. Waste Management permit PE 3755 allows the discharge of a maximum 17.5 m^3/day.

The Boys' and Girls' Club of Greater Vancouver operates a summer camp on the west shore of Howe Sound, about halfway between Port Mellon and Woodfibre, at the mouth of Potlatch Creek. The wastewater from the main washroom area and the dining hall complex is treated in a septic tank and discharged through a submerged outfall 38 m into Howe Sound at a depth of 23 m. Waste Management permit PE 6490 allows the discharge of 27 m^3/day.

Six cottage sites have been developed on the east side of Howe Sound, approximately four km southwest from Britannia Beach. Sewage is treated in a septic tank, prior to discharge through sand filters and a submerged outfall extending 122 m offshore 15 m below the mean low water mark. Waste Management permit PE 8754 allows the discharge of a maximum 5.5 m^3/day.

DISCHARGES LOCATED NEAR SQUAMISH

The Western Pulp (Woodfibre) mill, built in 1912 as a sulphite pulp mill, was converted to a bleached kraft mill during 1959-62. Wood chips are brought to the mill, where they are passed through digesters, prior to brown stock washing and screening, then bleaching with washing solutions of chlorine, caustic, hypochlorite, chlorine dioxide, caustic, and finally chlorine dioxide before the pulp is pressed and dried. A 1989 Waste Management permit application cited a desire to increase the pulp production up to 750 t/day on average and a maximum of 850 t/day. This would be accompanied by a secondary treatment of the effluent streams.

Waste Management permit PE 1239 allows the discharge of waste water as shown below and as applied for in the 1989 permit amendment application:

	Kraft		Hydraulic Debarker	
	Before	After	Before	After
Suspended Solids(kg/t)	17.5	10.0	0.64 kg/m^3	0.24 kg/m^3
BOD5 (kg/t)	30.0	7.5	0.64 kg/m^3	0.18 kg/m^3
96-hr LC50 (5 effluent)	30	100	30	100
Volume (x1,000 m^3/day)	76	76 + 10%	7	7 + 10%
pH	-	-	6-8	-
Dissolved Oxygen (mg/L min)	-	2.0	-	-
AOX (kg/t)	-	2.5	-	-
Temperature (°C)	35	35	-	-

F.M.C. of Canada has operated a chlor-alkali plant near Squamish since 1965. The basis of the process at the plant is the electrolysis of purified brine to obtain chlorine and sodium, followed by the mercury cell hydrolysis of the sodium to produce caustic soda (NaOH) and hydrochloric acid (HCl). Mercury entrained in cooling water is separated prior to the effluent's discharge to an effluent pond. The recovered mercury is returned to the cell. Cooling water is recycled to reduce mercury vapour loss, and this cooling water is also treated in the mercury separator. The sludge generated in the process is also contaminated with mercury, which is partially removed with hypochlorite leaching.

Waste Management permit PE 138 was issued in 1965 for the disposal of the sludge slurry. A settling pond with 24-hour retention was constructed in 1970, at which time the company began to separate and dry the sludge while continuing to discharge liquid waste through the settling pond. The process cooling water and the filtrate from the mercury recovery system are discharged to the settling pond. Effluent from the pond is discharged to Howe Sound through an intertidal outfall. Waste Management permit PE 138 allows the discharge of 55,000 m^3/day with the following maximum concentrations: 30 mg/L suspended solids (mean concentration of 20 mg/L), 27°C, 0.008 mg/L mercury (mean concentration of 0.005 mg/L), 0.15 mg/L residual chlorine (mean concentration of 0.008 mg/L), 0.5 mg/L sulphide (mean concentration of 0.2 mg/L), 15 mg/L hydrogen peroxide, and a 96-hr LC50 of 100%.

Since 1970, the sludge solids have been discharged to a solid waste disposal site. Waste Management permit PR 1627 allows the disposal of the sludge filter cake and solids from the effluent treatment backwash. Because the waste has been classed as a "special waste," the old site used for disposal was covered with a 10 mm thick polyethylene membrane and then a clay cover in 1981. The new cell area is lined with a double flexible membrane liner. It covers an area of about 55 m by 46 m. Waste Management permit PR 1627 allows the disposal of 30 m^3/week (mass of 5 kg/week) of the mercury contaminated sludge which is to be a mixture of 40% sand and 60% sludge, with the mercury contamination of the sludge not to exceed 100 mg/kg and the pH to be a minimum of 9.5.

The Canadianoxy Industrial Chemicals plant has produced liquid sodium chlorate by electrolysis of brine since 1973. It is located on the east bank of Cattermole Creek, to the north of F.M.C. A saturated solution of brine is mixed and then treated with sodium hydroxide (NaOH) and sodium carbonate (Na_2CO_3). The solution is passed to a brine clarification tank where insoluble salts which have formed are precipitated out. The sludge from the brine clarifier consisting of calcium and magnesium precipitates is periodically removed and discharged without treatment to a landfill. The sludge is basic (pH of about 10) in nature.

Sodium dichromate ($Na_2Cr_2O_7$) is added to the clarified saturated brine prior to it passing to the electrolytic cells where a weak solution of hydrochloric acid (HCl) is added. The products of the electrolysis are sodium hydroxide at the cathode and chlorine at the anode. These are mixed to form sodium hypochlorite (NaOCl), prior to being oxidized to form sodium chlorate ($NaClO_3$). The finished cell liquor is treated with urea to destroy any remaining hypochlorite.

Only cooling water is discharged. The electrolytic cells are cooled by a closed cooling water circuit with a cooling tower. Waste Management permit PE 1700 allows the discharge of a maximum of 20 m^3/day of overflow from the cooling water system, at a maximum temperature of 30°C, and with a chlorine residual of less than 0.2 mg/L.

Since 1962, Weldwood of Canada (Empire Lumber Division) has operated a sawmill/planermill complex on the east bank of Mamquam Blind Channel in Squamish. Logs are trucked to, and sorted on, the west bank of Mamquam Blind Channel, prior to being boomed. The hemlock logs are mechanically debarked, with the hogged materials being sold. The finished lumber is graded and dried, with some of the lumber being treated in a dip tank.

Cooling water from three compressors is discharged directly through two outfalls into Mamquam Blind Channel. Waste Management permit PE 4951 allows the discharge of a up to 390 m^3/day at a maximum temperature of 35°C. Squamish Terminals has operated a deep sea berth and barge slip for forest products since 1970. Wastewater from the equipment services (floor wash water) and steam cleaning pad water are treated in two oil separators prior to discharge into a rock seepage pit. Waste Management permit PE 1749 allows the discharge of 2.3 m^3/day with a maximum oil and grease concentration of 70 mg/L.

The District of Squamish operates two high-rate activated sludge secondary sewage treatment plants which discharge effluent to the Squamish River. The Central Squamish Sewage Treatment Plant (STP), constructed in 1972 for the southern area of Squamish, was designed for flows of 4,545 m^3/day. The Mamquam STP began operating in 1973 and is designed for flows of 5,450 m^3/day.

The Central Squamish STP, under Waste Management permit PE 1533, allows the discharge of a maximum 4,550 m^3/day, with a maximum suspended solids concentration of 40 mg/L and a maximum BOD5 of 40 mg/L. The Mamquam STP is under Waste Management permit PE 1512, allows the discharge of a maximum 5,500 m^3/day, with a maximum suspended solids concentration of 60 mg/L and a maximum BOD5 of 45 mg/L. The effluents from the two plants are not disinfected due to a concern for toxicity to the fisheries resources of the Squamish Estuary.

HOWE SOUND PULP AND PAPER LIMITED (PE 1149)

Howe Sound Pulp and Paper at Port Mellon on the west shore of Howe Sound operates both kraft and thermo-mechanical pulping processes. The kraft mill has a production rate of 1,400 ADt/day, while the thermo-mechanical pulp mill has a production rate of 750 ADt/day.

Wastewater is treated in an oxygen-activated sludge secondary treatment system. Effluent is discharged through a submerged outfall at a depth of 115 m and at a distance of 250 m from shore at low water. Waste Management permit PE 1149 allows the discharge of a maximum of 76,000 m^3/day with a range of pH from 6.0 to 8.0; a maximum temperature of 35°C; a dissolved oxygen concentration > 2.0 mg/L; a 96-hr LC50 > 100%; equivalent maximum and average suspended solids of 283 mg/L, 10.0 kg/ADt, and 21,500 kg/day; equivalent maximum and average BOD5 of 212 mg/L, 7.5 kg/ADt, and 16,125 kg/day; and with the following average and maximum AOX values: 1.5 kg/ADt and 3.0 kg/ADt, respectively; 2,100 kg/day and 4,200 kg/day, respectively; and 28 mg/L and 55 mg/L, respectively. After June 30, 1992, the maximum AOX values are to be 42 mg/L, 3,220 kg/day, and 2.3 kg/ADt.

Also discharged through the same outfall is treated domestic sewage from the mill. Sewage is treated using two types of secondary treatment facilities, a rotating biological contactor and an extended aeration type plant. Permit PE 1149 allows the discharge of a maximum 118 m^3/day treated sewage with maximum concentrations of 45 mg/L of BOD5 and 60 mg/L suspended solids.

Permit PE 1149 also covers the discharge of cooling water and stormwater through eight additional submerged outfalls. The maximum allowable discharge is 76,000 m^3/day with a pH from 6.0 to 8.5, a maximum temperature of 35°C, and a 96-hr LC50 of > 100%.

BRITANNIA MINE

The Britannia Mine complex is located on the east shore of Howe Sound, about 45 km north of Vancouver. It consisted of six open pits in a tributary (Jane Creek) to Britannia Creek, as well as several shafts and adits. The copper mining and milling operation began in 1905 and shut down in 1974. During the operation of the mine, over 52 million tons of ore were processed, yielding 0.6 million tons of copper, 15.3 tons of gold, and 181 tons of silver (Moore, unpublished).

Acid mine drainage from the Britannia complex was carried for more than seventy years in Britannia Creek, until a pipe was laid on the bottom of

Britannia Creek to carry the drainage water into Howe Sound through a submerged marine outfall.

THE MUNICIPALITY OF THE VILLAGE OF LIONS BAY

This discharge, 10.5 km north of Horseshoe Bay is from a 140-unit condominium and five single family residences. The wastewater is provided secondary treatment in a rotating biological contactor prior to discharge through a submerged outfall located 180 m beyond the low tide mark at a depth of 60 m. Sludge is taken to the Lions Gate sewage treatment plant in West Vancouver.

Waste Management permit PE 5188 allows the discharge of 340 m^3/day with a maximum concentration of 45 mg/L BOD5 and 60 mg/L suspended solids. Due to the small volume of discharge, and the fact that it is provided such a high level of treatment, it is unlikely that this discharge will affect the water quality of Howe Sound.

ENVIRONMENTAL IMPACTS FROM WASTEWATER DISCHARGES

While much impact-related data for benthos have been collected in the last few years by the companies and Environment Canada, the efforts of the B.C. Ministry of Environment have been concentrated on water column monitoring, plankton monitoring, sediment, and toxicity. Sampling sites used by the Ministry are shown in Figure 1.

Results from 1989 showed that the water column concentrations of chloroguaiacols and chlorophenols were undetectable (<0.0002 mg/L and <0.0001 mg/L, respectively), although detectable concentrations were found near the mills in the sediments, sediment extracts, and in plankton. The highest sediment concentrations for Port Mellon were at PM2, with concentrations of 0.30 µg/g tetrachloroguaiacol and 0.11 µg/g trichloroguaiacol, while at Woodfibre the highest concentrations were 0.43 µg/g and 0.10 µg/g, respectively, at WF2. These concentrations compare to 0.08 µg/g and <0.01 µg/g, respectively, at the Howe Sound control site located at the north end of Bowen Island.

In the plankton tissue, concentrations in samples from PM2 were 0.69 µg/g tetrachloroguaiacol and <0.05 µg/g trichloroguaiacol. At WF2, the concentrations in the plankton tissue were 0.200 µg/g and 0.068 µg/g, respectively. Values in the plankton collected at a control site were <0.05µg/g tetra- and trichloroguaiacol.

Copper-complexing work undertaken in 1990 near the Britannia mine site showed that copper levels radiating out from Britannia Beach, both in the surface water samples and those collected at depth, were extremely high (up to 0.886 mg/L in the surface sample and 0.170 mg/L at 15 m depth) (Fig. 2). The complexing capacity of Howe Sound waters near Britannia Beach has been exceeded; however, sediment extract analyses for metals and chlorinated organics showed that typically, sediment contaminants are not released back into the water column at concentrations which would be a concern.

Total dioxin concentrations measured in the sediments at PM2 and WF2 were 6,680 pg/g and 5,805 pg/g, respectively, compared to a concentration of 69 pg/g at the control site. The associated toxicity equivalents (to 2,3,7,8-TCDD) were 146.7, 55.7, and 1.7, respectively. For total furans, the concentrations were 640 pg/g, 848 pg/g, and 20.9 pg/g, respectively, with associated toxicity equivalents of 30.9, 28.9, and 1.2, respectively. The International Joint Commission (Environment Canada, 1990) has established a water quality objective of 10 pg/g of 2,3,7,8-TCDD for sediments. The toxicity equivalents calculated for the measured dioxins and furans at sites WF2 and PM2 are well above this value.

Water column monitoring in 1991 has shown that mercury levels are extremely low (<0.005 µg/L), and that metals concentrations in sediments throughout the Sound are generally acceptable, except near Britannia Beach where copper concentrations are high. Copper concentrations in the water column near the mine were again high in 1991, with maximum concentrations measured of 1.75 mg/L in a surface sample and 0.22 mg/L in a sample collected at a depth of 15 m.

At this site, copper concentrations in sediments were 828 µg/g and zinc concentrations were 362 µg/g. Concentrations in the interstitial water were 60.5 mg/L and 0.033 mg/L, respectively. Interestingly, copper concentrations measured in sediments from two other sites near the Britannia discharge were 1,610 and 1,570 µg/g in 1985. For comparison, Stancil (1980) indicated that an area of Sturgeon Bank with 200 µg/g copper in sediments had been severely impacted by the former discharge from the Iona Sewage Treatment Plant.

During 1991, toxicity was tested by a variety of bioassays, including sand dollar bioassays, and microtox EC50 tests on sediment, pore water, and directly on the sediment (solid phase). Only the solid phase technique gave positive (toxic) results (Fig. 3). The data illustrate that the greatest toxicity is associated with sediment from Woodfibre, followed by that from Canoxy, Britannia, and then Port Mellon.

From the overview perspective that this paper was intended to provide, the major concerns in Howe Sound at present are contamination by dioxins and related organochlorines emanating from the mills, and copper and related metals radiating out from the Britannia mine site. Remedial measures have begun to some degree at the mills by installing or planning to install secondary treatment. Even at reduced loadings, we do not know if dioxin degradation will be adequate.

With respect to the mine, remedial measures have been discussed, but no action has yet been taken.

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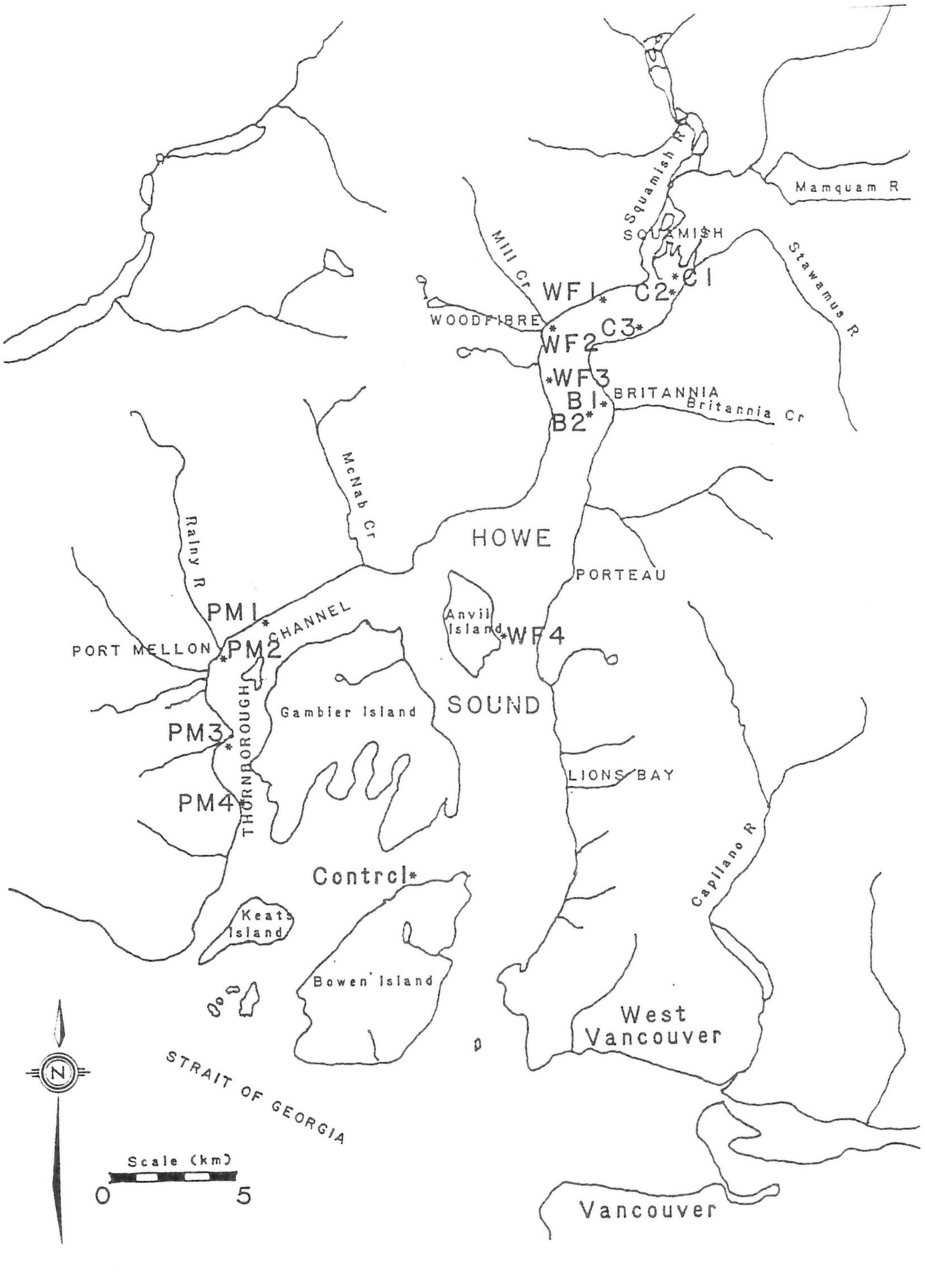

Figure 1. Howe Sound B.C. Ministry of Environment Sampling Sites.

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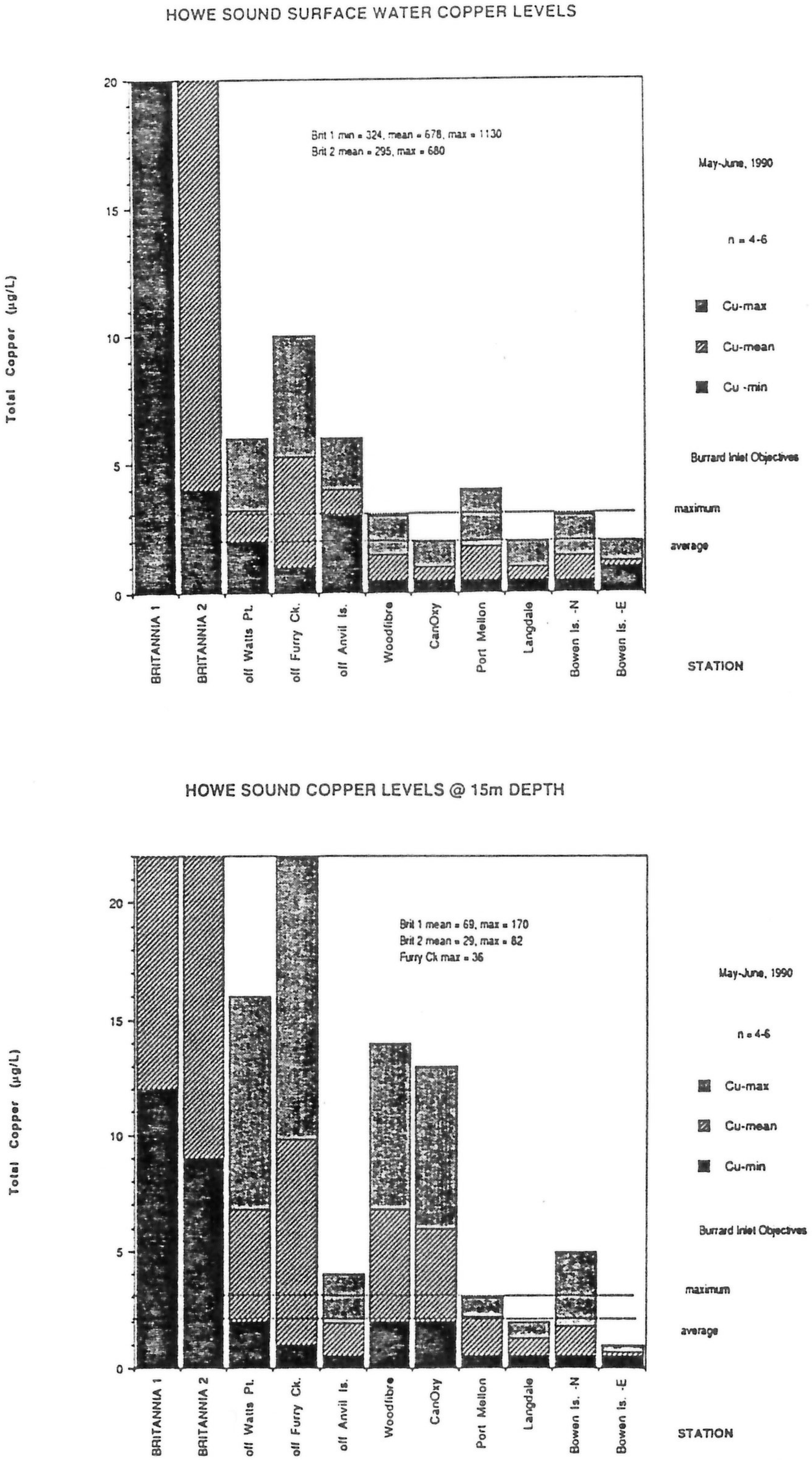

Figure 2. Copper Concentrations in the water column near Britannia.

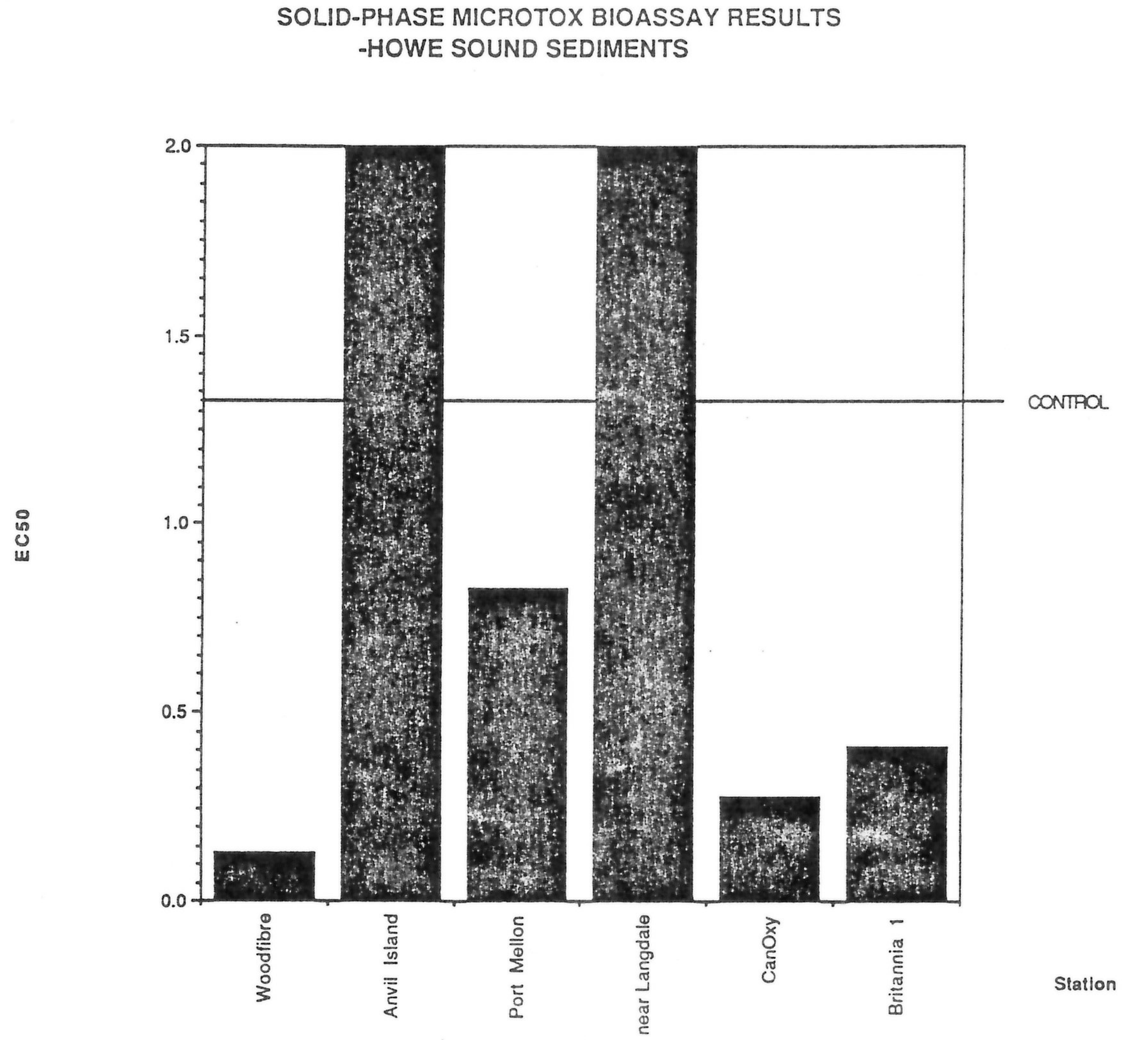

Figure 3. Microtox Bioassay Results.

ENVIRONMENTAL MONITORING THROUGH NATURAL HISTORY RESEARCH

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ABSTRACT

Documentation of newly discovered natural history phenomena is the primary goal of Vancouver Aquarium research in Howe Sound. Ancillary to that goal is the desire to provide a basis for future comparisons, a continuum of baseline data on marine life in Howe Sound. Emphasis has been on early life history of marine fishes and shrimps, but those life stages are ephemeral, with expected interannual and long-term fluctuations. To balance this emphasis on planktonic larval forms, projects more recently have been initiated for monitoring larger, more long-lived forms such as harbour seals, intertidal starfish, and glass sponges.

Accomplishments to date from ichthyoplankton surveys include disproving the assumption that planktonic drift is a dispersal mechanism for larval rocky shoreline fishes, demonstration of larval polymorphisms, new taxonomic descriptions of larval fishes, and documentation of the distribution of the late larval forms of Pacific whiting. Beds of Agarum kelp have been identified as juvenile nursery habitat for spot prawns, and year-class fluctuations of spot prawns have been documented. Enumeration of harbour seals at Popham Island has included photographic identification of individuals and seasonal changes in sex and age composition of the colony have been monitored. Studies of seasonal and tidal movements of Pisaster starfish and growth rates and environmental limits of hexactinellid sponges provide monitoring results from more stable populations of benthic life. Long-term commitment to these projects will provide a basis for gauging changes which may occur in the quality of Howe Sound as a habitat for marine life.

INTRODUCTION

In 1983, the Vancouver Aquarium entered a nominal lease agreement for use of Popham Island, in southwestern Howe Sound, as a research base. Construction of a field station building was undertaken in 1988, along with necessary repairs to the breakwater and installation of a dock and ramp. Field work from the station is supported by a 6 m aluminum boat and the 15.3 m MV *Aquarius*. October 19, 1989, marked the official opening of the Murray A. Newman Field Station for Howe Sound Research, the designation honouring the man who has directed the Aquarium since its opening in 1956.

Popham Island is a private nature refuge, exclusive access being granted to Aquarium research staff and their assistants. In addition to the caretaking protection of the island which this research arrangement provides, the natural history monitoring of Howe Sound marine life, based from this island, provides a data record which can provide for correct environmental assessments in the future. The Vancouver Aquarium is the only institution committed to a continuous research presence in Howe Sound. This research is privately funded by tourism income, with no regular taxpayer support.

Aquarium research emphasizes basic studies at the descriptive level. Interest in larval forms of local marine fishes and shrimps originated with captive spawnings in the Aquarium's display tanks, which form the basis for a propagation laboratory at the Aquarium. In conjunction with the laboratory culture, ichthyoplankton surveys have been conducted in the field since 1983, with special emphasis on the southern Howe Sound basin.

EARLY LIFE HISTORY STUDIES

Ichthyoplankton taxonomy is a relatively recent and rapidly developing discipline. Larvae of the manacled sculpin, Synchirus gilli, were first described from material taken in Howe Sound (Marliave et al., 1985). New descriptions of NE Pacific Liparis species, including material from Howe Sound, have clarified the phylogenetic significance of exclusively larval morphological features in this genus (Marliave and Peden, 1989). Additionally, microgeographic population variations have been documented in larval tidepool sculpins, *Oligocottus maculosus*. Both clinal variation through the Strait of Juan de Fuca and polymorphic variation within populations in Howe Sound have been documented for larvae of this species (Marliave, 1988).

A standard assumption about larval stages of marine organisms is that larval distribution is random or uniform. The phenomenon of planktonic larval drift dispersal occurs for larvae of various pelagic marine fishes, but the larvae of rocky intertidal species in Howe Sound tend to remain where they hatch, without either alongshore or offshore dispersal (Marliave, 1986). The larvae of the Pacific whiting, *Merluccius productus*, show differences in distribution and habitat preference at successive stages in their larval development, the later stages associating with substrate at increasing depths (Marliave, 1989). Pacific whiting spawn at great depths on the west side of the Strait of Georgia (McFarlane and Beamish, 1985); intermediate larval stages accumulate along the shores of Howe Sound and then move deeper along the fjord walls as they grow (Marliave, 1989).

Similarly, the larvae of the spot prawn, *Pandalus platyceros*, shift from planktonic to non-planktonic distribution prior to settlement under *Agarum* kelp fronds. Several *Agarum* beds in Howe Sound have been monitored since 1985 (Marliave and Roth, submitted) and varying levels of "year-class strength" have been documented at different sites in different years. During 1990 there was a complete year-class failure of spot prawn settlement on the west side of the southern basin of Howe Sound, whereas the eastern side showed normal levels of recruitment to the nursery grounds. No obvious explanation is apparent for this trend in 1990. In 1991, nearly the opposite picture emerged, apparently due to the eastern site being in line with the fetch of northerly outflow winds, which destroyed the kelp bed habitats in comparable fashion to the damage done to trees during unusual winter storms.

Current Aquarium research utilizes novel procedures for discovering routes by which early life history stages of various marine species have previously gone through "disappearing acts," beyond detection by standard gear and techniques. A long series of data sets will permit observation of any patterns which may emerge; in the meantime, such observations provide documentation of basic natural history phenomena.

INDICATOR SPECIES

A recent trend in Aquarium research in Howe Sound is a focus on ecological indicator species. Recognizing that early life history stages, such as larval fish, are very susceptible to short-term variations due to weather effects, added focus has been placed on long-lived, prominent organisms such as boot sponges, starfish, and harbour seals. On fjord walls, basic studies of growth in boot sponges, *Rhabdocalyptus dawsoni*, will provide for long-term data on a major faunal component of Howe Sound's deep waters. Similarly, on rocky shores, study of seasonal and tidal movements of the purple starfish, *Pisaster ochraceus*, will provide for long-term records of an intertidal keystone species. A colony of harbour seals resides adjacent to Popham Island, providing opportunity for study of these seals at a time when public concern has been expressed over their growing numbers in B.C. waters.

GLASS SPONGES

Howe Sound apparently has the shallowest known rossellid sponges outside of Antarctica. Glass sponges in B.C. typically range at depths greater than 20 m, but various sites in Howe Sound have been found with Rhabdocalyptus dawsoni at depths starting as shallow as 12-15 m below extreme low water.

Six individual sponges at a site near Hutt Island were tagged on February 9, 1990, for growth monitoring, and for use as reference points for locating other sponges at the same site. A census on February 6, 1990 revealed that 170 sponges were then present, none smaller than about 30 cm in length. During September and October 1991, this site was precisely mapped and a total of 396 sponges were counted. The colony approximately doubled in numbers over two growth seasons.

Morphology appears to be plastic in boot sponges (Fig. 1), as the osculum size and shape is highly variable and the circumference somewhat less variable. During late winter of 1990, some were observed to collapse (Fig. 1). Some sponges grew larger, then smaller in circumference (Fig. 2), possibly on the basis of changing levels of turgor, although evidence for resorption or loss of glass spicules exists from reversible patterns of healing of biopsy plug holes. These variations ranged beyond the possible level of error for measures. Maximum circumference approximated length, and the greatest variability over time in circumference was in the largest sponges, for which circumference exceeded length (Figs. 2 & 3). Sponge #3 was repairing damage and grew least.

In late February 1991, the smallest sponges found at that time (Fig 3: A-G) were 2-3 cm height and 2-4 mm osculum diameter. Sponge lengths for these "underyearling" sponges increased far more rapidly than for the six tagged "adult" sponges (Fig. 3: #1-6), and the small sponges increased up to 71% in length by the end of August (6 months) as opposed to less than 20% for large sponges. At the end of June, growth had been less in the small sponges (Fig. 3: C,D,E) above the average upper depth limit for adult sponges (Fig. 4), compared to that for those below the average limit (Fig. 3: A,B,F,G). All of the small sponges monitored below the modal limit survived through July and August, whereas the three small sponges at shallower depths (Fig. 3: C,D,E) perished between the end of June and the end of August.

The smallest sponges found to date were observed in fall of 1991, ranging from 1-2 cm in length. These new sponges occurred in dense patches at a variety of depths. No search was made in fall of 1990, so the small sponges from February 1991 can only be presumed to have also been 1-2 cm in fall of 1990. Thus, reproduction apparently occurs during summer. Sloughing of exterior layers of all boot sponges was observed in early summer of 1991. Thus, bioherms, the reefs made up of dead sponge material, may be deposited episodically by colonies of living sponges.

The upper depth limits of boot sponges in Howe Sound appear correlated to deep water conditions bounded by about 28°/oo salinity and 10°C summer temperature (Fig. 4). Profiles of temperature/salinity were conducted by divers only on the two occasions depicted in Figure 4, but remote profile readings were made from an anchored boat adjacent to the site on nine other dates between February and September 1990. The discontinuity in temperature/salinity always occurred above the level of the sponges, and the extreme data for temperature/salinity combinations at the depth of the sponges were 7°C/27°/oo, 12°C/27°/oo, and 11°C/24°/oo. Temperature/salinity profiles within a tidal cycle during different seasons have yet to be fully documented, but existing data suggest that the seasonal discontinuity forms an upper physical limit to occurrence of boot sponges.

Three transplants at the Hutt Island site were cut off at the base and strapped into concrete blocks with electrical cable-ties or "zap-straps," then the blocks were placed at an angle against the cliff on ledges, including a control at the base of the cliff. The mortality rate of small sponges above the modal upper depth limit (Fig. 4) was different than the survival for over one year of a large sponge transplanted from below the modal depth limit to 2 m above. That is, the surviving sponge occurred 1 m above the extreme upper limit of naturally occurring sponges at this particular area, which happens to be the shallowest known site for boot sponges, about 12 m below low water. Another transplant 2 m higher (4 m above the modal upper limit) perished within a few months during autumn of 1990. Thus, depth involves a mortality factor, presumably related to the seasonal discontinuity of temperature and salinity, which appears more critical to younger sponges than to older individuals. Tissue plugs have been removed from boot sponges at various depths, seasons, and sites in Howe Sound. William C. Austin (Khoyatan Marine Laboratory, Cowichan Bay) will assess the spicules from these tissue samples for growth analysis and taxonomic verification.

INTERTIDAL STARFISH

Pisaster ochraceus, the common intertidal ochre starfish, has been observed to undergo exponential population increases in the English Bay/Howe Sound region during both the late 1970's and the late 1980's (personal observation). With the population level recently at a peak, it has been possible to observe seasonal and tidal patterns of movement, both in the horizontal and in the vertical. With assistance from the B.C. Environment Youth Corps, large-scale transplants of P. ochraceus were undertaken, including transplants of the relatively rare orange morph (1-3% of Howe Sound population, personal observation). The orange morph is readily distinguished from the more prevalent purple morph, and provides a natural marker for short-term transplant studies. Grids and transects have been conducted on one vertical cliff face at Popham Island to quantify vertical and horizontal variation in distribution over different tidal cycles.

Transplants at different times of the year (unpublished data) have shown very little horizontal movement of these starfish between mid-December and mid-March, although vertical movement, as well as feeding, continued. After the vernal equinox, horizontal movements rapidly accelerated, and the higher rate of movement remained apparently constant until the approach of the winter solstice and decay of the seasonal thermocline. Although horizontal movements were nearly random, the "tagged" orange morphs indicated that starfish spread more rapidly toward low density areas (cleared by transplant) than into normal high density areas. Furthermore, orange morphs placed at a cliff corner moved more rapidly and in higher numbers along a turbulent, current-swept face than into a calm, back-eddy area around the corner of the study area.

There is also evidence for regulation of vertical movement in synchrony with the higher low water of the semidiurnal tidal pattern typical of B.C. Only when there is an upward trend toward high plateaus (higher low tide approaching height of high tides), will the P. ochraceus move up through the entire Mytilus/Balanus zone. These high plateaus coincide with extreme low tides. During most portions of the tidal cycle, the ochre starfish is at sea level or up to 0.5 m above sea level at lower low water, with maximum vertical movements on the order of one metre. With high plateaus, however, the starfish gradually move higher up the shore, initially becoming exposed by less than one metre at extreme low tide by virtue of vertical movements of just over two metres. Toward the end of such a phase, however, the vertical movement rate decreases back to the order of one metre, resulting in low tide exposures of over two metres above sea level. Such extreme aerial exposures thus tend to occur toward the latter part of an extreme low tide series, mostly because the starfish exploit the high plateaus and perhaps overextend their capability of vertical movement (usually only about one metre). Vertical limits of starfish during moderate and extreme tidal fluctuations are shown in Figure 5.

A final observation regarding vertical movements of ochre starfish concerns the effect of direct sunlight on height of aerial exposure. During a tide series with constant cloud and rain, extreme low tide exposure was observed. During a period of constant summer sunshine, however, starfish exposed to direct sun were observed to be 1 m lower in the intertidal at extreme low tide than those on the shaded side of a sloped cobble beach. This difference in tidal height resulted in those starfish on the shaded side being 15 m further inshore, horizontally, than those on the sunlit side. Shaded *Mytilus*/*Balanus* areas thus may suffer more *Pisaster* predation than adjacent areas exposed to direct sun.

HARBOUR SEALS

Dr. H. Dean Fisher, Professor Emeritus of Zoology at UBC, has been an Aquarium Research Associate since 1987, studying the Howe Sound harbour seal (*Phoca vitulina*) population. Attempts are underway to identify individual seals on the basis of pelage patterns. Various natural history observations on the harbour seal have also been made in Howe Sound. Generally, the physiology and anatomy of this species are very well documented, but its secretive habits have resulted in little natural history documentation anywhere.

Harbour seals have increased in number in Howe Sound from about 60 to 600-700 since the end of the seal bounty about 20 years ago (H. D. Fisher, pers. comm.). Pupping was observed to occur in Howe Sound from 1983 to 1985, from April through August, but pupping has not been evident in Howe Sound in the last two years. The offshore haul-out rock at the west end of Popham Island is perhaps the second most regular haul-out area in Howe Sound, after Pam Rocks in Queen Charlotte Channel. The seals around Popham Island also tend to use west Whorlcombe Island, east Hermit Island, and other areas in the Pasley Island group around Popham Island. Particularly during winter, the seals hauling out at Popham Island are exclusively mature males, so some aspect of bachelor herding, known for sea lions, may exist for harbour seals, at least in winter.

CONCLUSIONS

The proximate goal for the studies based out of the Murray A. Newman Field Station for Howe Sound Research is the descriptive documentation of new data on natural history phenomena. Perhaps the ultimate goal of our work is the correct understanding of the marine ecology of Howe Sound. An intermediate goal of considerable significance, however, is to maintain a continuum of observational data which will provide a sound basis for comparisons in the future. Should the quality of Howe Sound as a habitat for marine organisms change in the future, these data sets will provide the basis for demonstrating any significant changes, and hopefully, may also indicate some explanatory basis for such changes.

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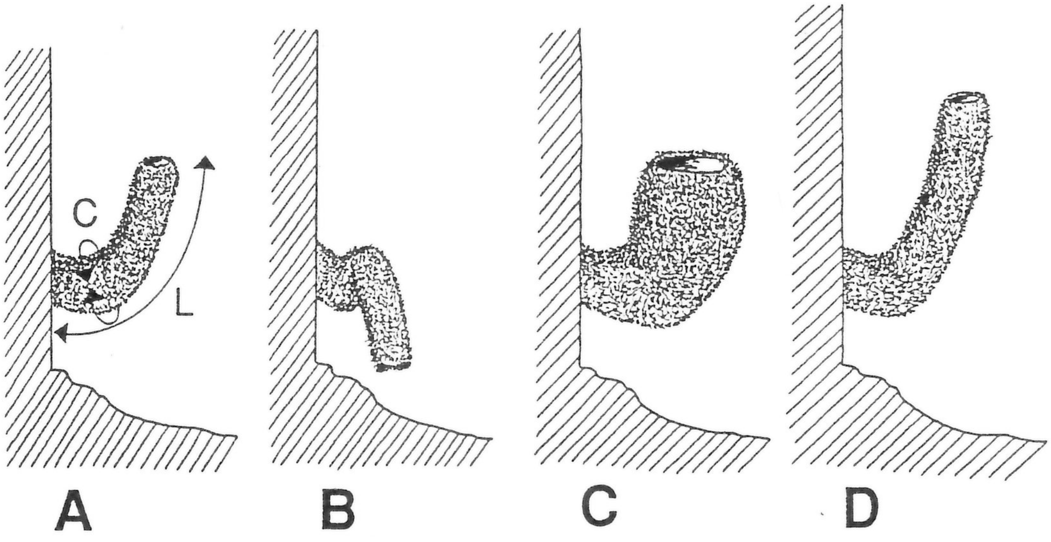


Figure 1. Schematic depiction of measurements and growth patterns in boot sponges (Rhabdocalyptus dawsoni). Maximum length, L, from base to osculum and maximum circumference, C, were measured (**A**). The sequence from A to D has been observed in individual sponges, where collapse (**B**) occurred most frequently during midwinter (e.g., January 1990), then extreme increases in circumference (**C**) typically occurred during summer, with net increase in length (**D**) observed over time.

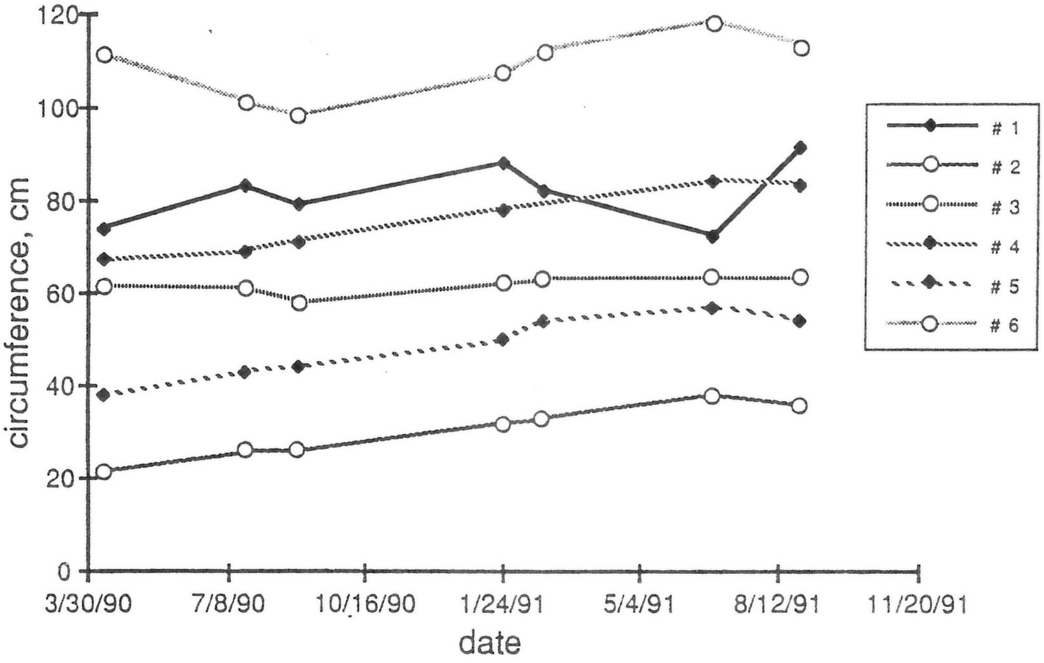
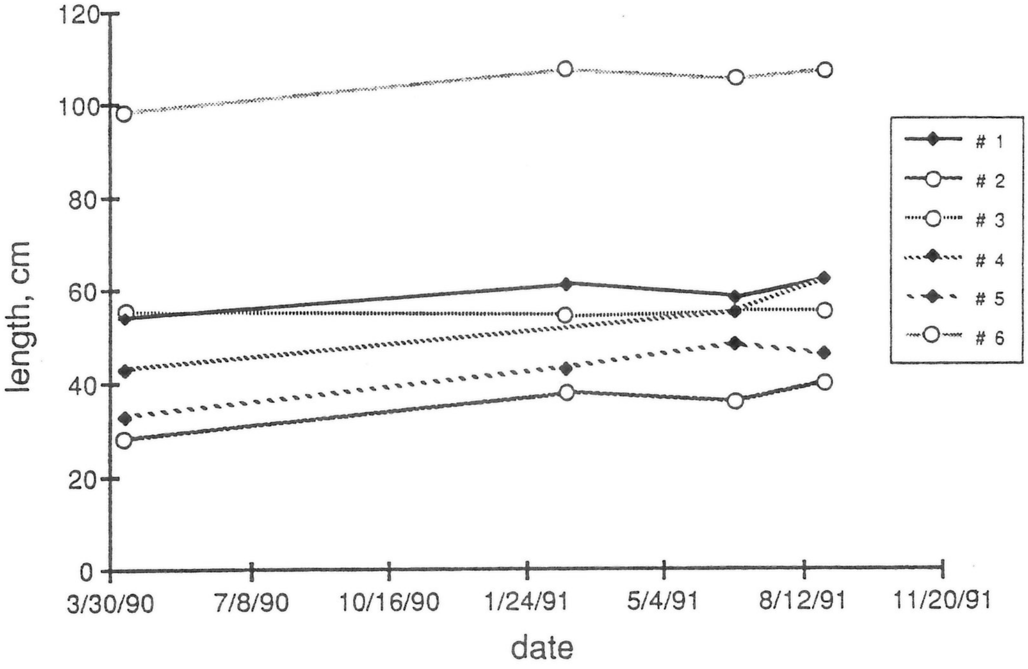


Figure 2. Circumference of six tagged sponges, # 1-6, at the Hutt Island study site.



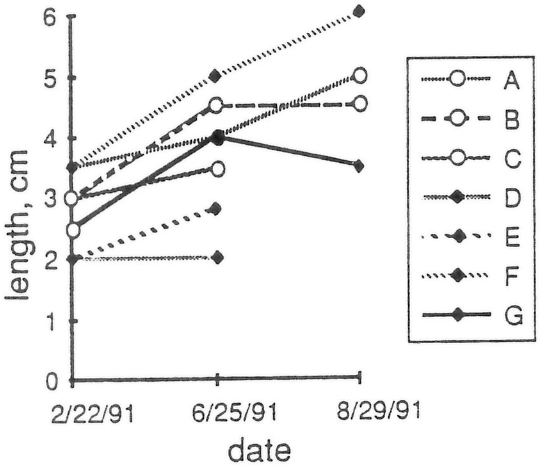


Figure 3. Growth in length for six large boot sponges (#1-6) and for seven small, "underlyearling" sponges in 1991 (A-G). Sponges C, D, and E were above the modal depth limit (Fig. 4), and perished.

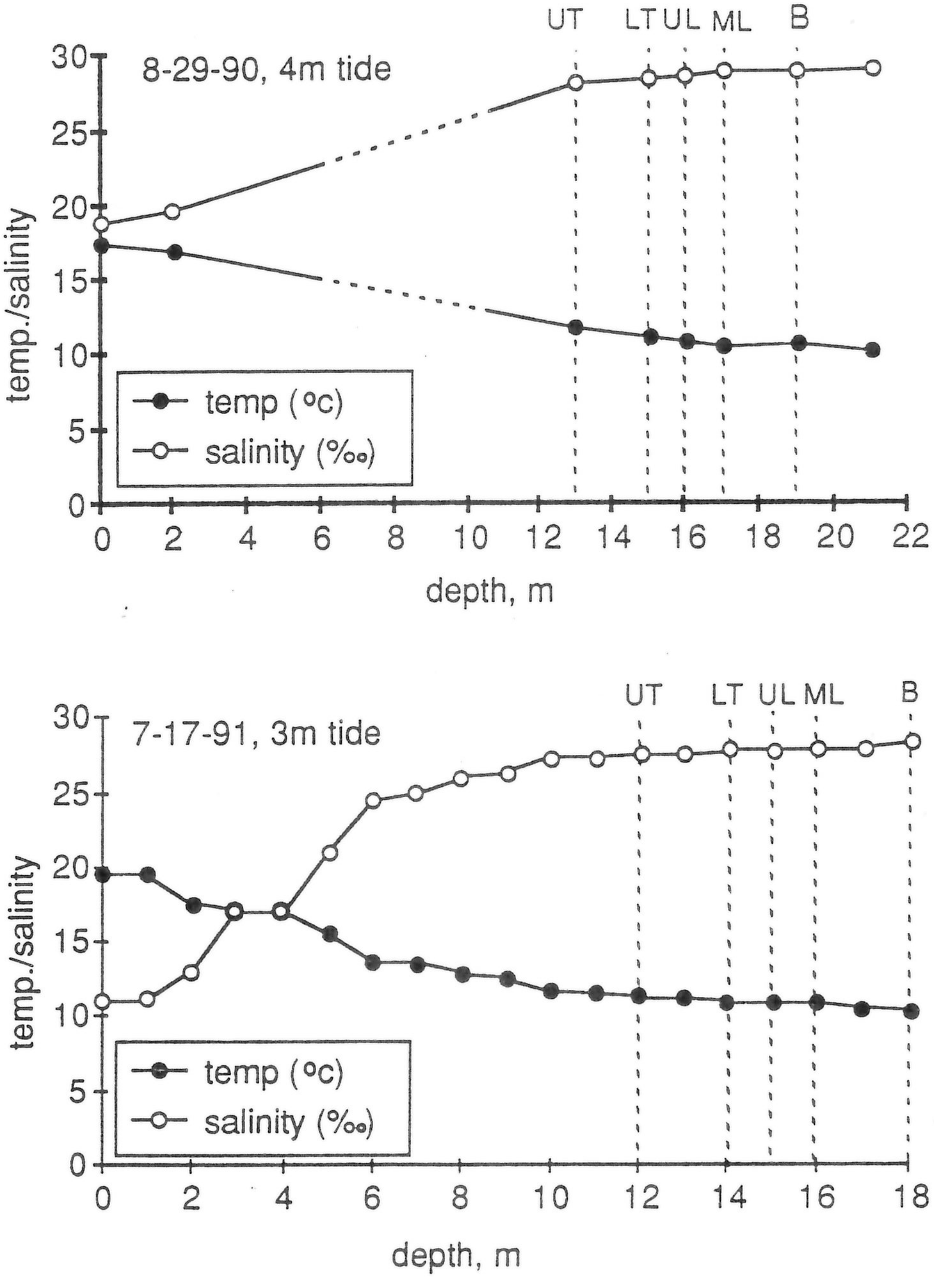


Figure 4. Temperature/salinity profiles for the site on Hutt Island were studied, summer 1990 and 1991. These data were obtained by divers placing a temperature/salinity probe adjacent to sponges at the following depths: B=bottom of cliff face, ML=modal upper depth limit of sponges, UL=extreme (outlier) upper depth limit, LT=lower transplant, UT=upper transplant. The majority of sponges occur below or at the ML depth, with a visible horizontal boundary.

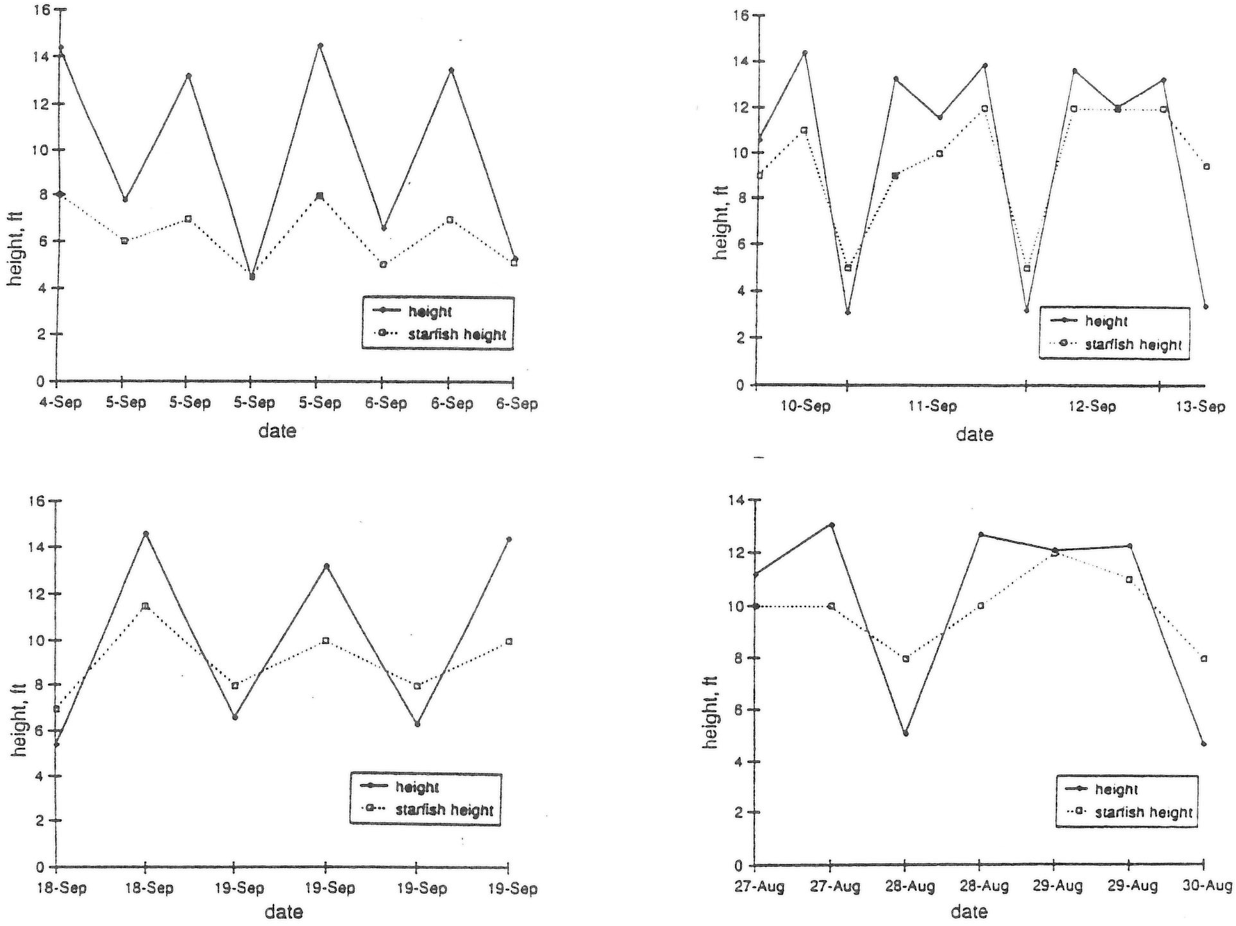


Figure 5. Vertical movement of upper limit of starfish, *Pisaster ochraceus*, according to tide height under different patterns of semidiurnal tides at Popham Island, Howe Sound, B.C. Dates are from 1990.

WOODFIBRE MILL, WESTERN PULP

by

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The Woodfibre mill is located at the mouth of Mill Creek approximately 5 kilometres from the head of Howe Sound on the western shore. Industrial activity has been continuous at this site since the beginning of this century. Following several years of sawmill operation, pulp production began in 1912, utilizing an unbleached sulphite process. The mill was converted to the bleached kraft (sulphate) process in 1961.

In 1986, the company completed a $200 million modernization program that was largely environmentally driven. This included a new low odour recovery boiler with electrostatic precipitators designed to meet the most stringent air emission standards. This, together with incineration of non-condensible gasses in the new lime kiln, have virtually eliminated the characteristic kraft mill odour. In 1985, the mill started up Canada's first R-8 chlorine dioxide generator and Kamyr displacement bleach plant. Our mill was, therefore, in a position to quickly and effectively address the dioxin problem when it first became known, and to reduce other chlorinated organic compounds. All of the effluent streams (some of which previously discharged into Mill Creek) were consolidated, and after primary treatment, are now discharged through a deep water diffuser 22 metres below low tide.

The Squamish mill produces 700 tonnes per day of bleached kraft market pulp. All of the fibre supply is in the form of residual chips from sawmills in the lower mainland and Vancouver Island areas. With no road access, all of the raw materials to the mill come in by barge or truck/ferry. A deep sea dock at the mill facilitates shipment of the finished product to markets around the world.

The desired blends of Douglas-fir, Hemlock and Cedar chips are cooked in a Kamyr and five batch digesters. A new 300 tonne blow tank and double atmospheric diffusion washers on the Kamyr line and a new drum washer on the batch line provide thorough brown stock washing. This is followed by three stages of pressure screening before passing over a decker-rewasher to further minimize the carry-over of organic materials to the bleaching process. Medium consistency chlorination with three high shear mixers precedes the computer controlled dynamic bleaching process. The mill uses a D_c E_o DED bleaching sequence with over 50% chlorine dioxide substitution in the first stage. About one-third of the production is currently bleached without any molecular chlorine using chlorine dioxide, oxidative extraction and hydrogen peroxide in a D E_o DP bleaching sequence.

In 1989, Western Pulp committed a further $70 million to improve effluent quality. This included the new brown stock washing facilities mentioned above, upgrading the chlorine dioxide generator to enable the mill to sustain high substitution levels, and secondary treatment.

Site constraints at the mill, situated on a narrow bench at the base of a mountain, precluded conventional aeration ponds. A compact, but more costly activated sludge system was chosen. To establish the optimum design parameters, an extensive series of pilot plant studies were undertaken. The results of this research were published and have been widely referenced in scientific journals as one of industry's most thorough analysis of biodegradation of organochlorines. A low rate oxygen activated sludge effluent treatment system with 12 hours of hydraulic retention time was chosen. After excavating over 400,000 m^3 of mountainside, construction of the secondary effluent treatment plant is well underway.

Negotiations are currently being held to enable the mill to construct a new wood waste power boiler with co-generation. This will greatly reduce particulate air emissions as well as making the mill self-sufficient in electricity. At present, the mill generates approximately 2 megawatts of hydro power and 3 megawatts from steam turbine generators; a further 13 - 15 megawatts are purchased from B.C. Hydro.

The Woodfibre mill's impact on the Howe Sound watershed can be summarized as follows:

Effluent

Average volume - 65,000 m^3/day
Suspended solids - 3 tonnes/day
Biochemical oxygen demand (BOD) - 17 tonnes/day, (2 tonnes/day by late 1992)
Chlorinated organic compounds measured as adsorbable organic halogens - 1.5 tonnes/day

Particulate emissions

Recovery boiler - 0.8 tonnes/day sodium sulphate and sodium chloride
Lime kiln and dissolving tank combined - 0.4 tonnes/day, primarily Ca & Na carbonate
Power boiler - 2.0 tonnes/day fly ash (0.5 tonnes/day with new boiler by 1994)

Based on a review of research done in the 60's and 70's, the environmental impact of the mill's effluent was confined to a localized area adjacent to the outfall. Good circulation and flushing of surface waters due to the Squamish River flow were interpreted as limiting the impact (Nelson, 1979). Studies did show depleted communities of invertebrate taxa on the beach area for several hundred metres adjacent to the mill (Levings and McDaniel, 1976). Installation of a submerged outfall and diffuser system in early 1986 was designed to improve water quality and intertidal life near the mill.

Recent receiving water surveys conducted by Hatfield Consultants, beginning in 1989, show a more widespread impact. Highly chlorinated catechols and guaiacols were detected in sediments up to 10 kilometres from the mill. Dioxins and furans, though not exclusively from the pulp mills, were detected in crab hepatopancreas in increasing concentrations in samples approaching the mill outfall (Dwernychuk, 1989, 1990).

Process changes in the last two years have virtually eliminated the dioxin discharge and reduced the effluent organochlorine loading by well over 50%. The new oxygen activated sludge effluent treatment system currently under construction, will further reduce these unwanted compounds as well as rendering the effluent non-toxic.

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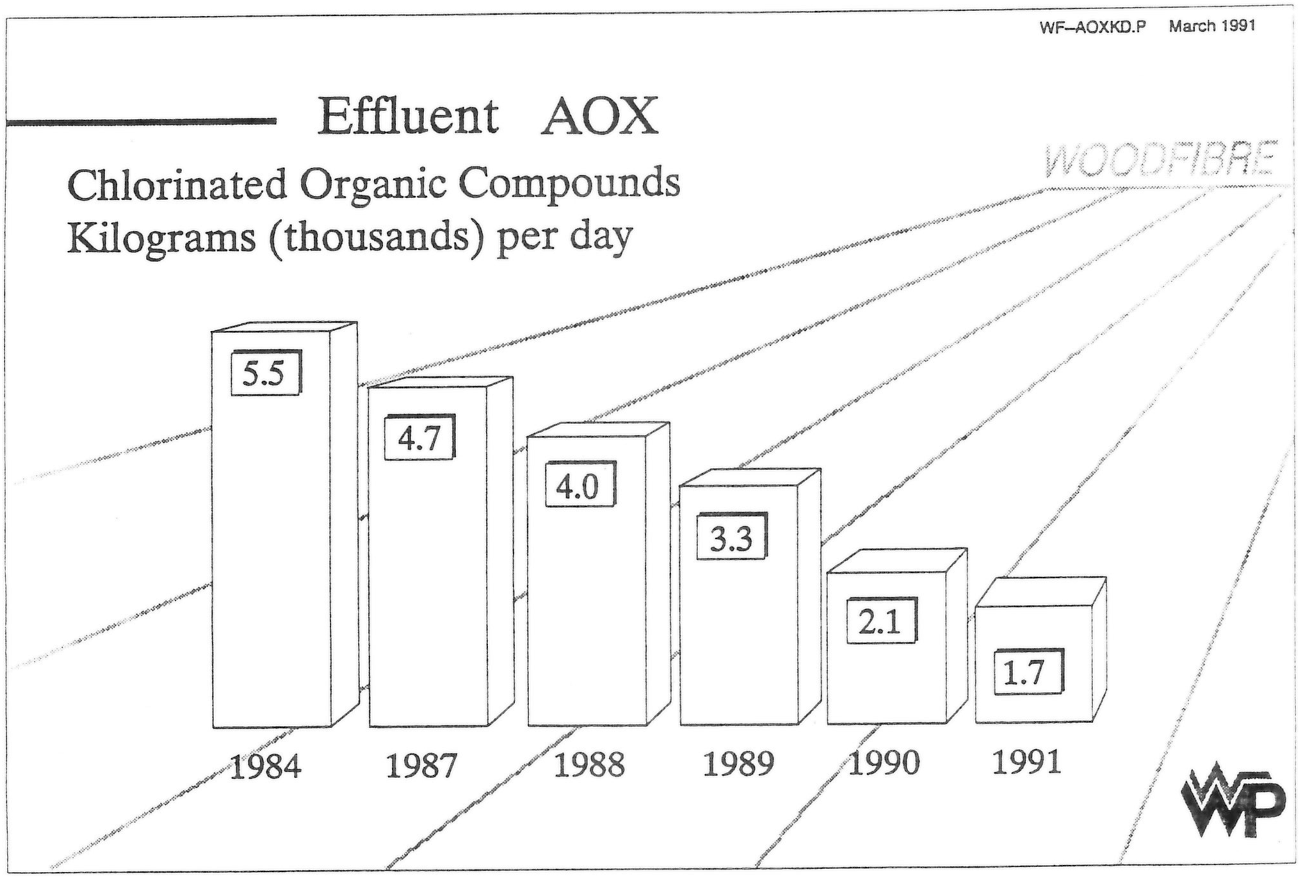

WF–AOXKD.P March 1991

Effluent AOX

Chlorinated Organic Compounds
Kilograms (thousands) per day

DIOXIN MEDIATED SHELLFISH CLOSURES IN HOWE SOUND

by

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ABSTRACT

In early 1988, a monitoring program was initiated to document the presence and concentration of dioxins and furans in aquatic organisms near British Columbia pulp and paper mills. Preliminary data for selected finfish and shellfish from Howe Sound indicated that elevated levels of certain dioxin and furan congeners were present in prawns and in the hepatopancreas (digestive gland) of Dungeness crab. Subsequently, more intensive monitoring led to the closure, in November 1988, of a portion of Howe Sound near the Port Mellon and Woodfibre pulp mills to all harvesting of prawn, shrimp, and crab. In June 1989, the prawn, shrimp, and crab closure was expanded to include an additional part of the Sound in the vicinity of Keats Island and the remainder of Howe Sound was closed to commercial crab fishing. A consumption advisory was also issued recommending that the hepatopancreas of crab taken from that portion of Howe Sound open to non-commercial harvesting not be consumed. Finfish collected from the Sound contained non-detectable or low levels of dioxins and furans. Monitoring of aquatic organisms in Howe Sound is continuing and results obtained will be used to determine when areas closed to prawn, shrimp, and crab fishing can be reopened.

INTRODUCTION

Prior to the mid-1980s, the presence of polychlorinated-p-dioxins (dioxins) and polychlorinated dibenzofurans (furans) in British Columbia bleached kraft pulp mill effluents had not been documented and contamination of the aquatic environment from these substances was not a significant concern. In 1986, certain congeners of dioxins and furans, specifically the most toxic form, 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), were reported in kraft pulp mill sludge at mills in the eastern United States and in Ontario (Ontario Ministry of the Environment, 1986). Such reports stimulated interest in determining if dioxins and furans were present in B.C. mill effluents and the receiving environment into which these mills discharged their effluents. The Canadian Wildlife Service measured dioxins and furans in the eggs of Great Blue Herons collected near Crofton, B.C., the site of a bleached kraft pulp mill, and other Strait of Georgia locations in studies between 1983 and 1987. Suspected sources of these contaminants found in the heron eggs of the Crofton colony were chlorophenols, a chemical used to treat lumber prior to export, and pulp mill effluent (Elliot et al., 1988). In early 1988 the environmental organization Greenpeace reported the presence of a variety of dioxin and furan congeners in a marine sediment sample collected near the outfall of the Harmac pulp mill on Vancouver Island (Greenpeace, 1988).

The Department of Fisheries and Oceans (DFO) and Environment Canada (DOE) began the design of monitoring programs in 1987 and a small number of biota samples were collected that year by DOE. In early 1988, comprehensive monitoring began near B.C. pulp mills including the two bleached kraft pulp mills on Howe Sound, Woodfibre and Port Mellon, which discharge their effluents into the Sound. This report summarizes selected dioxin and furan data from the Howe Sound monitoring programs and describes the subsequent closures to shellfish harvesting implemented within the Sound.

HOWE SOUND FISHERY RESOURCES

Howe Sound supports diverse finfish and shellfish populations that are harvested in Native, commercial, and recreational fisheries. The generalized distribution of major species groups within the Sound is illustrated in Figure 1. Dungeness crab, shrimp, and prawn are the principal shellfish species harvested. There are small commercial longline fisheries for lingcod, rockfish, and dogfish. The Sound and the streams draining into it (e.g., the Squamish River) support important stocks of all five species of Pacific salmon. The Sound is closed to commercial harvesting of salmon for conservation reasons but is an important recreational fishing area, primarily for chinook and coho salmon. Numerous other species of invertebrates and fish comprise the aquatic biological community of Howe Sound.

OVERVIEW OF MONITORING PROGRAMS

In January 1988, samples of dungeness crab (Cancer magister), prawn (Pandalus platyceros), softshell clam (Mya arenaria) and quillback rockfish (Sebastes maliger) were collected near the Port Mellon and Woodfibre pulp mills (Fig. 2). The samples were analyzed for dioxins and furans by the Department of Fisheries and Oceans' Ultra Trace Laboratory in Burlington, Ontario. A more extensive series of samples was collected from the Sound in May 1988. Dungeness crab, prawn, shrimp (Pandalopsis dispar and Pandalus sp.), quillback rockfish, red snapper (Sebastes ruberrimus) and chinook salmon (Oncorhynchus tshawytscha) were obtained from the sites indicated in Figure 3 and submitted to the DFO Burlington laboratory for analysis. Chum salmon were also collected from two sites in November 1988 (Fig. 4).

The next round of sampling in the Sound was carried out between December 1988 and February 1989. Samples were collected by DFO and by consultants for the two Howe Sound pulp mills under the direction of DFO and DOE. Species sampled were dungeness crab, red rock crab (Cancer productus), prawn, shrimp, and mussel (Mytilus edulis) (Fig. 4). Samples collected by DFO were analyzed by the Burlington laboratory and those collected by the mills, by Seakem Analytical Services Ltd. of Sidney, B.C. The last available data are for prawn samples collected by DFO in December 1988 and April 1989 and analyzed at Burlington (Fig. 5).

Tissues analyzed were those commonly consumed (e.g., fish fillet and shellfish body muscle or soft tissue). Because the analysis of a few initial samples of crab hepatopancreas (digestive gland) indicated the presence of elevated concentrations of dioxins and furans and because some individuals consume this organ, the hepatopancreas was also analyzed.

FISHERY CLOSURES AND SUMMARY OF RESULTS

Other reports (in prep.) will detail the dioxin and furan data obtained from Howe Sound and other coastal B.C. sites. This paper presents a selected summary of data with emphasis on those dioxins and furans that are typically associated with bleached kraft pulp mill effluent namely, 2,3,7,8-TCDD and 2,3,7,8-TCDF (tetrachlorodibenzofuran) (NCASI, 1990; Berry et al., 1991). Certain 2,3,7,8-substituted forms of hexachlorodibenzo-p-dioxin (H6CDD) have also been discharged by mills, particularly those that used wood chips contaminated with chlorophenols. When present at sufficiently elevated concentrations, H6CDD can contribute significantly to overall toxicity on a toxic equivalency basis (North Atlantic Treaty Organization, 1988). For the purposes of this paper, the total concentration of H6CDD is presented because some data sets did not include the analysis of specific H6CDD isomers.

All data were assessed by the Department of Health and Welfare (H&W) to determine if concentrations measured posed a health risk to human consumers. All congeners of dioxins and furans present in the samples were considered by H&W in the health assessments. DFO subsequently used the H&W health assessments to determine if fishery closures or consumption advisories were required. A description of the factors considered and methodology used by H&W in conducting health assessments of the dioxin and furan data, including the concepts of tolerable and probable daily intakes, are discussed in Huston (1992).

The results in this section are presented in accordance with the date of their public release.

MAY 1988

In May 1988, all available data for Howe Sound and other sites in Canada were released to the public. Concentrations of dioxins and furans in Howe Sound bottomfish were low; the level of 2,3,7,8-TCDD was below detection limits and the maximum concentrations of 2,3,7,8-TCDF and total H6CDD dioxin were 27 and 15 pg/g (parts per trillion, or ppt), respectively. Maximum concentrations of 2,3,7,8-TCDD, 2,3,7,8-TCDF and total H6CDD for clam, prawn, crab muscle, and crab hepatopancreas are shown in Figure 6. Of particular interest are the high values reported for crab hepatopancreas (662 ppt 2,3,7,8-TCDD; 24,968 ppt 2,3,7,8-TCDF; 4,682 ppt total H6CDD). At the time these data were assessed, hepatopancreas was not considered to be normally consumed. For this reason and because only very few samples had been analyzed, H&W did not recommend any consumption restrictions. H&W did, however, recommend that further samples be analyzed from sites near and extending outward from the pulp mills to determine if the early sample results were representative (Government of Canada, 1988a).

NOVEMBER AND DECEMBER 1988

In November and December 1988, the second and third sets of dioxin data for Howe Sound were released to the public and fishery closures for crab, shrimp, and prawn near the two pulp mills were implemented. Data on bottomfish confirmed the low levels reported in May 1988. Maximum concentrations of 2,3,7,8-TCDD (3 ppt), 2,3,7,8-TCDF (28 ppt), and total H6CDD (6.4 ppt) were measured in quillback rockfish. The chinook salmon concentrations were also low from a human health perspective (maximum values of 19 ppt 2,3,7,8-TCDD; 15 ppt 2,3,7,8-TCDF; 24 ppt total H6CDD). No consumption restrictions were required for any finfish species (Government of Canada, 1988b and c).

Dioxin and furan concentrations in crab, prawn, and shrimp collected near the mills were elevated above limits considered safe for human consumption. Maximum levels of 2,3,7,8-TCDD, 2,3,7,8-TCDF, and total H6CDD are shown in Figures 3 and 7. The high concentrations in crab hepatopancreas were again significant in terms of human health with maximum values of 115 ppt 2,3,7,8-TCDD, 4,461 ppt 2,3,7,8-TCDF, and 1,530 ppt total H6CDD recorded. H&W advised that crab, prawn, and shrimp from near the Woodfibre and Port Mellon mills could pose a health hazard if eaten frequently. As a result, DFO closed that portion of Howe Sound (Fig. 8) near the two mills to all harvesting of these species (Government of Canada, 1988b).

MAY 1989

In May 1989, data on concentrations of dioxins and furans in Pacific salmon from various locations, including the chum salmon collected from Howe Sound in November 1988, were released. Concentrations of all dioxin and furan congeners in the chum salmon were below detection limits except for 2,3,7,8-TCDF (maximum of 8.9 ppt). As with salmon from other B.C. locations, the non-detectable to low concentrations of dioxins and furans measured precluded the need for consumption restrictions or fishery closures (Government of Canada, 1989a).

JUNE 1989

Howe Sound data for samples collected from December 1988 to February 1989 and some samples of prawns retained from the May 1988 sampling program were released in June 1989. Dioxin and furan values recorded for prawn, shrimp, crab (muscle and hepatopancreas), and mussel are shown in Figures 4 and 9. Elevated concentrations in prawn, shrimp, and crab muscle were again recorded near the mills as well as an area in the vicinity of Keats Island seaward of the previously closed portion of the Sound. Maximum values of 2,3,7,8-TCDD, 2,3,7,8-TCDF, and total H6CDD in crab hepatopancreas were 330 ppt, 15,000 ppt, and 2,400 ppt, respectively. Concentrations in crab hepatopancreas samples from sites some distance from the mills were also unacceptably high for human consumption. For example, the hepatopancreas of dungeness crab collected near Horseshoe Bay contained concentrations of 29 ppt 2,3,7,8-TCDD, 1,300 ppt 2,3,7,8-TCDF, and 270 ppt total H6CDD.

The health assessment of these data resulted in DFO extending the boundary of the area previously closed to crab, prawn, and shrimp harvesting into that portion of the Sound in the vicinity of Keats Island (Fig. 8). Furthermore, the entire remaining part of the Sound was closed to commercial crab harvesting because of elevated dioxin and furan concentrations in crab hepatopancreas samples collected over the extent of Howe Sound. Non-commercial harvesting of crab in this same part of the Sound is permitted subject to a health advisory against the consumption of the hepatopancreas (Government of Canada, 1989b).

APRIL 1990

The data for prawn samples collected in December 1988 and April 1989 formed part of a larger set of B.C. data released in April 1990. Low levels of dioxins and furans were found in the samples (Fig. 5) and were not considered to pose a health hazard (Government of Canada, 1990). Maximum levels reported were 3.1 ppt 2,3,7,8-TCDD, 72 ppt 2,3,7,8-TCDF, and 13.3 ppt total H6CDD. Although one of the samples was from the area of the Sound previously closed to prawn, shrimp, and crab harvesting, no changes to the fishery closure boundaries were made.

COMPARISONS WITH OTHER SITES

The highest values of 2,3,7,8-TCDD and 2,3,7,8-TCDF in crab hepatopancreas, prawn, and shrimp collected near B.C. coastal pulp mills occurred in Howe Sound. The body meat or muscle of crab from Howe Sound also contained the highest recorded 2,3,7,8-TCDF value. The highest 2,3,7,8-TCDD value (31 ppt) was for crab collected near the pulp mill at Prince Rupert. Figures 10 and 11 provide a comparison of the maximum values of 2,3,7,8-TCDD and 2,3,7,8-TCDF in crab muscle and hepatopancreas from the coastal sites sampled. Elevated levels of these and other congeners of dioxins and furans have led to crab fishery closures in the vicinity of mills at Campbell River, Crofton, Gold River, Kitimat, Harmac (Nanaimo), Powell River, and Prince Rupert as well as Howe Sound. Prawn fishery closures are in effect in Howe Sound and near Gold River while shrimp fishery closures are in place in Howe Sound and near the Prince Rupert mill (Figs. 12 & 13).

DISCUSSION

The monitoring strategy employed in Howe Sound was directed at determining the concentration of dioxins and furans in fishery resources, the extent of contamination, and the significance of levels recorded in terms of human health. Initial monitoring focused on the receiving environment near the pulp mills and species harvested in various fisheries. Subsequent monitoring targetted sites at progressively greater distances from the mill outfalls to determine the spatial extent of the contamination. Shellfish fishery closures affecting crab, shrimp, and prawn were first implemented in November 1988 and subsequently extended in June 1989.

The decision by DFO to prohibit harvesting of the affected species followed receipt of health assessments completed by H&W. In prohibiting both commercial and non-commercial harvesting, the department's first priority was to provide maximum protection to anyone who consumed crab, shrimp, and prawn from Howe Sound. A second major consideration involved the possible negative implications of the analytical results on the integrity of the shellfishing industry in B.C. and the confidence consumers had in the quality of B.C. coastal shellfish. As shellfish consumers typically are unaware of the precise origin of the shellfish they purchase, DFO wanted to assure consumers that the seafood products they were purchasing were not contaminated, regardless of their origin. This assurance was required for all consumable parts of shellfish, including crab hepatopancreas. For this reason, all of Howe Sound was closed to commercial harvesting of crab in June 1989 even though for a large part of the Sound the health concern pertained to elevated levels of dioxins and furans in crab hepatopancreas, not crab body meat. Thus, commercial shellfish closures implemented in Howe Sound and other coastal areas near pulp mills ensure that shellfish with unacceptable levels of dioxins and furans in any edible tissue do not enter the marketplace. Non-commercial harvesters, however, can continue to catch crab in that part of the Sound closed only to commercial harvesting but are advised not to consume the hepatopancreas.

A key question related to the fishery closures in Howe Sound and elsewhere is the rate at which contaminated areas will recover and tissue concentrations in affected species decrease to acceptable levels. Recently, the mills in Howe Sound and elsewhere in B.C. have taken steps to reduce the concentration of dioxins and furans in their effluents. Large loads of dioxins and furans were, however, discharged into the environment prior to this abatement. Important factors which will affect environmental recovery include the environmental stability and persistence of dioxins and furans; the bioavailability of previously discharged dioxins and furans; oceanographic processes; sedimentation rates and sinks; benthic infaunal activity (bioturbation); and the ability of the affected shellfish to metabolize dioxins and furans. Certain shellfish such as crabs, unlike fish, cannot metabolize many dioxin and furan isomers (Oehme et al., 1989; Cooper, 1989). This, among other factors, likely accounts for the much higher levels of dioxins and furans in crab compared to fish. Current studies in Howe Sound (Cretney et al., 1992) are directed at understanding the fate and persistence of dioxins and furans which reside principally in the bottom sediments of the Sound. Should these dioxins and furans remain biologically available, rapid decreases in the concentrations of these contaminants in crab, shrimp, and prawn may not occur. For this reason, further monitoring of Howe Sound biota is necessary and is being carried out to document when the levels of dioxins and furans in the affected organisms have been reduced to levels which will not affect human health. Areas closed to shellfish harvesting will be reopened when these acceptable levels have been reached.

ACKNOWLEDGEMENTS

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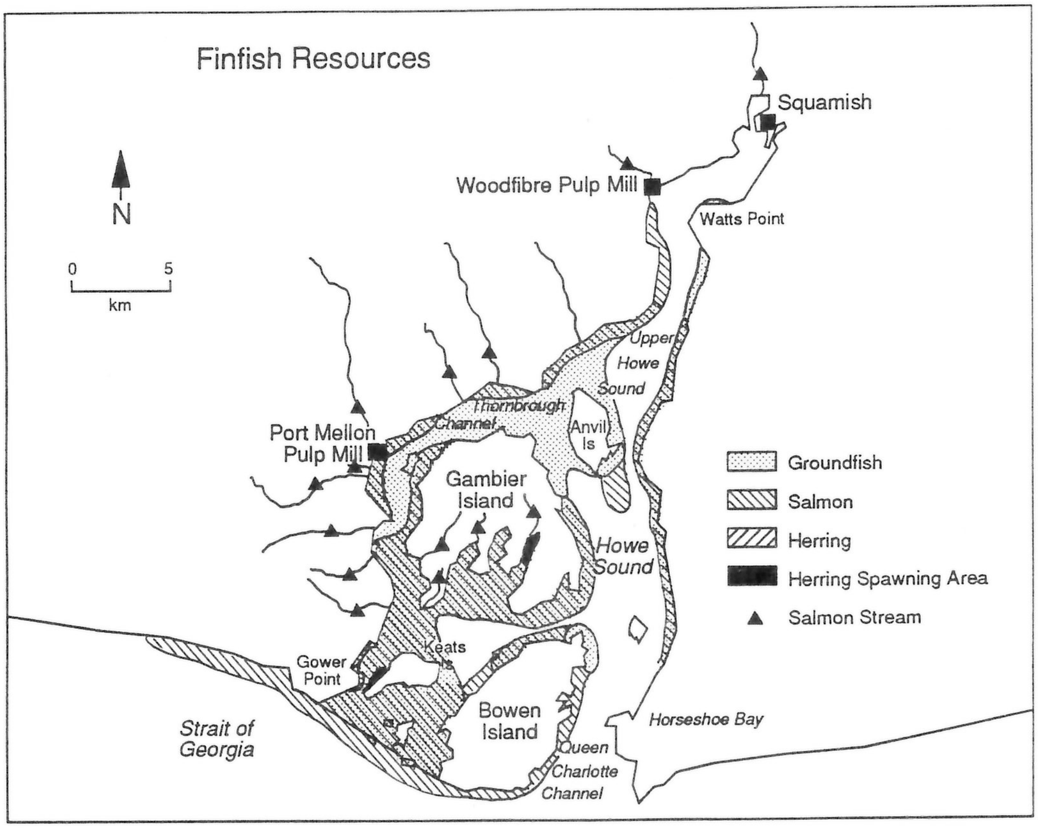

Figure 1a. Howe Sound finfish resources.

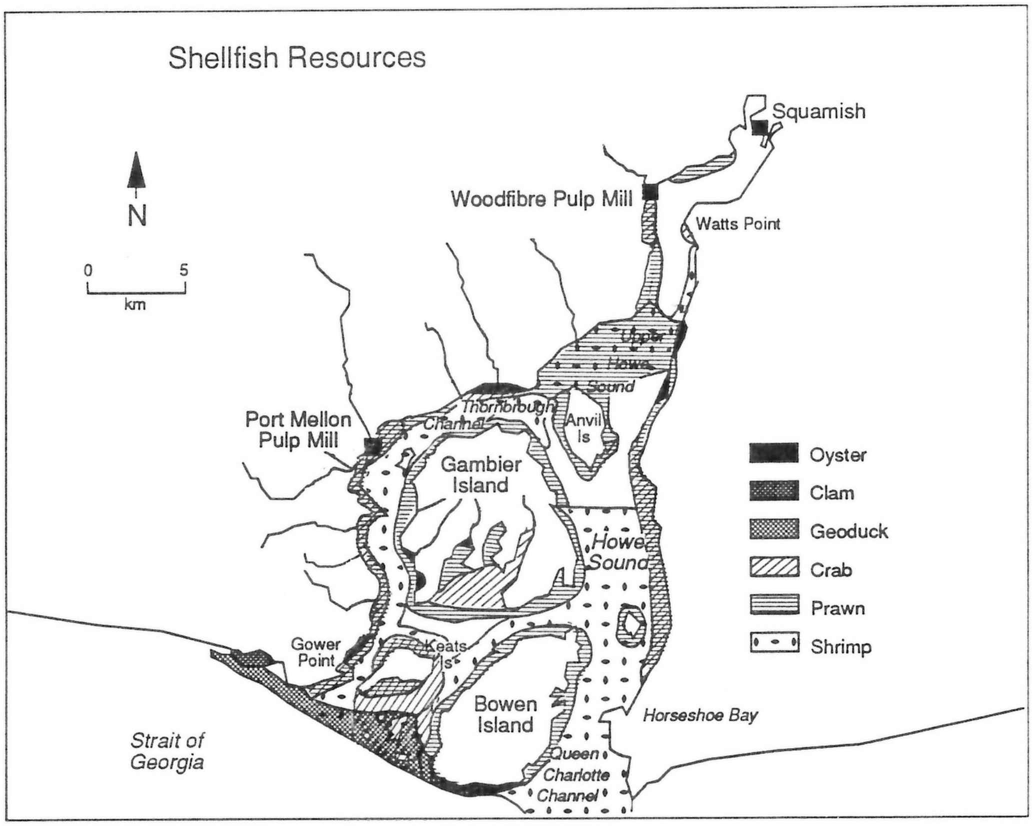

Figure 1b. Howe Sound shellfish resources.

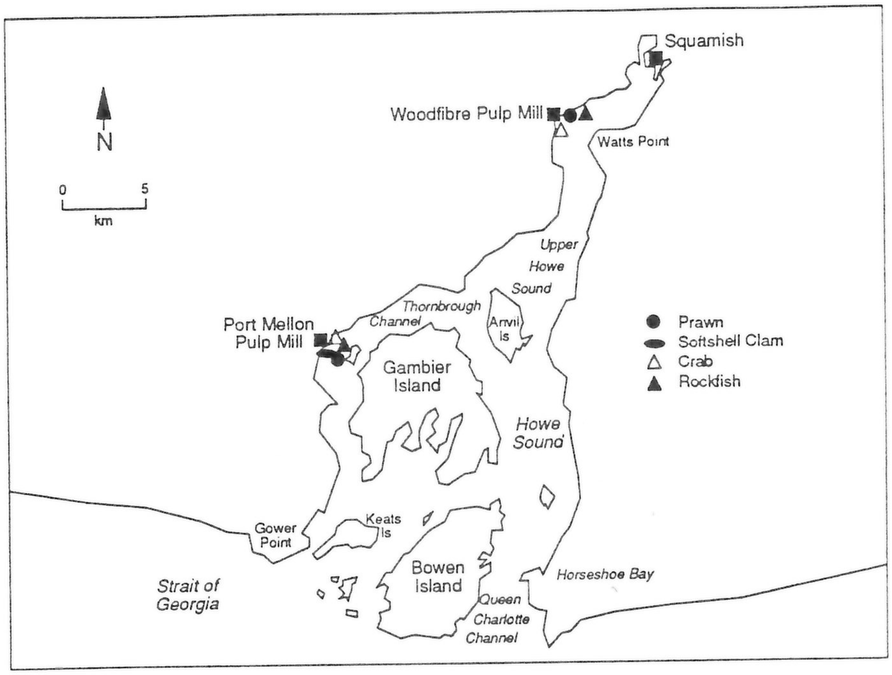

Figure 2. Location of Howe Sound samples collected in January 1988. (From Government of Canada, 1988a).

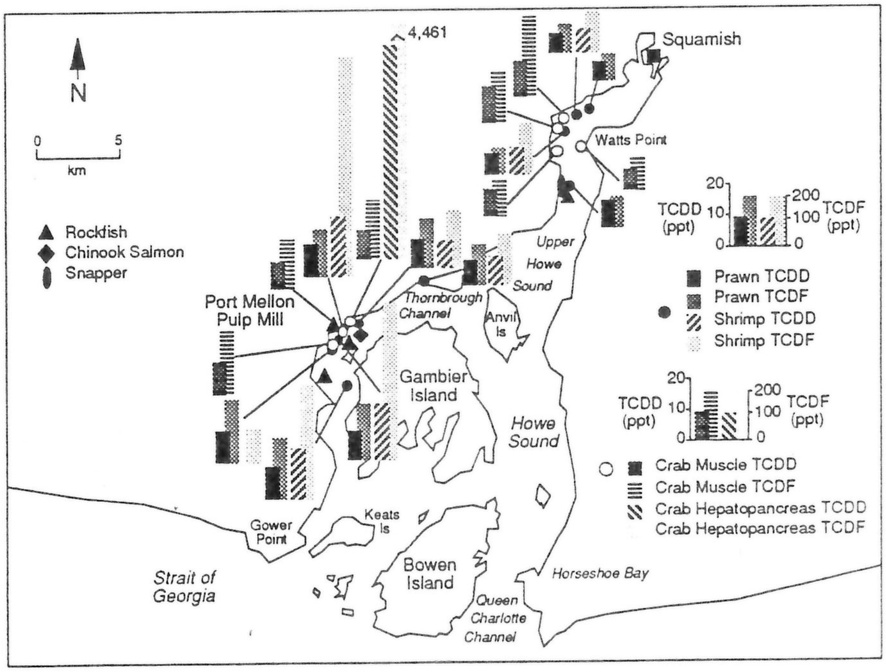

Figure 3. Location of Howe Sound shellfish and finfish samples collected in May 1988 and maximum levels of 2,3,7,8-TCDD and 2,3,7,8-TCDF in crab, shrimp, and prawn. (From Government of Canada, 1988b).

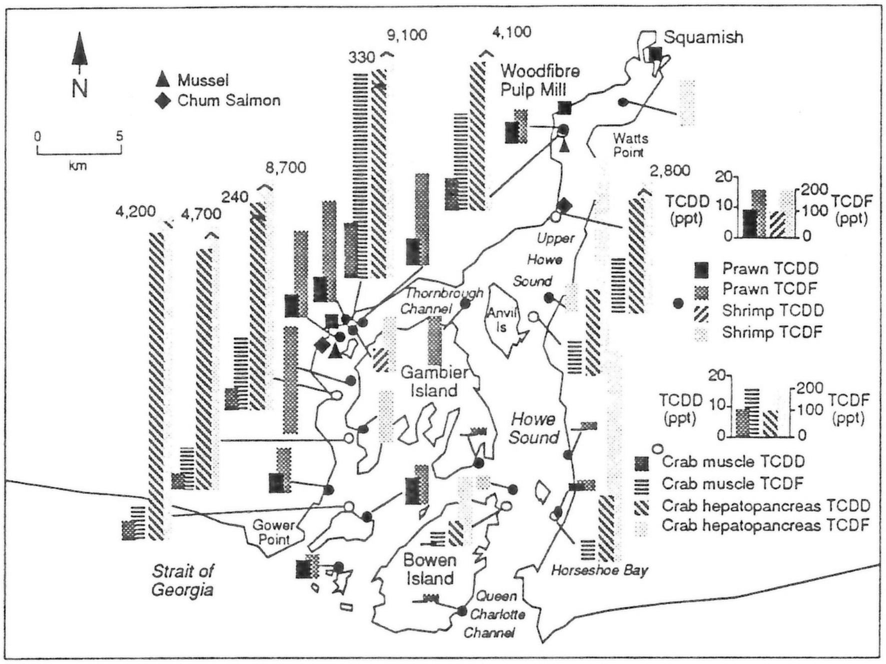

Figure 4. Location of Howe Sound shellfish and finfish samples collected in May 1988 and December 1988 - February 1989 and maximum levels of 2,3,7,8-TCDD and 2,3,7,8,-TCDF in crab, shrimp and prawn. (From Government of Canada, 1989a).

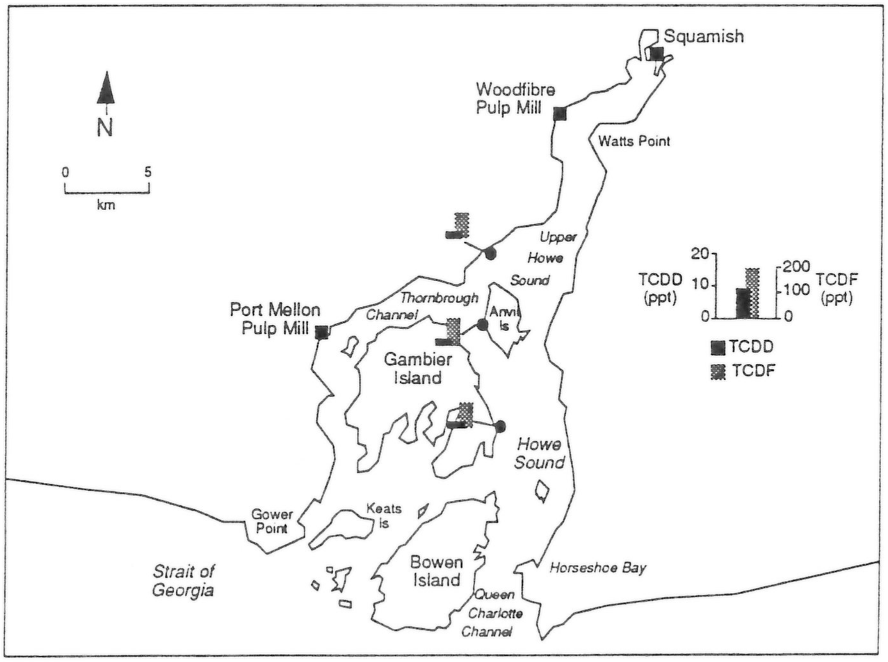

Figure 5. Location of Howe Sound prawn samples collected in December 1988 and April 1989 and maximum levels of 2,3,7,8-TCDD and 2,3,7,-TCDF (From Government of Canada, 1990).

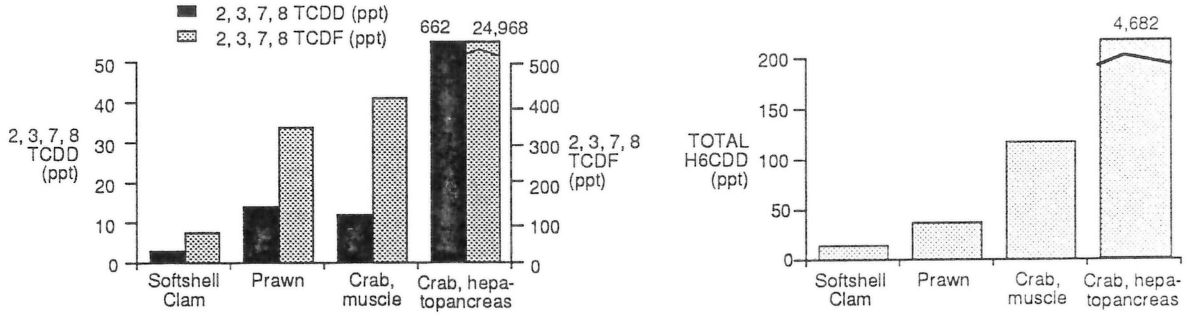

Figure 6. Maximum levels of selected dioxins and furans in Howe Sound shellfish collected in January 1988. (From Government of Canada, 1988a).

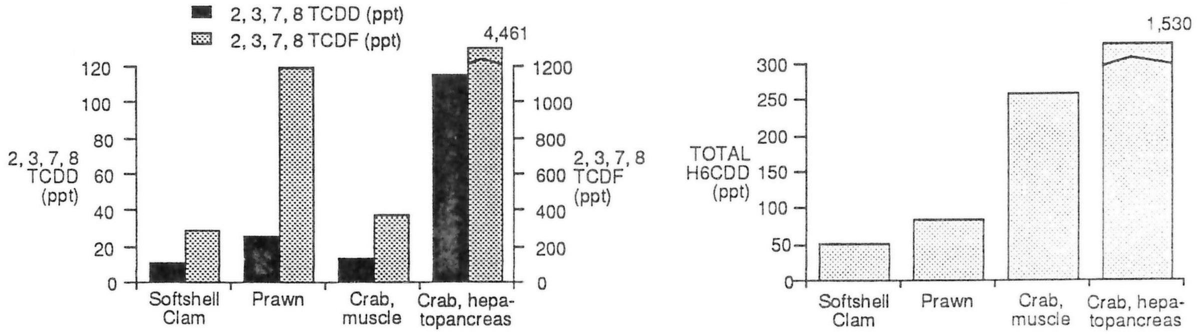

Figure 7. Maximum levels of selected dioxins and furans in Howe Sound shellfish collected in May 1988. (From Government of Canada, 1988b).

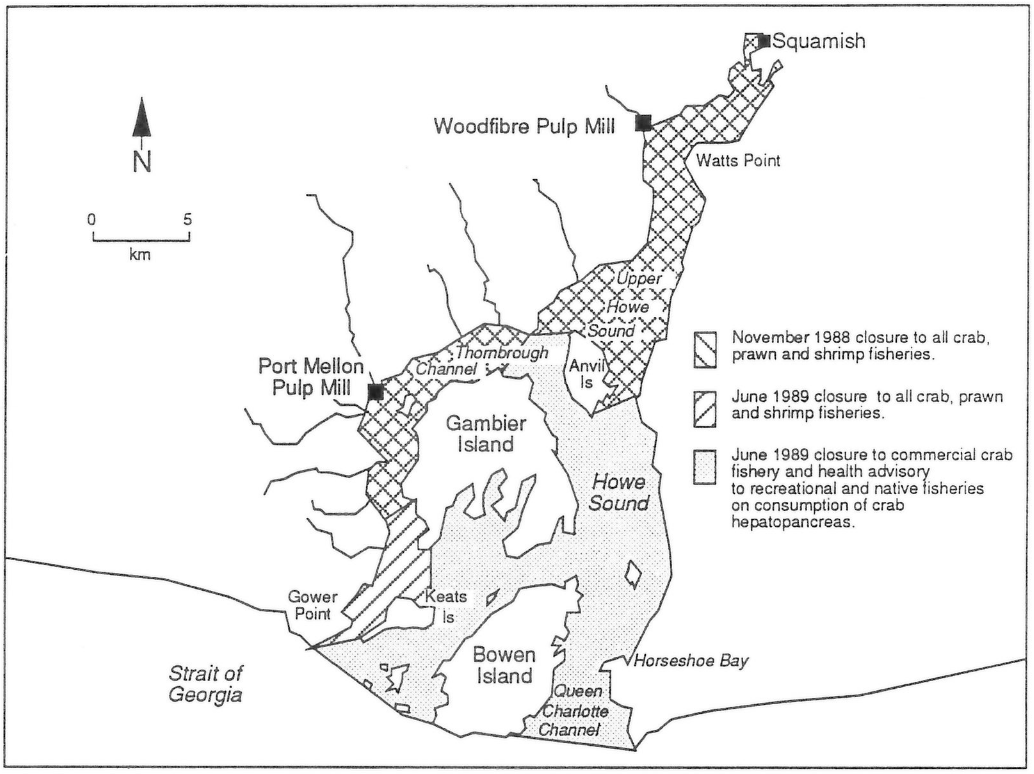

Figure 8. Howe Sound dioxin contamination closure boundaries.

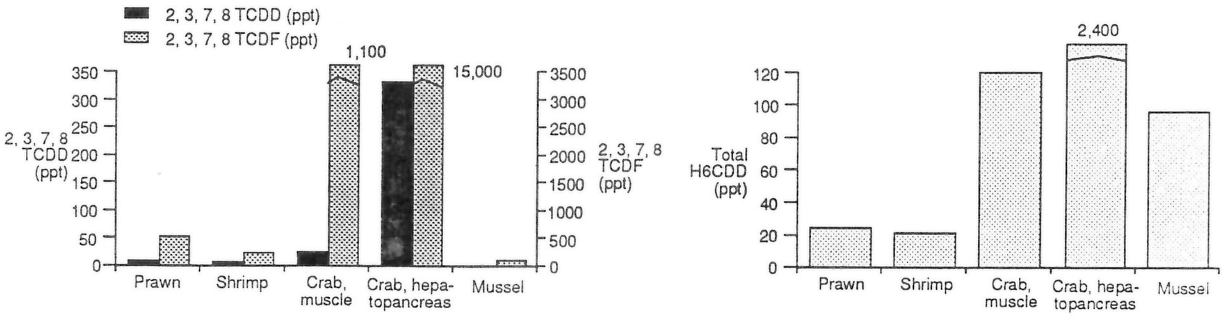

Figure 9. Maximum levels of selected dioxins and furans in Howe Sound shellfish collected in May 1988 and December 1988 - February 1989. (From Government of Canada, 1989b).

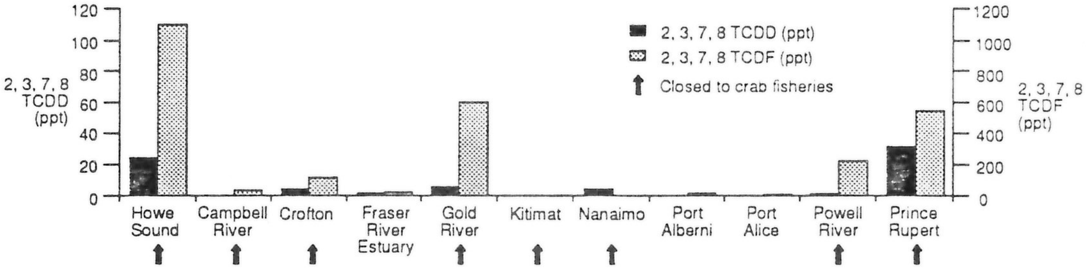

Figure 10. Maximum levels of 2,3,7,8-TCDD and 2,3,7,8-TCDF in B.C. crab muscle.

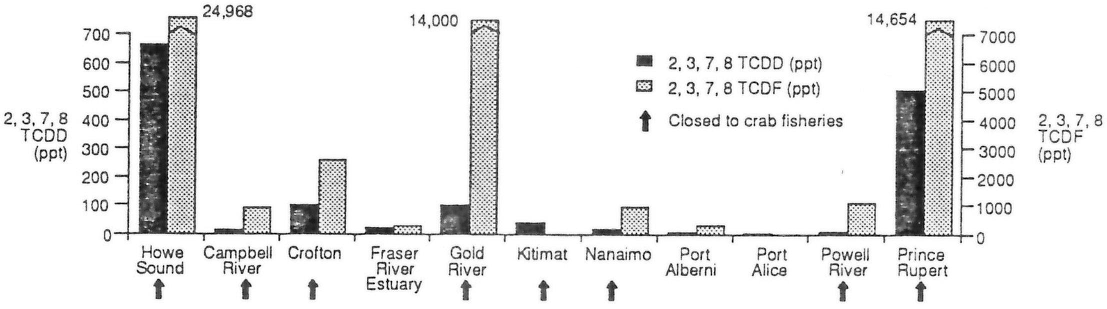

Figure 11. Maximum levels of 2,3,7,8-TCDD and 2,3,7,8-TCDF in B.C. crab hepatopancreas.

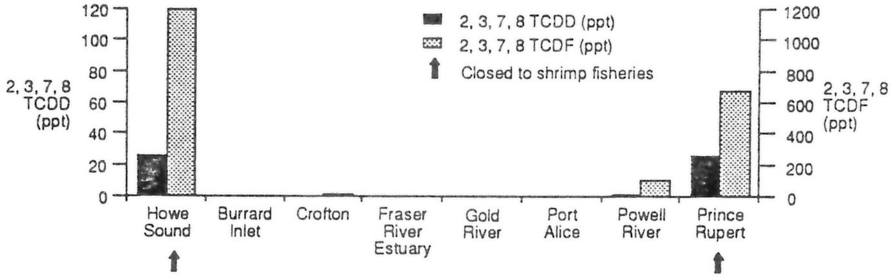

Figure 12. Maximum levels of 2,3,7,8-TCDD and 2,3,7,8-TCDF in B.C. shrimp.

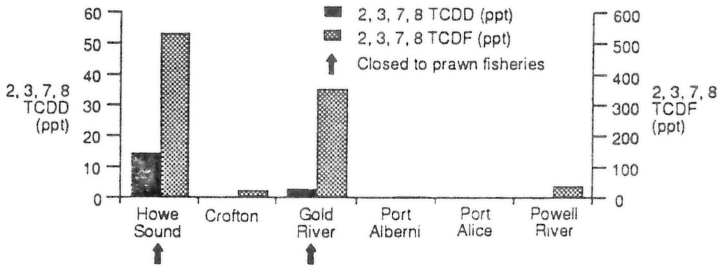

Figure 13. Maximum levels of 2,3,7,8-TCDD and 2,3,7,8-TCDF in B.C. prawn.

LEVELS OF POLYCHLORINATED DIBENZO-P-DIOXINS AND POLYCHLORINATED DIBENZOFURANS IN WATERBIRDS OF HOWE SOUND, BRITISH COLUMBIA

by

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ABSTRACT

In 1988 - 1990, eggs from Double-crested Cormorants (*Phalacrocorax auritus*) and livers and breast muscles of six species of diving ducks were collected from Howe Sound, B.C., as part of a Canadian Wildlife Service program to monitor contaminants in coastal habitats. The major PCDD and PCDF congeners identified in the cormorant eggs were 1,2,3,6,7,8-HxCDD > 1,2,3,7,8-PnCDD > 2,3,7,8-TCDD > 2,3,4,7,8-PnCDF, with the exception of 1989 when 2,3,7,8-TCDD > 1,2,3,7,8-PnCDD. Residue levels declined by more than 50% between 1988 and 1989; 1990 residues were relatively unchanged from 1989 levels. PCB contamination of cormorant eggs was significantly lower in 1990 than in 1988.

The levels of PCDDs and PCDFs in diving ducks varied considerably among species and between liver and muscle of the same species. 2,3,7,8-TCDF was the only contaminant found in all samples analyzed. Fish-eating species were the most contaminated and, for a given species, the liver contained higher concentrations of dioxins and furans than did the breast muscle. A health advisory regarding the consumption of livers from Western Grebes (*Aechmophorus occidentalis*) and Common Mergansers (*Mergus mergus*) from Howe Sound has been issued by Health and Welfare Canada.

INTRODUCTION

Since 1977, the Canadian Wildlife Service (CWS) has used the eggs of waterbirds to monitor the levels of environmental contaminants in the Strait of Georgia, British Columbia. High levels of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) have been found in the eggs of Great Blue Herons (*Ardea herodias*) from some colonies in the Strait (Elliott et al., 1989a; Whitehead, 1989). These contaminants are produced during the manufacture of bleached kraft wood pulp (Amendola et al., 1987). Chlorophenol, formerly used by the lumber industry as wood preservative, also contributes to PCDD contamination (Norstrom et al., 1988).

Howe Sound, a fjord contiguous with the Strait of Georgia, contains two bleached kraft mills: one at Port Mellon and another at Woodfibre. Unacceptably high levels of dioxins and furans in shellfish from the Sound led to the closure of the commercial harvest of shrimp, prawns, and crabs in some areas in 1988 (Dwernychuk, 1991). In that year, CWS expanded its monitoring program to include birds nesting and/or feeding in Howe Sound. Eggs from Double-crested Cormorants (*Phalacrocorax auritus*), and livers and breast muscles from six species of diving ducks were used to examine the dioxin and furan contamination of birds that use the marine habitat. Human health concerns also prompted the inclusion of waterfowl in the monitoring scheme as many species of waterfowl are hunted for food.

MATERIALS AND METHODS

SAMPLE COLLECTION

Double-crested Cormorant eggs were collected from the colony on Christie Islet (Fig. 1). Single eggs were collected from seven nests in June 1988, ten nests in July 1989 and seven nests in July 1990. The contents of the eggs were placed in acetone-rinsed jars with foil-lined caps. Samples were frozen and sent to the National Wildlife Research Centre (NWRC) in Hull, Quebec for analysis.

Adults of six species of waterfowl were collected from the locations indicated in Figure 1 in April 1990. The birds were shot on the water and sent to NWRC where the livers and breast muscles were removed and pooled by species and organ.

CHEMICAL ANALYSIS

The Double-crested Cormorant eggs were pooled, on an equal weight basis, for PCCD and PCDF analysis in 1988 and 1989; analysis was performed on individual samples in 1990. Residue levels were determined by gas chromatography/mass spectrometry following the procedure described by Norstrom et al. (1991). Results were accepted when recoveries for (13-C-12)-PCDDs were between 80% and 110%. Analysis of a quality control sample, a pool of 117 naturally-contaminated herring gull eggs collected from Hamilton Harbour in 1986, was performed along with the samples. There was good agreement with the control results.

PCB levels in the cormorant eggs were determined using a pooled sample in 1989, whereas individual samples were used for analysis in 1988 and 1990. Residue levels were determined according to the method described by Peakall et al. (1986). In 1989 and 1990, the sum of PCB congeners was calculated. In 1988, Aroclors 1254:1260 (1:1) was calculated. This value can be converted to the sum of PCB congeners by multiplying by 0.385 (see Turle et al., 1991 for procedure). The conversion factor used is applicable only to PCB levels in Double-crested Cormorants from British Columbia.

PCDD and PCDF levels in waterfowl liver and muscle were determined by Zenon Environmental Inc. Samples were ground with sodium sulfate, extracted with methanol:dichloromethane (1:2) and the lipids were removed by gel-permeation chromatography. Residual interfering organic material was separated using acid silica gel/alumina column chromatography and carbon column chromatography with reverse toluene elution. PCDDs and PCDFs were quantified using gas chromatography/mass spectrometry. Data quality was assured by NWRC.

RESULTS

The relative levels of the main PCDD congeners identified in Double-crested Cormorant eggs were the same in all three years of the study: 1,2,3,6,7,8-HxCDD > 1,2,3,7,8-PnCDD > 2,3,7,8-TCDD > 1,2,3,7,8,9-HxCDD, with the exception that in 1989 2,3,7,8-TCDD > 1,2,3,7,8-PnCDD (Table 1). All eggs or egg pools had detectable levels of these PCDD congeners. Residue levels of the above compounds decreased by more than 50% between 1988 and 1989, but increased slightly or remained almost unchanged between 1989 and 1990. In contrast, 1,2,3,4,6,7,8-HpCDD and OCDD were found at very low levels in 1988 and 1990, but were slightly higher in 1989.

The only PCDF consistently present in all eggs and pools was 2,3,4,7,8-PnCDF. Residues of 2,3,4,7,8-PnCDF were higher than those of 2,3,7,8-TCDF in the three years examined. The pattern of PCDF contamination was similar to that of the main PCDDs: levels fell between 1988 and 1989, but increased or remained relatively constant between 1989 and 1990.

PCB residues in Double-crested Cormorant eggs declined by 21% between 1988 and 1989 and by 43% between 1989 and 1990. The decline between 1988 and 1990 was significant (t-test performed on log-transformed data; $t = -5.34$, $df = 12$, $P < 0.01$).

The only PCDD or PCDF congener present in all waterfowl species and tissues examined was 2,3,7,8-TCDF (Table 2). In addition, the levels of 2,3,7,8-TCDF were higher than those of the other contaminants in all samples analyzed. The highest dioxin and furan levels were found in Western Grebes (Aechmophorus occidentalis) and Common Mergansers (Mergus mergus). The breast muscles of the Common Goldeneye (Bucephala clangula) and Harlequin (Histrionicus histrionicus) were the least contaminated: 2,3,7,8-TCDF was the only contaminant detected. In those species for which both breast muscle and liver were analysed, PCDDs and PCDFs were higher in the livers.

DISCUSSION

The results presented here indicate a decrease in the PCDD, PCDF and PCB contamination of Double-crested Cormorant eggs from Howe Sound between 1988 and 1990. PCDDs and PCDFs exhibited a large decrease between 1988 and 1989 and PCBs were significantly lower in 1990 than in 1988.

The PCDD residues in Christie Islet cormorant eggs fall within the range found in previous studies of contaminants in Great Blue Heron eggs collected from various sites around the Strait of Georgia (Elliott et al., 1989a; Bellward et al., 1990); both species are primarily piscivorous. The cormorant eggs contained lower residues than those found in heron eggs from the Crofton colony, which is next to a bleached kraft pulp and paper mill. The cormorant eggs were more contaminated, however, than heron eggs from a colony at UBC; birds from the UBC colony forage in the lower Fraser River, an industrial urban area that receives wastes from pulp and paper mills as well as wood treatment plants along the Fraser River.

The high relative abundance of the 1,2,3,7,8-PnCDD and 1,2,3,6,7,8-HxCDD congeners in cormorant eggs from Howe Sound is similar to the pattern reported for heron eggs from the Strait of Georgia (Elliott et al., 1989a; Bellward et al., 1990). The levels of 1,2,3,7,8-PnCDD and 1,2,3,6,7,8-HxCDD found in eggs from the B.C. marine ecosystem are higher than residues reported for other fish-eating birds in Canada (Norstrom and Simon, 1983; Stalling et al., 1986) and suggest that the source is related to chlorophenols (Norstrom et al., 1988). Tetrachlorophenols and pentachlorophenols were used as wood preservatives by the forest products industry in B.C. The practice of stacking treated lumber uncovered resulted in chlorophenols in the stormwater runoff from mills (Krahn et al., 1987). In addition, chlorophenol-contaminated wood chips were used in pulp mills. It is probable that the high PnCDD/HxCDD in the Strait of Georgia biota is a result of the use of contaminated wood chips (Norstrom et al., 1988). Grey Herons (Ardea cinerea) in the Netherlands had similar patterns of contamination by these PCDD congeners; chlorophenols have been suggested as the source of the residues for these birds (Van den Berg et al., 1987).

2,3,7,8-TCDD and 2,3,7,8-TCDF are produced during the chlorine bleaching process at kraft pulp and paper mills (Amendola et al., 1987). The level of these compounds in Double-crested Cormorant eggs from Christie Islet in 1988 was below that reported for Great Blue Heron eggs from Crofton and UBC in the same year (Bellward et al., 1990). 2,3,4,7,8-PnCDF is found, along with 2,3,7,8-TCDF, in commercial PCB mixtures (Van den Berg et al., 1985). Results from analyses of Great Blue Heron eggs from the Strait of Georgia and Grey Heron and cormorant eggs from the Netherlands suggest that PCBs are the most important source of 2,3,4,7,8-PnCDD contamination in these areas (Van den Berg et al., 1987; Elliott et al., 1989a). The level of 2,3,4,7,8-PnCDF in cormorant eggs from Howe Sound in 1988 was higher than those reported for herons in any of the Strait of Georgia colonies. Similarly, in 1988 PCB residues were higher in the cormorant eggs than in heron eggs. The reason for the elevated levels of PCBs in Howe Sound in 1988 is unknown.

The patterns of PCDD and PCDF contamination found in waterfowl species collected from Howe Sound differ from those found in Double-crested Cormorant eggs. The main congeners identified were 2,3,7,8-TCDF and 2,3,7,8-TCDD. This suggests that the primary source of the contaminants is the chlorine bleaching process at kraft pulp mills. Western Grebes contained elevated levels of highly substituted PCDDs, indicating a chlorophenol source as well.

The highest residues were found in the two fish-eating species: Western Grebes and Common Mergansers. The other four species are primarily benthivores and contained very low levels of most congeners with the exception of 2,3,7,8-TCDF. The levels of 2,3,7,8-TCDD in the Western Grebe and Common Merganser livers were within the range found in Double-crested Cormorant eggs from the same region. The waterfowl contained much higher levels of 2,3,7,8-TCDF, however, than did the cormorant eggs. The apparent species difference in TCDF values may have a pharmacodynamic basis as residues were measured in the eggs of the cormorants, but in the liver and breast muscle of the waterfowl.

High levels of PCDDs and PCDFs in several species of waterfowl from the Somass River estuary near Port Alberni in 1989 led Health and Welfare Canada to issue a health advisory concerning the consumption of livers from Common Mergansers and Surf Scoters (Melanitta perspicillata). Based on the results presented here, a similar health advisory was issued in 1990 for Common Mergansers and Western Grebes from Howe Sound. Residues of most PCDDs in Common Mergansers from Howe Sound were similar to those from the same species in the Somass River estuary; 2,3,7,8-TCDF levels, however, were about 50% higher in the Howe Sound birds (Whitehead et al., 1990). In contrast, Western Grebes and Surf Scoters from Howe Sound were generally less contaminated than their Somass estuary counterparts.

Avian contamination by PCDDs, PCDFs, and PCBs may produce toxic effects including edema, weight loss, hepatotoxicity, and decreased reproductive success (Flick et al., 1972; Poland and Knutson, 1982; Safe, 1984; Brunstrom and Reutergardh, 1986). Species sensitivity to these compounds varies widely. Verrett (1970) reported edema, teratogenic effects and embryonic mortality in chicken eggs injected with 10 ng/kg TCDD. In contrast, no effects on Great Blue Heron productivity were noted at the Crofton colony in 1986 (mean egg level of 66 ng/kg 2,3,7,8-TCDD) (Elliott et al., 1989a) and hatching success of lab-reared heron eggs from the Crofton colony in 1988 was similar to that of eggs from an uncontaminated site (Hart et al., 1990). Elliott et al. (1989a) concluded that Great Blue Herons are less sensitive to the embryotoxic action of PCDDs and PCDFs than are chickens.

Toxic effects of PCDDs, PCDFs, and PCBs on waterbirds have been reported. Hart et al. (1990) found that heron chick body growth was inversely related to TCDD levels in eggs. The same study reported that the incidence of subcutaneous edema in heron chicks increased with the level of PCDD and PCDF contamination. Bellward et al. (1990) found a significant correlation between 2,3,7,8-TCDD levels in Great Blue Heron eggs and hepatic microsomal monooxygenase activity in newly hatched chicks. These effects have also been noted in chickens (Flick et al., 1972; Sawyer et al., 1986).

PCB contamination may also cause embryotoxic effects in waterbirds. In the field, PCB levels (mean egg residue of 4.1 mg/kg) were negatively correlated with embryonic weight in Black-crowned Night Herons (Nycticorax nycticorax) from San Francisco Bay (Laporte, 1982).

The data presented here indicate that PCDD, PCDF and PCB levels are declining in Howe Sound. This is the first evidence of a decline in dioxin and furan contamination in the B.C. coastal environment. Unfortunately, cormorant eggs were not collected in Howe Sound prior to 1988. PCB levels have declined in the Strait of Georgia since the mid-1970's. A significant decline in the levels of PCBs in Great Blue Heron eggs from the UBC colony between 1977 and 1987 was reported by Whitehead (1989). PCBs decreased significantly in Double-crested Cormorant eggs (1973 to 1990) and in Pelagic Cormorant eggs (Phalacrocorax pelagicus) (1973 to 1984) collected from Mandarte Island in the Strait (Elliott et al., 1989b; Elliott et al., in press). These data show the usefulness of fish-eating birds as indicators of ecosystem contamination.

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Table 1. PCDD, PCDF and PCB levels in Double-crested Cormorant eggs from Howe Sound, British Columbia, 1988-1990. For analyses performed on individual samples, results are arithmetic means ± SD (range in brackets).

	Residue Level[a]		
Year N[b]	1988 7	1989 10	1990 7
2,3,7,8-TCDD	68	30	38.7 ± 16.5 (30 - 65)
1,2,3,7,8-PnCDD	101	23	42.0 ± 10.6 (30 - 57)
1,2,3,6,7,8-HxCDD	237	36	69.1 ± 28.5 (40 - 114)
1,2,3,7,8,9-HxCDD	23	10	2.7 ± 1.3 (4[c] - 5)
1,2,3,4,6,7,8-HpCDD	5[c]	12	8[c]
OCDD	10[c]	14	10[c]
2,3,7,8-TCDF	4	2[c]	3.6 ± 3.5 (2[c] - 10)
2,3,4,7,8-PnCDF	51	12	12.4 ± 3.5 (8 - 19)
Total PCBs	2.229 ± 1.260 (0.737 - 3.702)	1.764	1.005 ± 0.425 (0.508 - 1.622)
% H_2O	83.5	84.0	84.33 ± 1.22
% Lipid	4.5	5	3.69 ± 1.02

[a] PCDD and PCDF levels reported in ng/kg, wet weight; PCB levels reported in mg/kg, wet weight

[b] No. of eggs in pooled sample or no. of individual samples

[c] Minimum detectable level

Table 2. PCDD and PCDF levels (ng/kg, wet weight) in waterfowl from Howe Sound, B.C., 1990.

Species	Tissue	PCDDs				PCDFs				No.
		2378-	12378-	123678-		2378-	Total	%	%	in
		TCDD	PnCDD	HxCDD	OCDD	TCDF	PnCDF	H_2O	Fat	Pool
Western Grebe	Liver	46.0	29.0	77.0	<11	109.0	43.5	71.6	4.0	10
(*Aechmophorus occidentalis*)										
Common Merganser	BM[a]	21.0	7.3	7.8	1.4	116.5	10.8	68.6	3.4	9
(*Mergus mergus*)	Liver	37.0	20.0	19.0	<4.1	163.0	19.1	69.0	5.1	9
Surf Scoter	BM	2.2	<2.4	<3.8	<14	31.0	<1.5	71.6	2.8	11
(*Melanitta perspicillata*)	Liver	8.7	<1.7	4.3	<12	34.0	<1.6	70.8	3.1	11
Harlequin	Liver	<2	<1	<2.5	<8	36.0	<1	69.4	4.7	3
(*Histrionicus histrionicus*)										
Oldsquaw	Liver	9.2	<1.7	14.0	3.2	9.6	6.8	66.9	4.1	3
(*Clangula hyemalis*)										
Common Goldeneye	BM	<1.4	<0.6	<1.7	<5.5	30.0	<0.7	67.7	3.4	12
(*Bucephala clangula*)	Liver	7.1	<2.4	<4.1	<16	66.0	4.5	71.6	3.6	12

[a] Breast Muscle

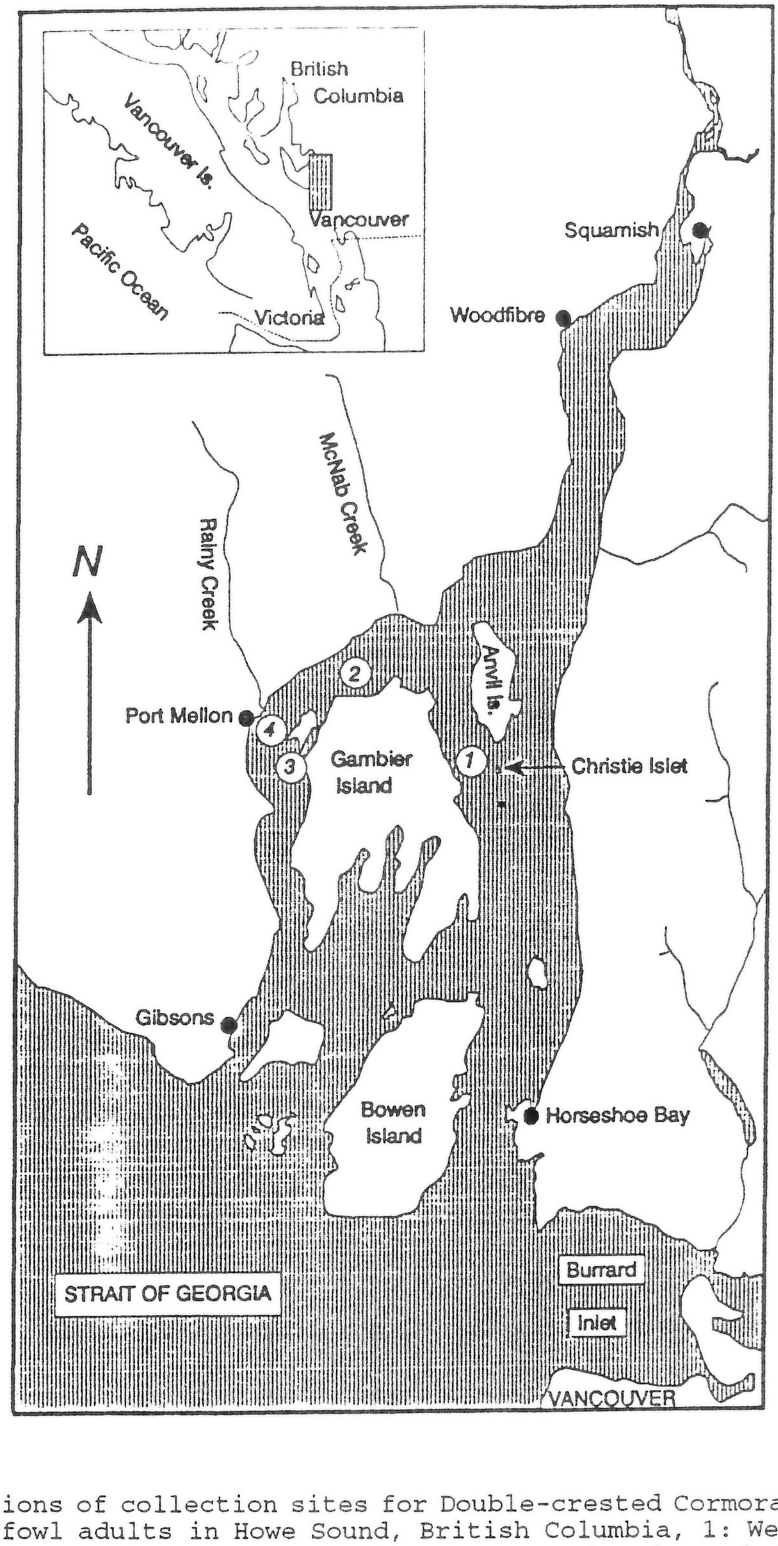

Figure 1. Locations of collection sites for Double-crested Cormorant eggs and waterfowl adults in Howe Sound, British Columbia, 1: Western Grebe; 2: Common Merganser; 3: Surf Scoter, Harlequin and Oldsquaw; 4: Common Goldeneye.

PREVALENCE OF IDIOPATHIC GILL AND LIVER LESIONS IN ENGLISH AND FLATHEAD SOLE COLLECTED NEAR PULP MILLS OF HOWE SOUND

by

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ABSTRACT

Sublethal toxicity tests make it possible to detect incipient effects on fish and aid in the estimation of threshold concentrations for various pollutants. Histopathology is an effective approach for documenting exposure to and evaluating the effects of pollutant stress. Our research is concerned with the examination of the impact of two pulp mills, Woodfibre and Port Mellon, on two marine species of flatfish, Parophrys vetulus and Hippoglossoides elassodon. Results revealed a 30% prevalence of idiopathic liver lesions in flatfish and the presence of fused gill secondary lamellae due to hyperplasia, as well as stunted and split lamellae. This approach provides an early warning bioindicator and insight into causal relationships between stressors and effects resulting from a complexly contaminated marine environment.

INTRODUCTION

Marine environments near industrial and urban centres are exposed to a wide range of chemicals that may be transformed, either biologically or chemically, into new, potentially toxic compounds (Malins and Hodgins, 1981). Chemical analysis and acute toxicity responses are insufficient to assess the long-term impacts of various pollutants on aquatic ecosystems. In this context, sublethal toxicity tests may make it possible to detect incipient effects on fish and shellfish and to estimate threshold concentrations. There is a positive link between certain xenobiotic chemicals present in sediments, seawater, or food organisms, and histopathological conditions in demersal fish species (Myers, et al., 1987). In particular, high tumor incidences have been identified in the livers of wild fish from areas receiving industrial effluents (Brand, 1990; Malins et al., 1988; McCain et al., 1982; Mix, 1986; Myers et al., 1987). Fish with liver lesions exhibit the effects of long-term exposure to a broad range of pollutants. Hence, liver of wild fish has been chosen as the primary target organ in monitoring the effects of xenobiotic chemical toxicants and carcinogens.

Fish gills appear to be more susceptible than other tissues to these irritants, both chemically and physically, due to their external location and constant contact with water. Gill lesions are seldom present in the absence of other systemic changes. For example, in "nutritional gill disease" liver damage usually takes the form of degeneration and regeneration of liver parenchyma and cytopathological changes. Thus, gill damage correlated with other systemic changes often identifies the causative agent or agents producing gill lesions (Eller, 1975).

To date there is no information on the occurrence of histological disorders in fish collected near pulp mills located along the British Columbia coastline. The objective of this study is to ascertain whether any histopathological relationship exists. With this established association between certain histological conditions in fish and their exposure to xenobiotic chemicals, monitoring for neoplasia and related cell disorders has merit (Goyette et al., 1988). The study was conducted to screen the receiving environment at two pulp mill locations, Woodfibre and Port Mellon, and at one reference site, Satellite Channel. In this report, types and frequencies of histopathologic conditions in English sole (Parophrys vetulus) and flathead sole (Hippoglossoides elassodon), with emphasis on idiopathic liver lesions and gill abnormalities, are described.

MATERIALS AND METHODS

English sole, Parophrys vetulus, and flathead sole, Hippoglossoides elassodon, were collected from Woodfibre and Port Mellon, Howe Sound, B.C. in April and December 1990 and from the reference site, Satellite Channel, in July 1990 and March 1991. All collections were carried out aboard the survey vessel C.S.S. *Vector* using an otter trawl with a 3.8 cm mesh net and a 5.8 m throat.

Trawls were towed with a 3:1 scope (wire length vs. depth) at a speed of approximately 1.5 knots, over an average distance of 0.5 nautical miles as determined by radar bearings. Livers and gills were excised and fixed in buffered formalin or Deitrich's fixative and then shipped to the University of Victoria for histopathological analysis. Gill tissue was also fixed in glutaraldehyde for scanning EM analysis.

Formalin fixed tissues were washed in water, dehydrated, cleared, and embedded in paraffin. Skip serial sections were cut at 7 µm. Sections were stained with Delafield's haematoxylin and eosin (Humason, 1979) for general histology. Liver tissue was also stained with PAS for glycoproteins and mucopolysaccharides (Humason, 1979) and Perls' method (Prussian blue) for ferric iron (Pearce, 1972). Gill tissue was stained with phloroglucinol (Clark, 1981) for cellulose and Grams iodine (Humason, 1979) for bacteria. Liver abnormalities were classified using nomenclature consistent with Myers et al. (1987) and Mallatt (1985) for gill structural changes.

Gills fixed in 2.5% glutaraldehyde (0.1 M phosphate buffer, 3.5% sucrose, pH 7.4) were post-fixed in 1% osmium tetroxide before dehydration in alcohols. Specimens were critical-point dried, gold sputter-coated, and analyzed on a JEOL 200 scanning electron microscope.

Age determination of specimens was completed by otolith analysis (using break and burn methods recommended by Chilton and Beamish, 1982).

RESULTS AND DISCUSSION

Through otolith analysis, average age ranged from 6-8 years between the sites and the species collected.

LIVER HISTOLOGY

Sole with normal liver tissue were found at all sampling sites (Fig. 1). Normal liver is composed of hepatocytes with a muralial tubulosinusoidal (1 to 2 cell layers) architecture, often irregularly arrayed about the central veins. Bile ducts, pancreatic acini, and melano-macrophage centres are found scattered irregularly throughout the parenchyma. The hepatocytes are often vacuolated due to the presence of glycogen and lipid and generally are eosinophilic or basophilic depending on the spawning and nutritional status of the fish (Myers et al., 1987).

Two types of idiopathic lesions are observed in the fish collected from the vicinity of pulp mills. These lesions are: a) foci of cellular alteration; clear cell, eosinophilic and basophilic foci (Figs. 2, 3 and 4) and b) the neoplasm, liver cell adenoma; clear cell type; and eosinophilic type (Figs. 5 and 6).

Foci of cellular alteration are arranged in discrete micronodular centres with borders blending indistinctly into the surrounding muralia and minimal or no compression of adjacent parenchyma. Foci rarely contain other hepatic elements (i.e., bile, duct, pancreatic acini, or melano-macrophages). The muralial architecture within the foci is generally normal. Clear cell foci contain vacuolated hepatocytes due to either lipid accumulation or glycogen storage (Fig. 2). These types of lesions are rarely found close to other types of idiopathic lesions (Myers et al., 1987) and were present in 16.6% of the fish collected from Woodfibre. Eosinophilic foci, present in 13.3% of the fish from Woodfibre and 10% from Port Mellon, showed a slight to dramatic hepatocellular hypertrophy, increased cytoplasmic eosinophilia with a granular texture, and varying degrees of pleomorphism of the nuclei (Fig. 3). Eosinophilic foci are occasionally found proximate to basophilic foci (Myers et al., 1987). Basophilic foci characteristically possess hyperbasophilic cytoplasm in normal-sized hepatocytes with pleomorphic nuclei (Fig. 4). They were found in 23.3% of the fish from Woodfibre and 30% of the fish from Port Mellon. This lesion has been shown to be a precursor in the pathogenesis of liver neoplasms in rodents; however, this relationship remains to be confirmed (Myers et al., 1987). Through co-occurrence analysis, Myers et al. (1987) hypothesized that clear cell and eosinophilic foci are putatively preneoplastic lesions and basophilic foci are presumptively preneoplastic lesions which may immediately precede the development of the neoplasms, liver cell adenomas, and hepatocellular carcinomas.

The neoplasm, liver cell adenoma (Figs. 5 and 6), was observed in 10% of the fish from both Woodfibre and Port Mellon, plus a single fish collected from the reference site, Satellite Channel (5%). The adenomas exhibit compression of surrounding tissue, well-defined separation of proliferative tissue from normal tissue, increased cellular density, normal muralial architecture, and the absence of other hepatic elements (bile ducts, pancreatic acini, and melano-macrophage). Cytologically, there is an increase in the nuclear:cytoplasm ratio and the tinctorial quality was either clear cell or eosinophilic type.

The intracytoplasmic storage disorder, hepatocellular hemosiderosis (Figs. 7 and 8), is a condition suggestive of an underlying metabolic disorder characterized by excessive accumulation of intracytoplasmic iron within the hepatocytes (Myers et al., 1987). This condition was identified histochemically by the Prussian blue reaction for iron. It was found in all of the sole collected from the vicinity of pulp mills, but absent in the fish from the reference area. Myers et al. (1987) noted a weak association of hemosiderosis with the preneoplastic lesions, eosinophilic foci, and basophilic foci; however, to date this disorder has not been experimentally induced in fish by hepatocarcinogens-hepatotoxins. It was therefore decided in this report not to include hemosiderosis as an idiopathic lesion.

The incidence of idiopathic liver lesions is strongly dependent on location of capture ($0.01 < P(X^2\ 0.05,2 > 6.89) < 0.025$). Both trawl stations, Woodfibre and Port Mellon gave the highest prevalence of both preneoplastic and neoplastic liver lesions with 30% of the fish affected. Fish collected from Satellite Channel had a prevalence of 5% with idiopathic liver lesions. Only preneoplastic (foci of cellular alteration) and neoplastic (liver cell adenomas) lesions were considered in calculating these frequencies. Other idiopathic liver lesions were omitted due to the uncertainty in their relationship to exposure to xenobiotic, carcinogenic chemicals.

The positive correlation that exists between idiopathic liver lesions and sampling site may partly be due to the strong homing instincts present in sole. Tagging studies conducted in Puget Sound by Day (1976) showed that English sole, after being displaced (maximum distance 20 km), rapidly returned to the area of capture. Those that migrated out of the area during the fall and winter spawning period to deeper waters also returned to their home territory. The pronounced homing of the displaced fish suggests that resident English sole may be territorial and the population stratification extends down to the level of the individual territory (Day, 1976).

Studies of wild fish populations from polluted environments have shown a high prevalence of hepatic lesions (Harshbarger and Clark, 1990). For instance, a number of areas in Puget Sound (e.g., Eagle Harbour and Duwamish Waterway) (Malins et al., 1984 and 1988) and Vancouver Harbour (Brand and Goyette, 1989; Brand, 1990) have shown a positive correlation between sediment-associated polycyclic aromatic hydrocarbons (PAHs) with prevalences of several categories of idiopathic liver lesions in English sole. Fish from Woodfibre and Port Mellon pulp mill areas may be exposed to a wide range of chemical contaminants including compounds with hepatotoxic and hepatocarcinogenic properties, due to either mill effluents, creosote pilings, or woodchip preservatives.

GILL HISTOLOGY

Gill histology was not examined from the Woodfibre site; however, unpublished data from the Crofton mill (east coast of Vancouver Island) was used for comparative purposes. All fish, including the control, possessed normal gill secondary lamellae (Fig. 9) as well as damaged lamellae. All fish exhibited some degree of vascular constriction and congestion, and epithelial lifting similar to those illustrated by Mallatt (1985). In addition, all sites displayed examples of moderate to heavy external parasitic flatworm and Trichodina sp. infections, encysted copepods, and Rickettsiales. However, fish examined from pulp mill areas had a higher prevalence of mucus cell proliferation (Fig. 10), non-focal hyperplasia (Fig. 11) and fusion of secondary lamellae (Fig. 12). Mallatt's (1985) review of fish gill histology lists five lesion classes that are preferentially associated with chronic, long-term, sublethal studies. These included hyperplasia and mucus cell proliferation. Stunting of secondary lamellae (Fig. 13), and splitting of primary (Fig. 14) and secondary lamellae were found only in fish from the vicinity of pulp mills (60% of the Port Mellon sample showed these deformities).

Hyperplasia of the lamellae is a condition that is conducive to excess mucus production (Khan, 1990); when it occurs as discrete pockets it is likely associated with some physical agent, whereas chemical damage generally takes on a more diffuse appearance (J. Bagshaw, Pacific Biological Station, Nanaimo, B.C., pers. comm., 1991). The characteristic non-focal nature of the hyperplasia (non-focal refers to observations of one or more completely hyperplastic primary branches/tissue section) from mill site fish may suggest the agents of stress are more chemical than physical. In addition, the absence of physical artifacts was further confirmed by gram staining suspect regions of gill tissue for the presence of bacterial populations and by phloroglucinol staining for cellulose or wood debris; in all cases tested, the results were consistently negative. Epithelial lifting and fusion of secondary lamellae (Haensly et al., 1982; Solangi and Overstreet, 1982; Khan and Kiceniuk, 1988; Grizzle, 1986) and stress responses such as gill ectoparasites, in particular monogeneids (Khan and Kiceniuk, 1988; Khan, 1990) have been linked to a broad spectrum of environmental xenobiotics. Excluding parasitic infection, these abnormalities generally act to slow entry of toxicants, but at the same time reduce the surface area of effective gill tissue, ultimately to the point of suffocation (Mallatt, 1985).

The reference site in Satellite Channel is exposed to other forms of marine pollution - in particular, heavy recreational and industrial boat traffic and municipal output. Given the frequency of conditions like clavate lamellae (a third characteristic sub-lethal, long-term lesion) at this site, these traits can only be indicative of general stress responses. The nonspecificity of branchial alterations suggests that they primarily represent general physiological reactions of gills to stress, and many of them are logically considered defense responses (Mallatt, 1985). In addition, fish gill tissue has extensive regenerative capacities, and many alterations, especially focal lesions, may be short-term if contaminant exposure is not continuous (J. Bagshaw, Pacific Biological Station, Nanaimo, B.C., pers. comm., 1991).

The manner in which gill changes occur is often an accurate indicator of the causative agent, for example, bacteria, diet, or chemical. However, various agents may produce gill lesions simultaneously. Extensive damage from a specific agent may overshadow or mask gill injury produced by a second or third agent. Gill alterations such as hyperplasia and hypertrophy of gill epithelium represent basic physiological problems. Such changes occur singly, or in combination, in fish diseases or toxicosis and are often directly related to disorders in gill functions which, with long-term exposure, may affect physiological parameters (e.g., reproduction).

One lesion not mentioned in the aforementioned literature, but frequent at all sites (25% at Port Mellon, 40% at Crofton, and 50% at Satellite Channel) were cartilaginous nodules (Figs. 15 and 16) (R. Spies, Applied Marine Sciences, Livermore, CA, and D. Hinton, University of California, Davis, CA, pers. comm. 1991.) or otherwise termed ectopic ovulation (Munday and Brand, 1992). Munday observed these lesions in bearded cod 2 km away from a pulp mill site, and determined that they enclosed displaced ova in the primary filament of the gill. He had no explanation for the cause of such an extreme physiological abnormality, but did confirm by viewing stained slides of Port Mellon English sole that these lesions were identical to those found in the cod. Spies et. al., (unpublished data) observed this lesion in surfperch exposed to a petroleum seep. This group also observed splitting lamellae similar to those seen in this study. The presence of these more severe, potentially more permanent tissue deformations like stunting and splitting of secondary lamellae may be a more specific indicator of chemical, pulp mill-linked stressors. The possible mutagenic properties of this type of damage needs further study.

CONCLUSIONS

Although many of the English and flathead sole liver and gill samples showed no gross visual signs of abnormalities, histological examination revealed a significant number of idiopathic lesions. The observed different types of idiopathic lesions are to be expected in fish that are continuously exposed to various hepatocarcinogens and hepatotoxins in marine sediments (Myers et al., 1987). It is predicted that in ten years time the concentration of present anthropogenic xenobiotics could be diluted to 50% due to the characteristic sedimentation rate of Howe Sound (W. Cretney, Institute of Ocean Sciences, Sidney, B.C. pers. comm., 1991). Taking this into consideration, plus the improvements made by the mills in waste output, it would be interesting to repeat this histopathological study in ten years to see if the frequency of idiopathic lesions has also decreased by 50%.

ACKNOWLEDGEMENTS

The following people require special mention for their valuable assistance in making this study possible. Darcy Goyette from Environment Canada for generating my interest in fish neoplasia research. Jeff Thompson from the Institute of Ocean Sciences for allowing us to share his ship time. Captain R. MacKenzie, the officers and crew of the survey vessel, C.S.S. *Vector*, for their cooperation during the field surveys. H.F. Deitrich and T. Gore of the University of Victoria for the histological and photographic equipment. Karen Leask for assistance with histological sectioning. The research was supported by grants from the World Wildlife Toxicology Fund and the Department of Fisheries and Oceans Subvention Grant.

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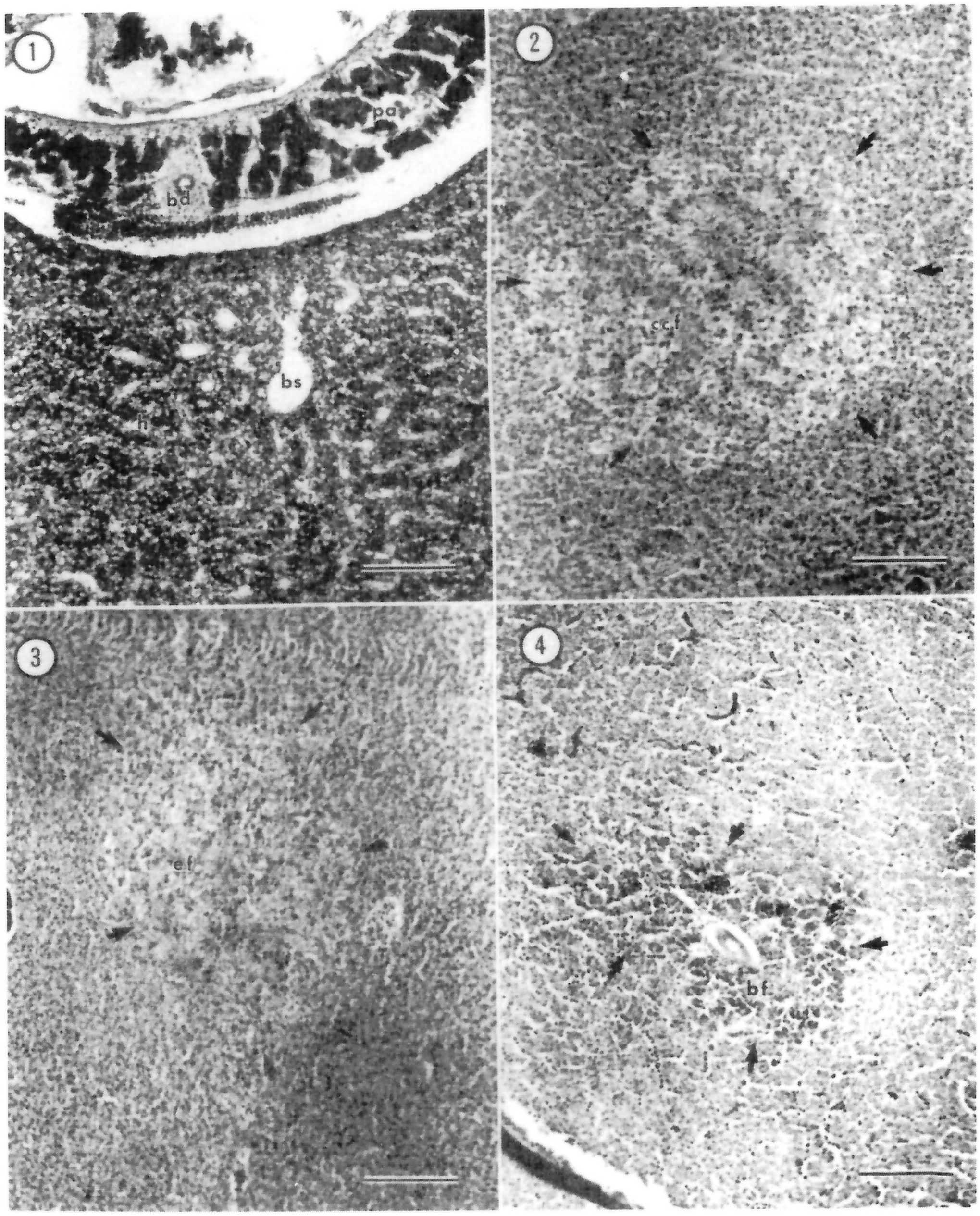
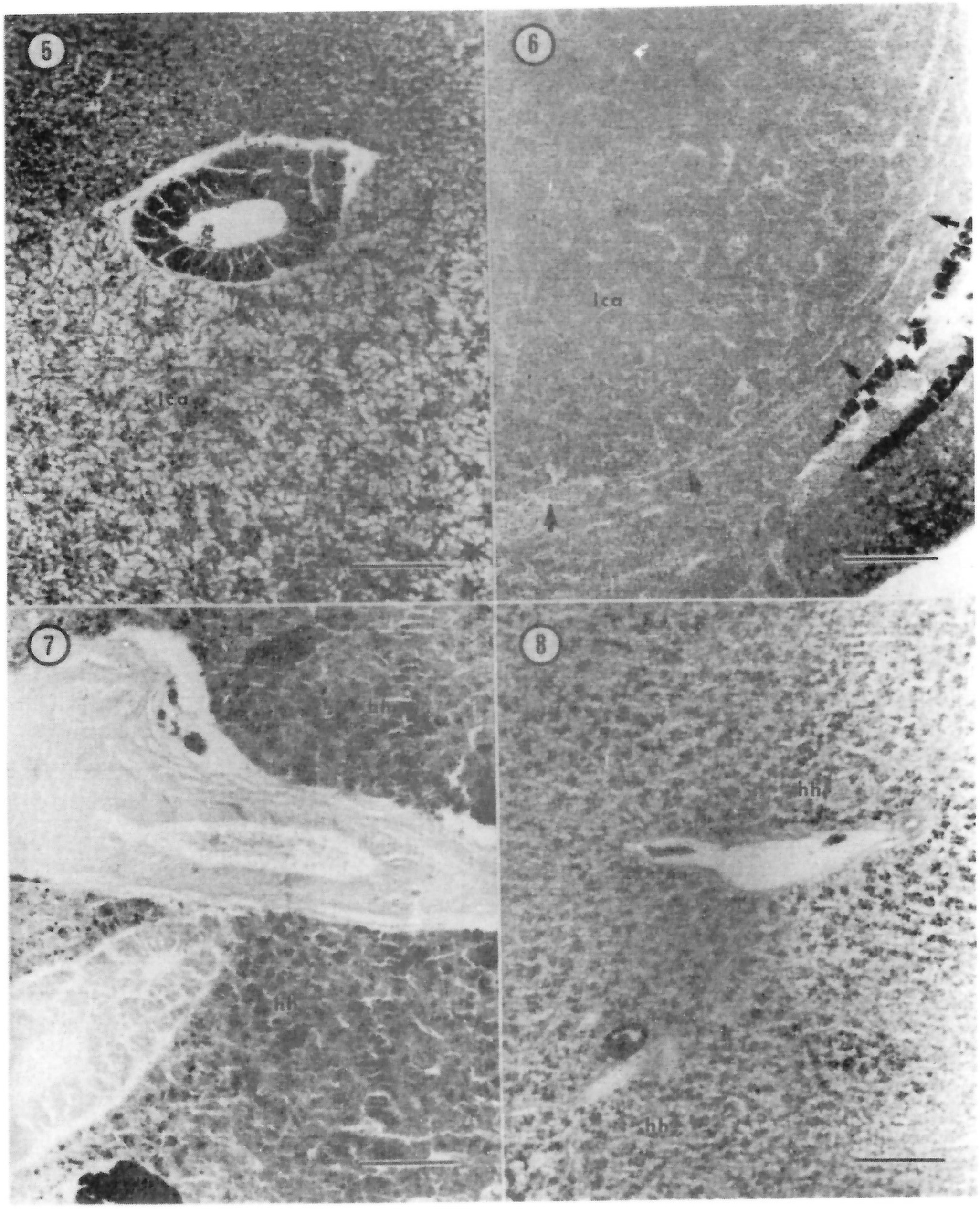


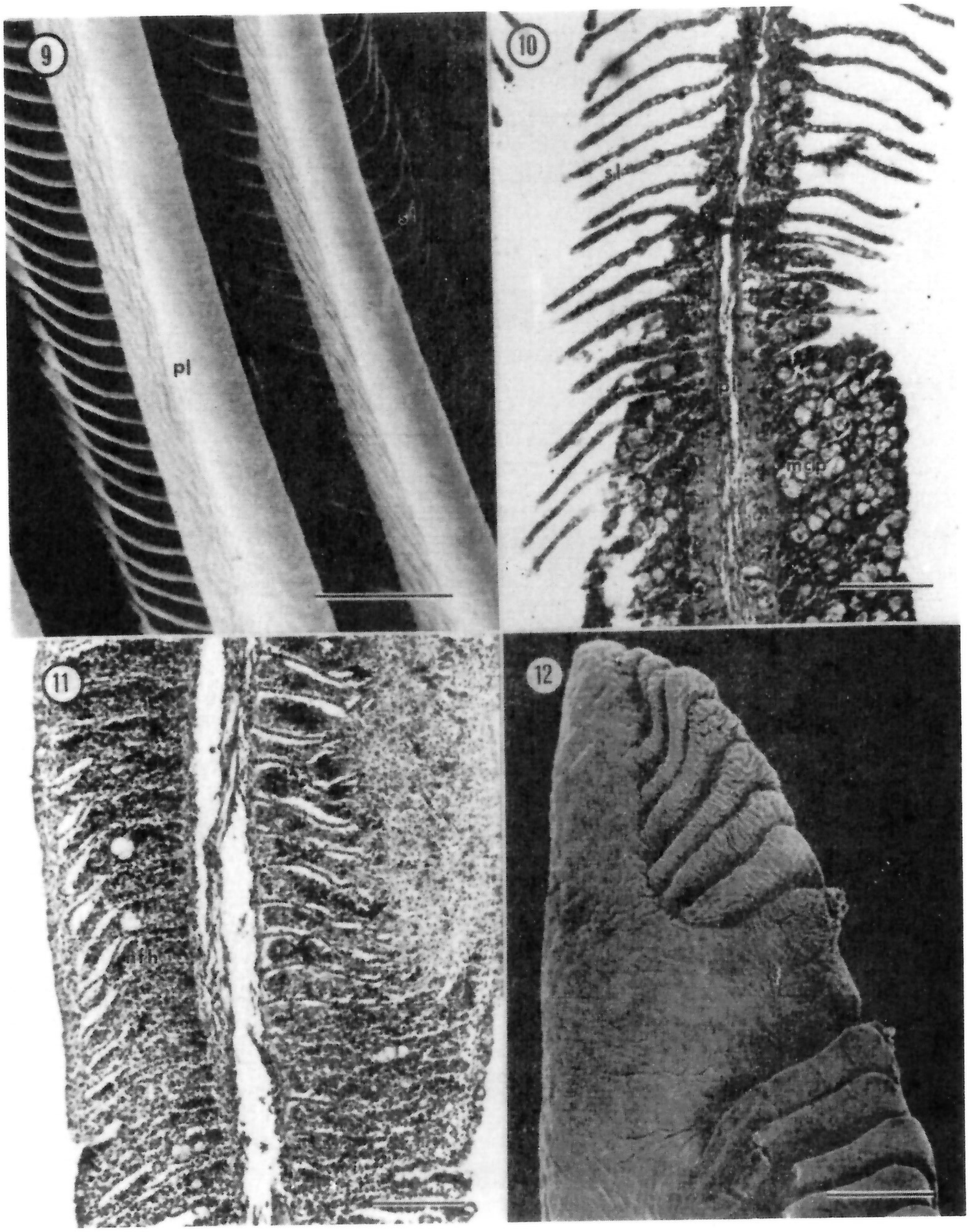
Figures 1-4. Haemotoxylin/eosin stained liver tissue from Flathead sole (Hippoglossoides elassodon).

1. Normal liver, showing hepatocytes (h), bile duct(bd), blood sinus (bs), and pancreatic acini (pa).
2. Clear cell foci (ccf), border outlined by arrows.
3. Eosinophilic foci (ef), border outlined by arrows.
4. Basophilic foci (bf), border outlined by arrows. Bar = 100μm



Figures 5-8. Liver tissue from English sole (Parophrys vetulus) and Flathead sole (Hippoglossoides elassodon).

5. Liver cell adenoma (lca) clear cell type, H&E stained, border outlined by arrows.
6. Liver cell adenoma (lca) eosinophilic type, H&E stained, border outlined by arrows.
7. The intracytoplasmic disorder, hepatocellular hemosiderosis (hh) in a Woodfibre Flathead sole, Perls' iron stained.
8. Hemosiderosis (hh) in a Port Mellon Flathead sole, Perls' stained. Bar = 100μm



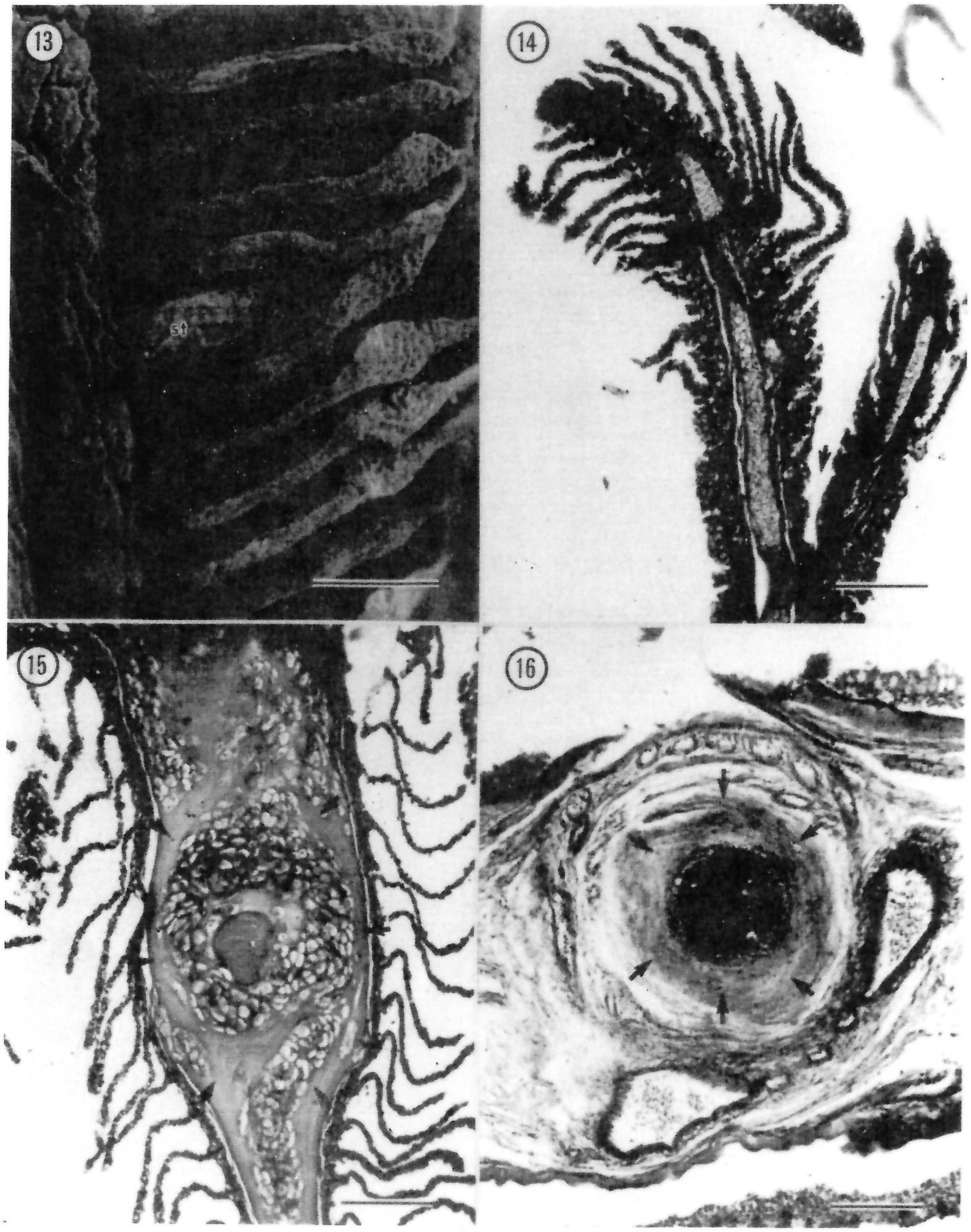
Figures 9-12. Gill tissue from English sole (Parophrys vetulus) and Flathead sole (Hippoglossoides elassodon).

9. Scanning electron micrograph of normal gill, showing primary (pl) and secondary (sl) lamellae. Bar = 100 µm.

10. Mucus cell proliferation (mcp) resulting in fusion of secondary lamallae, H&E stained. Bar = 100 µm.

11. Non-focal hyperplasia (nfh) over a complete primary lamellum, and hypertrophy (arrows), H & E stained. Bar = 100 µm.

12. Scanning electron micrograph showing the fusion (f) of 3-4 secondary lamallae. Bar = 50 µm.



Figures 13-16. Gill tissue from English sole (*Parophrys vetulus*) and Flathead sole (*Hippoglossoides elassodon*).

13. Scanning electron micrograph of a stunted (st) secondary lamella. Bar= 50µm.
14. A split (arrows) in the primary lamella, H&E stained. Bar = 100µm.
15. A cartilaginous nodule or ectopic ovulation (arrows) with its fibrous and cartilaginous covering, H&E stained. Bar = 100µm.
16. A cartilaginous nodule (arrows), closer to the central core of ova, H&E stained. Bar = 100µm.

ABSTRACTS

ASPECTS OF POSTGLACIAL SEDIMENT SUPPLY TO THE SQUAMISH RIVER

by

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Recent work has focused upon two major components of the postglacial sediment supply to the Squamish River: mass movement from Mt. Cayley, and the reworking of glacial deposits.

Mt. Cayley is the largest Quarternary volcano in the central portion of the Garibaldi Volcanic Belt. Stratigraphic work examining debris avalanche and backwater deposits along the bottom of the Squamish Valley reveal a long chronology of debris avalanches and river impoundments attributed to debris avalanches. This chronology began with a massive collapse of the Mt. Cayley volcanic cone ~4,800 years BP which generated the largest of the debris avalanches (~2×10^8 m^3). Subsequent debris avalanches have been smaller (up to ~2×10^7 m^3), but have occurred regularly up to the present day. These debris avalanches and related secondary debris flows form an episodic sediment supply to the Squamish River. The present unstable character of the Mt. Cayley cone suggests that they will continue to supply the river in the future.

Extensive incised valley fill deposits in the five major tributary valleys identify the occurrence of a major sediment transfer into the trunk valley. The valley fill deposits relate to the Fraser Glaciation and consist of ice-contact glaciofluvial, and glacio-lacustrine, deposits. Radiocarbon dating of fluvial terraces excavated into the valley fills indicates that the incision generally ceased thousands of years ago, with the most representative date being ~4,150 years BP from Ashlu Valley. The volume of material involved varies considerably between valleys (6×10^6 to 3.6×10^8 m^3), reflecting local valley morphology and late Quaternary history. The incision of the valley fills is believed to represent the primary source of the reworked component of paraglacial sedimentation.

The reworked and mass-movement components of the sediment supply condition the contemporary morphology of the Squamish River and also control the present position and rate of advance of the Squamish Delta.

GLACIER WATER INPUT INTO HOWE SOUND FROM GARIBALDI LAKE REGION

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The seasonal timing and volume of water input into the Howe Sound region is strongly modulated by the presence of glaciers, some of the largest of which occur in the Garibaldi Lake region. The impact of Sentinel Glacier on the level of Garibaldi Lake and the downstream string of lakes and streams through which the water discharges was studied. Glaciers make a large impact on the amount and timing of runoff generated, water stored enroute in lakes, and water discharged into Howe Sound from the Garibaldi Lake Basin, and because of the related hazard potential of large landslides at Barrier Dam and in the vicinity of Rubble Creek. Generally, the highest lake levels occur during late summer and have been assumed to be due to glacier runoff, although lake levels should be highest near the time of maximum snow melt in late spring to early summer. The issue was examined using a simple surface runoff and lake-water storage model, that was coupled to a model of the local groundwater flow and glacier mass balance behaviour.

Glacier extents have dramatically reduced in the region since the 1920's and have apparently caused a reduction in summertime runoff into the lake. Average glacier water input into Howe Sound was estimated using Sentinel Glacier as an index basin for the other relevant glaciated areas. Future trends of glacier runoff into Howe Sound from the basin were projected for doubling of atmospheric CO_2 and attendant warming; these were compared to effects of possible return to "Little Ice-Age" conditions. Glacier water input is an important component of the water balance in Howe Sound, and may change significantly during the next century.

MASS MOVEMENT AND SEDIMENT YIELD IN THE HOWE SOUND DRAINAGE BASIN: THE SIGNIFICANCE OF INDUSTRIAL DEVELOPMENT

by

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Landslides and debris flows are widespread natural processes in the Howe Sound drainage basin, as in all mountainous regions, and are responsible for much of the sediment entering river systems and the ocean. An important question for resource management is the extent to which industrial development, especially logging, has increased the sediment yield.

The watersheds of the upper Squamish River and several of its tributaries, which are extensively glacierized and include Quaternary volcanic centres, have very high sediment yields. Additional contributions of sediment from industrial activity are likely to be negligible. However, other watersheds have low natural sediment yields, which in some cases may be significantly increased by mass movement and erosion related to logging or other development. The Squamish River dominates sediment inputs to Howe Sound. Increased sediment input from other sources is probably not significant to the sediment budget of the Sound as a whole; however, it may be very important locally for streams or estuaries with valuable aquatic habitat or which are used for water supply.

The Mamquam River does not have extensive natural sediment sources, compared with other parts of the Squamish basin, but logging covers much of its watershed. Numerous landslides and debris flows during heavy rainstorms in 1990 illustrate the importance of logging roads and clearcuts as sediment sources, and show that mass movement may be delayed for several decades following logging. Mashiter Creek displays some evidence of an increase in sediment yield following logging, and a subsequent decrease a few decades later. In Britannia Creek, and possibly Furry Creek, mass movement directly or indirectly related to mining has substantially increased the sediment yield. Mass movement and soil erosion resulting from pipeline construction in 1990 have been significant as sediment sources in several watersheds.

FOREST ECOSYSTEMS IN WATERSHEDS DRAINING INTO HOWE SOUND

by

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The watersheds of the rivers (Cheakamus, Elaho, Mamquam, and Squamish), and streams that form part of the Howe Sound system, encompass an area approximately 463,000 ha and extend from sea level to 2,678 m at the peak of Garibaldi Mountain. Three of the 14 biogeoclimatic zones of British Columbia occur in these watersheds. The Coastal Western Hemlock (CWH) zone predominates. The Mountain Hemlock and Alpine Tundra zones are also found.

Some of the major upland forested ecosystem associations that are present are: Western Hemlock - Amabilis Fir - Blueberry; Western Hemlock - Flat Moss; Douglas-fir - Salal; Douglas-fir - Western Hemlock - Falsebox; and Mountain Hemlock - Amabilis Fir - Blueberry. On floodplains, Sitka Spruce - Salmonberry; Black Cottonwood - Red-osier Dogwood; and Black Cottonwood - Willow are the major forested ecosystem associations present. The ecosystems in the area have soil moisture regimes ranging from very dry to wet. Soil nutrient regimes tend to be very poor to medium due to the dominance of the granitic bedrock that was the parent material of many of the soils of the area.

Two ecological reserves have been established in the watersheds of the Howe Sound system: ER 69, Baynes Island - black cottonwood ecosystems on an island of the Squamish River (71 ha) and ER 48, Bowen Island - ecosystems representative of the drier maritime part of the CWH zone (397 ha). Parks also offer some protection of ecosystems (e.g., the montane and subalpine ecosystems of Garibaldi Provincial Park - 53,000 ha).

The forests of the area provide habitat for a wide variety of species; influence the quantity and quality of water that reaches streams and rivers, affecting drinking water, anadromous and resident fish and other species; provide a scenic view for travellers to destinations such as Squamish, Whistler, Pemberton, and the interior of the province; provide a recreational experience for many; stabilize soils on slopes; release oxygen; and are a sink for carbon dioxide. In addition, lower elevation forests have provided substantial timber for the forest industry and are expected to continue to provide it, albeit at reduced levels, in the future.

The Ministry of Forest's research in the area includes testing different genotypes of species, methods of controlling unwanted species, tree response to application of fertilizer, and characterizing forest ecosystems.

SEA FLOOR SEDIMENT TRANSPORT PROCESSES: HOWE SOUND, BRITISH COLUMBIA

by

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High resolution acoustic surveys of the sea floor in Howe Sound reveal a variety of high energy sedimentary processes that create distinctive bottom topography and near-surface sediment distributions. Interpretation of side scan sonar and sub-bottom profiler data indicate that very energetic underwater processes such as landslides, debris flows, and turbidity currents distribute sediment within the Sound.

At the front of the Squamish Delta, the river distributary channels carry coarse sediment and feed offshore channels incised into the subaqueous slopes. Associated features, such as flute marks and arcuate sea floor scarps, suggest a combination of turbidity current and shallow sliding.

Slope instability has been documented at the Woodfibre fan delta, where dramatic changes in nearshore bathymetry accompanied damage to the jetties. The underwater slopes of the fan delta are cut by chutes, scarps, and rotated blocks leading downslope to debris aprons arranged around the base of the fan wedge.

Subaerial floods, debris torrents, and debris flows feed sediment to the shoreline of the Sound at various locations, including Britannia Beach and M Creek. Offshore from Britannia Beach there are coarse-grained sediment splays that trend downslope to a large area where intricate patterns of intersecting scarps bound sediment blocks displaced by shallow translational sliding. Further downslope there are hummocky, blocky, debris accumulations marking the down-fjord limit of the landslide activity. Off M Creek and other similar high relief catchments along the eastern flank of the Sound there is evidence of sediment dispersal away from the shoreline by debris avalanching down the steep underwater slopes, forming distinct debris lobes, and sand and gravel splays.

THE HOWE SOUND FJORD; GEOLOGICAL AND GEOPHYSICAL: EVIDENCE FOR ITS ORIGIN AND QUATERNARY DEVELOPMENT

by

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Marine seismic profiles and regional maps are used to identify Howe Sound's geology and sedimentary processes. The fjord incises the Coast Mountains about halfway from Georgia Strait to the Garibaldi Arc. The narrow reach from the Squamish River mouth to the Porteau Sill has depths to 285 m. Flow is confined to <55 m over the sill while lower Howe Sound has depths >245 m. Bedrock relief is great and sediment thickness locally exceeds 500 m. Despite regional lineations of 41° and 131° in the geology, gravity, magnetics, and seismicity, no active faults are known.

Substrates include: modern sand to superhydrous silt, tailings and organic waste, glaciomarine turbidites, diamicts, and various bedrock types. Rock is restricted to slopes over 30° and hills. Layered reflectors and diffractors characterize proglacial turbidites (>17,000 BP), typically 150 to over 450 m thick. Variable offlap and lenticular deposits imply multiple ice lobes. Some strata suggest ice incursion from the south. Outcrop is restricted to the eroded fjord walls and floor. The top of this facies dips slightly from Porteau to Horseshoe Bay, possible due to ongoing uplift in the Coast Mountains.

The Porteau Sill is one of the few fjord sills in western Canada that is a terminal moraine. Built on eroded glaciomarine deposits and bedrock, it marks a stillstand or readvance during the last ice retreat. Its coarse sediment has an arculate structure with bedding dips that steepen upsection to 28°.

In upper Howe Sound the main source of modern sediment is the Squamish River delta. This acoustically coarse and gassy sediment thins to <10 m along the basin axis. Seismic data shows that no significant Squamish sediment traverses the sill to the south.

Silt from the Fraser River plume enters via Queen Charlotte Channel to accumulate on the flat basin floor in water >200 m. Since deglaciation, this has formed a transparent to faintly laminated wedge shaped deposit which tapers from >90 m off Horseshoe Bay to about a metre on the Porteau Sill and is absent further north. From seismic character and correlation, the sedimentation rate is highest in southeast Howe Sound, and there it is still less than 7.5 mm/yr. The Fraser silts also thin to the west, and do not extend into the westernmost Howe Sound or Thornbrough Channel. The distribution of the Fraser silt resembles that of the peak velocities for the surface currents. The only modern sediments in western Howe Sound are small debris fans from high gradient streams and local reworked lags.

In addition to the two main sediment sources restricted to the lower (Fraser) and upper (Squamish) Howe Sound, are local sources from erosion of unconsolidated sediment and from industry such as tailings, mills, and outfalls. The low sedimentation rates in many parts of this fjord imply that pollutants are not being buried or diluted and are likely to persist.

PHYSICAL OCEANOGRAPHY OF HOWE SOUND, B.C.

by

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Howe Sound is a British Columbia fjord which empties into the Strait of Georgia. There is a sill of 70 m depth about 17 km from the head. Beyond the sill the width increases from about 3.5 km to 20 km at the entrance. The outer triangular basin has many islands and an average depth of about 200 m. It is freely connected to the Strait and, except for the influence of the estuarine circulation of the upper region in the upper few metres, is oceanographically part of the Strait of Georgia. Inside the sill, the width is a roughly constant 2.5 km; the channel is somewhat sinuous and the inner basin has a maximum depth of almost 300 m.

The Squamish River flows in at the head and has an average annual discharge of 242 m^3/s, one of the larger outflows into a fjord in British Columbia. The runoff is seasonally modulated with a peak in late spring which is two or so times the annual average. This freshwater input causes a lower density layer of a few metres thickness and drives an outflowing surface current of a few centimetres per second. There is an estuarine return flow below of comparable magnitude. The tides also produce currents of a few centimetres per second. The tidal currents show considerable variation in amplitude and phase with depth indicating that internal tides are generated at the sill. Wind driven currents in the upper layer have amplitudes of tens of centimetres per second and totally dominate the near-surface currents. There are substantial lateral variations in the near-surface currents and in the estuarine return flow.

The deep water inside the sill is fairly homogeneous and usually has fairly low oxygen levels. Partial or total replacements occur from time to time raising oxygen and density values. Replacements to the bottom occur in late fall or early winter at intervals of one to three or four years. Replacements to intermediate depths occur more often and sometimes occur during freshet in late spring (or other times associated with short high rainfall periods) as well as in the late fall-early winter period.

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ASSESSMENT AND CONTROL OF ACID ROCK DRAINAGE FROM BRITANNIA MINE SITE

by

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The decommissioned Britannia Mine is located at Britannia Beach approximately 48 km north of the city of Vancouver, on the east shore of Howe Sound. The underground and open pit mine was operated by the Britannia Mining and Smelting company Ltd. from 1905 to 1963 at which time it was purchased and operated by Anaconda Mining Company until shutdown in 1974. During operation, approximately 45 million tonnes of ore were processed for recovery of copper and lesser amounts of silver, zinc and gold.

Acid rock drainage containing elevated acidity and metal levels has issued from the Britannia site since the operational period, discharging into Britannia Creek and Howe Sound. In 1972, in an attempt to improve drainage quality from the site, acidic mine water was diverted within the mine workings for treatment in a copper cementation plant prior to discharge at depth to Howe Sound. Recent investigations, however, have indicated that contaminated water is again draining directly into Jane Creek, then into Britannia Creek, and ultimately into Howe Sound.

We recently completed an investigation of ARD from the Britannia mine site for the B.C. ARD Task Force. An assessment of acid generation and the sources of contaminated drainage was conducted, and alternative options for control and remediation developed. Site water quality data was compiled in a Geographic Information System (GIS) with recent topographical data for graphical display of the sources of contaminated drainage, and the current physical nature of the site.

The Britannia site could provide a unique opportunity for research and investigation into ARD processes and control. The site is readily accessible by road with a long history of ARD potentially from all components of any mine site: open pits, underground, tailings, waste rock and construction materials. Consideration should be given to developing the site as a research facility, and also as an opportunity to disseminate information to the public regarding acid rock drainage and the measures that can be taken to assess and remediate these sites.

HEALTH HAZARD ASSESSMENT OF DIOXINS AND FURANS

by

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Health hazard assessment is made up of two major components, an exposure assessment and a toxicity assessment. The toxicity assessment of dioxins is based on studies carried out in laboratory animals with the most toxic dioxin congener 2,3,7,8-tetrachlorodibenzodioxin (2,3,7,8-TCDD) as well as comparative studies with the other dioxin and furan congeners. The toxicity of the other dioxin and furan congeners is normalized to the toxicity of 2,3,7,8-TCDD through the use of toxicity equivalence factors.

Based on all the toxicity information available, a Tolerable Daily intake (TDI) of 10 pg/kgbw/day total dioxin equivalents has been estimated. For the purposes of calculating exposure, consumption of fish and shellfish muscle as well as crab hepatopancreas has been estimated from various sources including the Nutrition Canada Survey, USA surveys, and anecdotal data. Based on these data, it is estimated that for eaters of fish and shellfish muscle, the average consumption is 40g/day while for eaters of crab hepatopancreas the average consumption is 20g/day. Using these criteria, it has been determined that consumption of crab hepatopancreas, from crabs caught in the certain areas of Howe Sound would result in intakes of total dioxin toxic equivalents much in excess of the tolerable intake for these substances. Hence, recommendations have been made to not consume crab hepatopancreas from these sites.

THE PHYTOPLANKTON ECOLOGY OF HOWE SOUND

by

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The production, distribution, and abundance of phytoplankton in Howe Sound were studied from 1972 to 1978. Results of this 6-year field study, coupled with laboratory bioassay experiments, revealed a very heterogenous population distribution with considerable spatial, temporal, and interannual variability. Greatest population abundances and highest daily and annual rates of carbon production were in the seaward boundaries of the Sound contiguous with the Strait of Georgia where average annual values often were >350 gC/m^2/yr. The least productive regions of the Sound were off the Squamish River delta and in waters adjacent to the pulp mills and Britannia copper mine where values were typically <50 gC/m^2/yr. Severe light attenuation in surface waters of the Sound extending from Squamish to Anvil Island and caused by the turbid, glacial Squamish River and stained pulp mill effluent discharges, were thought to be the major factors limiting rates of primary production in Howe Sound. Strong seaward flushing of the surface layer and stable stratification from May to October with summer declines in available nitrate-nitrogen also influenced phytoplankton dynamics in certain regions of the Sound. An annual spring diatom 'bloom' is a common, dominant feature in all coastal B.C. fjords. In Howe Sound, it usually commenced in April just off the Squamish delta and moved progressively seaward down the Sound over about a 3-4 week period. But in some years it was restricted and/or eliminated by poor spring weather conditions or early Squamish River discharge which influenced the production dynamics of the Sound. Autumn blooms were common in the seaward boundary waters but not in other regions of the Sound where turbidity and hydrographic conditions either prevented or dampened the autumnal response.