Academic year 2003-2004

A GIS-approach to assess the impact of two pulp mills (in Woodfibre and Port Mellon) on intertidal biodiversity in the Howe Sound region (British Columbia, Canada)

by
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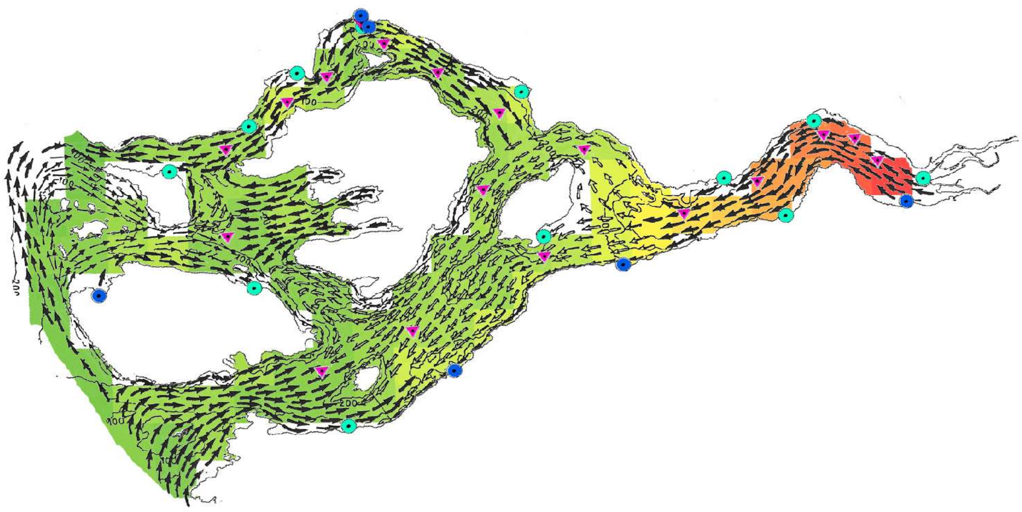

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Thesis submitted to obtain the degree of Master of Science in Advanced Studies in Marine and Lacustrine Sciences

Acknowledgement

I would like to thank Prof. Dr. Ann Vanreusel for being the promoter of my thesis and for providing me with the opportunity to go to Canada in the framework of the Biodaqua project; Prof. Dr. Shannon Bard (Environmental Programmes, Dalhousie University) for being the co-promoter and supervisor of my thesis and the warm welcome in the cold Canadian city of Halifax, Nova Scotia. Also I would like to thank James Boxall and Julie Beaumont (MAGIC, Dalhousie Libraries) for providing me with the GIS base maps and for resolving some GIS mysteries for me. I would like to thank also Martin Davies (Hatfield Consultants), for his expert advice on the data interpretation, and Mike Hagen and Bob More (Environment Canada, Pacific and Yukon Region, Environmental Protection Branch) for providing the dioxin data set and the expert advice, and Leslie Uhlig (Hatfield Consultants), for providing me with information on both pulp mills. Further my thanks go to Ebony for the review of my first draft and to Kaarin for her much needed logistic support. Joe VanBuskirk (Kimberley-Clark), for the very interesting tour of the pulp mill. My last “thank you” is for Fien, my fellow student on this project, for all the interesting discussions and help on the statistics.

A GIS-approach to assess the impact of two pulp mills (Woodfibre and Port Mellon) on intertidal biodiversity in the Howe Sound region (British Columbia, Canada)

Abstract:

Intertidal biodiversity data collected by Bard (1998) in 1990-1993 at nine sites in Howe Sound, a British Columbian fjord, were the source data for this paper. Two pulp mills located in Woodfibre and Port Mellon, discharge their effluent in this fjord. Several process changes took place in both mills just before and during the intertidal sampling. The goal of this paper is to assess the impact of mill effluent on intertidal biota, by comparing trends in intertidal biodiversity with known mill impact, derived from tracers: dioxin/furan levels in the sediment and in crabs. Because intertidal and contaminant sampling sites were different, the use of traditional statistic tests was not possible. Therefore, contaminant and intertidal data were combined in a Geographical Information System (GIS), which allowed to observe correlations. Also included in this GIS were mill effluent dispersion patterns, surface currents and sediment data, which allowed the integrated interpretation of the data. Confounding factors in the interpretation of intertidal data, including local oceanographic conditions and non-pulp mill pollution sources, are identified in this paper. As such, this paper serves to help interpret and plan the sampling scheduled for the summer of 2004. The classification of animal species in feeding guilds and algae in taxonomic groups provided new insights in the data. The general trend at all sites seems an increase in species diversity. Discoloration and even die-off in the vicinity of the mills, was found to be correlated with sodium chlorate spills. As a conclusion, intertidal monitoring is a valuable addition to the current practice of taking grab samples of the sediment, but on its own is not a representative tool for the deeper environment

Keywords: pulp mill pollution, intertidal biodiversity, GIS, Howe Sound, environmental monitoring

Introduction

Since the early 1900's, two pulp mills located in Woodfibre and Port Mellon, discharge their effluent in Howe Sound, a fjord in British Columbia (BC), Canada. As several deleterious effects of pulp mill effluent on marine biota and habitat became evident, scientific awareness rose and several contaminant monitoring programs were started. The attention has shifted from traditional effluent parameters such as Biological Oxygen Demand (BOD), Total Suspended Solids (TSS) and toxicity, towards the impact of dioxins/furans and other organochlorines, measured as Adsorbable Organic Halide (AOX) (Colodey and Wells, 1992). Organochlorines, which include dioxins/furans, are organic molecules which have one or more chlorines substitutions and are produced when chlorine is used in the pulp bleaching process. The impetus for the paradigm shift towards organochlorines was the discovery of elevated dioxin and furan levels in sediments and organisms in the vicinity of British Columbian pulp mills in 1980, by the Council of Forest Industry of British Columbia.

A similar study in 1987 by the Canadian Environmental Protection Agency (CEPA) indicated the failure of most mills to meet existing federal dioxin and furan regulations. As a consequence of this study, fisheries closures were enforced by the Department of Fisheries and Oceans (DFO) in the vicinity of most pulp mills, including the two mills in Howe Sound. As part of the federal Fisheries Act, pulp and paper mills were required to start monitoring the impact of their effluent on fish and invertebrate habitat and resources. This section of the Fisheries Act was put in effect in 1992 by the Pulp and Paper Effluent Regulations. The practical implementation of these regulations was specified in a Technical Guidance Document (Environment Canada and DFO, 1993), which included guidelines for the start up of an Environmental Effects Monitoring (EEM) program. The two primary objectives of the EEM program are: firstly, to assess the adequacy of effluent regulations by performing EEM at selected sites in the receiving environment and secondly, to achieve national uniformity in industrial site effect monitoring (Hatfield, 1994).

The first stage of the EEM program required each mill to submit a Pre-Design Document to Environment Canada in 1994. The objectives of this Pre-Design Document were to summarize the existing state of the environment through review of historical monitoring programs and to provide a basis for the design phase of the actual EEM in the first cycle of monitoring (1995-1996). The results of this monitoring study were compiled in the Cycle One Interpretive Report (Hatfield, 1996). The Cycle Two Interpretive Report described the period from 1997 till 2000, while the Cycle Three Interpretive Report covered the 2001 till 2004 time span.

The Pre-Design Document was refined during sessions of Local Monitoring Committees (LMC). Members of the Howe Sound LMC included representatives from Environment Canada, DFO, the British Columbia Ministry of Environment, Lands and Parks, as well as environmental managers from the mill in Woodfibre and in Port Mellon. The Pre-Design Document includes a summary of the history of the mills and the receiving environment. An overview of previous toxicological, biological and oceanographic studies in the Howe Sound region is given.

The dispersion of the effluent plume (Fig. 7) was determined by integrating oceanographic data, organochlorine monitoring and benthic community data with Effluent Dispersion Studies (Hatfield, 1994), also called Plume Delineation Studies. The result was the identification of a "1% effluent concentration zone" and a "maximum extent of effluent concentration zone", providing a basis for LMC members to select EEM sampling sites. The preparation of the Pre-Design Document was contracted to Hatfield Consultants. As both mills discharge in the same receiving environment, they are treated in one Pre-Design Document.

Another obligation of the Pulp and Paper Effluent Regulations was the installation of an effluent treatment system in each mill leading to significantly lower levels of BOD, TSS and wood fibers being discharged in the effluent. To decrease the levels of dioxin and furan in the effluent, elemental chlorine was substituted partially by chlorine dioxide. Chlorine dioxide substitution decreased the AOX output, and hence the output of dioxins and furans. Another improvement was the introduction of primary clarifiers, which allow the fibers to settle out of the effluent, preventing the build up of fiber mats near the diffuser. Wood chips, treated with wood preservatives, were no more used as hog fuel in the power boiler. In the pulping process, the use of defoamers, contaminated with dioxin/furan precursors, was put to an end.

The environmental impact of the mills on benthic organisms has been monitored extensively, as benthic invertebrates respond in a sensitive way to environmental changes and are mostly immobile and hence good indicators of local water quality (Weisberg et al., 1997). However, most attention has been given to subtidal benthos, collected by grab sampling. Intertidal monitoring is rare and difficult to compare, as methodology and sampling sites differ between sampling regimes.

The goal of this paper is to investigate the value of intertidal monitoring as a tool for assessing the impact of the two Howe Sound pulp mills on the marine environment. The data were graphically presented in a Geographic Information System (GIS), which allowed to observe visually the relation between contaminant and biodiversity data. This turned out very useful, as a regression of diversity parameters versus effluent exposure parameters was not possible (see Mat. and Meth.: Tracers).

Trends in intertidal biodiversity were compared with effluent discharge data from both mills and with tracers, which allowed to predict the exposure of a site to mill effluent. The tracers used in this paper are dioxin and furan levels in the sediment and in Dungeness crab (*Cancer magister*), measured near the intertidal sampling sites. The trends observed in a subtidal study near both mills are compared with intertidal trends, as the intertidal is a nursing ground for many subtidal species.

Confounding factors in the interpretation of intertidal data are identified in this paper. Such factors include local oceanographic conditions and non-pulp mill pollution sources. As such, this paper serves to help interpret and plan the sampling regime scheduled for the summer of 2004. Additionally, recommendations for future sampling are provided, as well as suggestions for the interpretation of these newly collected data.

Material and Methods

Study area

(adapted from Thomson, 1981)

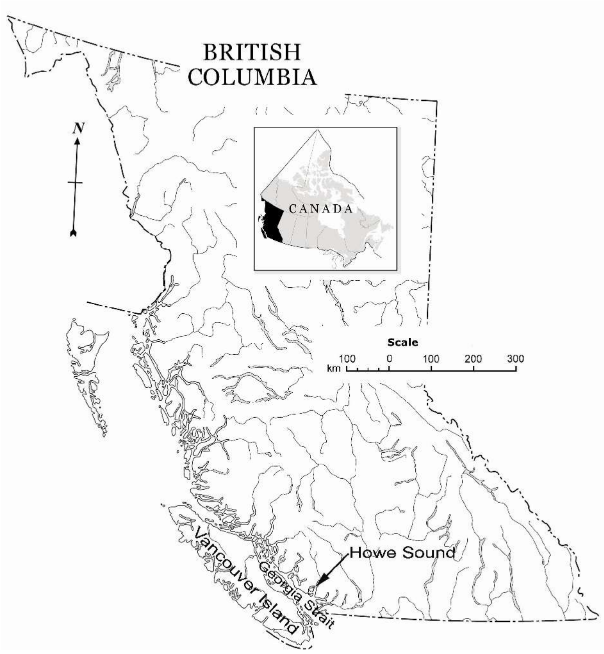

Fig. 1. Location of the study area (Atlas of Canada, Department of Natural Resources, 2002).

Two pulp and paper mills are located in the Howe Sound, a 43 km long fjord that mounds in the Georgia Strait and receives the Squamish River runoff. Geologically, Howe Sound has a glacial origin, which is still evident in the occurrence of a thick layer of glacial sediment on the bottom, overlaying the bedrock. As a consequence, the basin is flat by coastal standards with mid-channel reliefs of only a few meters. Near the shore and islands, the bathymetry mirrors the mountainous topography above water.

Several sills were left behind on the retreat of the glaciers. The inner sill, near Porteau Cove (Fig. 7), is the border between the upper and lower Howe Sound basin and has a depth between 13 to 61 m. It partially blocks the deeper currents between upper and lower Howe Sound. The Grace-Langdale sill is smaller and extends from the southern tip of Gambier Island to the mainland (Fig. 7). Having a minimum depth of only 30 m, it influences deeper currents leaving the Thornborough Channel. A third, discontinuous sill, the outer sill, extends across the mouth of Howe Sound with an average depth of 60 m. Deeper currents can still pass through breaches in the sill such as the Queen Charlotte Island Channel, with a depth of 245 m. Tides in Howe Sound are mixed semidiurnal/diurnal and have a mean range of 3.6 m at Woodfibre and Port Mellon (Hodgins and Knoll, 1990a, 1990b).

Upper Howe Sound basin, north of the outer sill, receives the Squamish River runoff. This river is the main freshwater input in Howe Sound, and is fed by glacial run-off. The discharge rate reaches a maximum of 750 m^3/s during freshet (May-September) and a minimum discharge rate of 75 m^3/s from December-April. The currents, salinity and temperature in upper Howe Sound show seasonal variation, linked with the input of melt water from the river. The Squamish River runoff entrains saline water from deeper layers, causing the salinity of the upper ten meters to increase seaward. This seaward flow is compensated by a counterflow immediately under the surface as well as a complex variation of flow with depth in the lower layers (Stronach et al., 1993). The counterflow helps aerate and refresh the deeper layers, but is limited in upper Howe Sound, because of the inner sill. In addition to the major effect of Squamish River run-off on the surface currents in Howe Sound, surface circulation is also wind driven to some extent (Ferguson and McPhee, 1991).

Upper Howe Sound can be regarded as an estuary, based on the high influence of river discharges and the obvious salinity gradient (Fig. 7) (McDaniel, 1973). The salinity gradient in upper Howe Sound exhibits a strong seasonal variation, closely linked with variations in Squamish River discharges. In the upper Howe Sound basin waters are highly stratified. Hodgins and Knoll (1990a) identified a halocline and thermocline at 2-8 m (8 m during high summer discharges), with a seasonal changing pycnocline depth. Salinities of 29-31 PSU persist year round below 50 m throughout Howe Sound, with slightly lower values in the upper basin due to the effect of the inner sill, limiting deep water exchange.

The runoff from the Squamish River is the main source of turbidity in upper Howe Sound and as a consequence primary production can drop due to shading during freshet in May-September. Buckley (1977) prepared a subjective flow field of the Squamish river current measurements and arial photographs of sediment loaded river (Fig. 7). Based on calculations of wave exposure, Hatfield (1994) stated that the area near the Woodfibre mill is semi-protected.

Aside from the main jet of the river, a few back eddies exist. In the lower Sound most of the rivers' outflow passes east of Anvil Island and continues along the eastern, deeper side of the Sound. The annual sediment transport by the Squamish River to Howe Sound is 1.5 x 10^6 m^3 (McLaren et al., 1993). Near the mouth of the Squamish River, sediment mainly consisted of silt (70%), while further south the percentage of clay increased (40 %), although silt remained the largest component (55%) (Hatfield, 1994). The 3D numerical model produced by Stronach et al. (1993) predicts the annual sedimentation throughout Howe Sound (Fig. 8), showing very high annual sedimentation near the Squamish estuary. Another sedimentation study predicted the net sediment transport pathways from grain-size distribution patterns in the whole Howe Sound basin (Fig. 8) (McLaren et al., 1993).

In lower Howe Sound, salinities gradually rise towards the Georgia Strait. Waters of the lower basin are much less stratified, as the river discharges have less influence. Thornborough Channel, the western channel of lower Howe Sound, receives effluent from the Port Mellon mill. This channel is deep in the north (>200 m), but becomes progressively shallower south of Port Mellon towards the Grace-Langdale sill. In 1990, currents in the Thornborough Channel measured at 7 m and 30 m showed a variation in both speed and direction (Hodgins and Knoll, 1990b). Based on sediment characterizations, McLaren and Cretney (1993) suggest that flows in the Thornborough Channel are entirely tidally-dominated. However, Hodgins and Knoll (1990b) suggest that the local circulation is mainly dependent on the circulation in the main channel, east of Gambier Island and the circulation in Georgia Strait. The area near the Port Mellon mill is considered protected from wave exposure (Hatfield, 1994).

Based on a 3D numerical simulation of the Howe Sound hydrodynamics, Stronach et al. (1993) found a relative maximum of surface layer density (density and hence salinity drops at both sides of this line). This line (Fig. 7) is the border between the Fraser River water entering the Sound and the Squamish River water leaving the Sound. The magnitude of the Fraser River influence remains, however, unknown. The model by Stronach et al. (1993), also predicted the average surface current direction and strength in lower Howe Sound (Fig. 7).

Throughout Howe Sound, water temperatures remain cool year round, with the exception of some shallow coves that warm up in the summer. The surface brackish layer of the Squamish River drops to 7°C in February, rising up to 18°C in July, exposing intertidal organisms to a broad temperature range (McDaniel, 1973). Below this layer temperatures are 8-10°C year round.

Pulp Mills

Woodfibre

The Western Pulp Limited Partnership mill (hereafter called the "Woodfibre mill") is located in Woodfibre, on the western shore of upper Howe Sound, just within Squamish Harbor. Pulp was first produced in 1912 through the calcium sulphate cooking process. In 1938, pulp bleaching started, using elemental chlorine and calcium hypochlorite. During a shutdown in 1958, conversion to the Kraft process and installation of a chlorine dioxide generator took place. In the Kraft process, pulp is produced by cooking wood at high pressure and temperature with the use of sodium salts in an alkaline medium.

Production resumed in 1961 and the recycling of cooking chemicals lowered pollution loads. Until January 1986, the effluent was discharged at the surface, thereafter effluent was disposed of through four diffusers spaced at intervals of 25 m and extending 27 m from the shore at a depth of 22.5 m. Since 1986, a primary clarifier removed settleable solids, greatly reducing TSS (Fig. 2). Since 1988, 30 % of elemental chlorine was replaced by chlorine dioxide in response to organochlorine concerns. Recovery systems for fiber and process chemicals were improved in 1989, leading to a further decrease in TSS. A major decrease in the use of chlorine took place in 1987 (Fig. 2). From 1990 onwards the level of chlorine dioxide substitution was increased to 50% and only residual chips from off-site sawmills were used, putting an end to the presence of log booms in waters adjacent to the mill.

After treatment in the primary clarifier, effluent is cooled and neutralized by adding lime slurry. pH of the primary effluent can be adjusted using caustic (NaOH) or sulphuric acid, as well as nutrients such as anhydrous ammonia and phosphoric acid can be added to sustain the biota within the biobasin. Installation in December 1992 of the Oxygen

Activated Sludge (UNOX) biological effluent treatment system, reduced BOD drastically (Fig. 2). In the UNOX system, effluent enters the biobasin where biological treatment takes place. After the biosolids (soil-like residue of materials) are removed in two 55 m diameter secondary clarifiers, effluent is discharged through the diffuser. During the time of the intertidal study (1990-1993) effluent volume was approx. 70000 m^3/day.

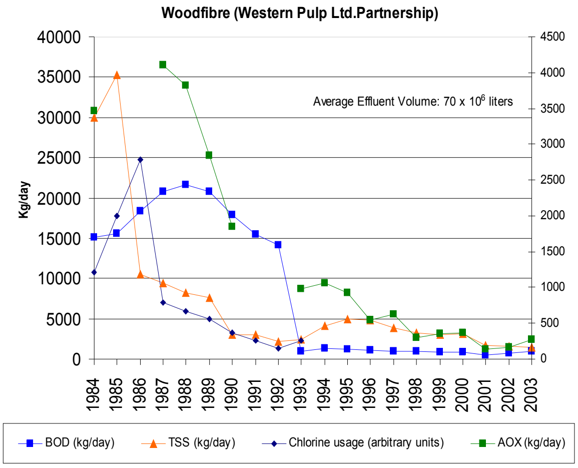

Fig. 2. Effluent discharge data for the Western Pulp Ltd. Partnership mill in Woodfibre. Data source: Hatfield

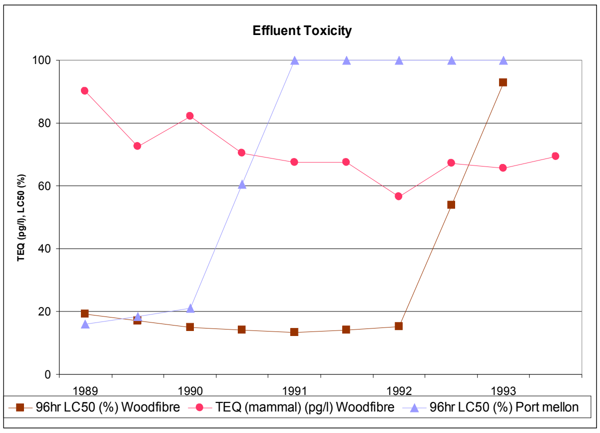

Fig. 3. Effluent toxicity for both mills (Hatfield, 1994).

In the Woodfibre mill twenty spills occurred in 1988, releasing at least 40000 liters of fluid of varying consistency and toxicity, directly into the surface water near the mill (Hatfield 1994). Fourteen spills happened in 1989 (total of >30000 l), seven spills in 1989 (total > 7000 l), five in 1991 and two in 1992 and in 1993 (Hatfield, 1994). Additionally, a spill of 20000 liters of sodium chlorate occurred in 1989 and a similar spill of 2000 liters occurred in 1990 (Hatfield, 1994). The impact of these spills is unclear, but as they are released directly in the surface water, contact with intertidal biota can be expected.

In order to study the dispersion of the effluent plume, Effluent Dispersion Studies (Hodgins and Knoll, 1990a-b) were performed by injecting dye into the effluent pipe for approx. 90 minutes and subsequently measuring the concentration of the dye in the waters near the mill. The Effluent Dispersion Study revealed that effluent from the Woodfibre mill rises to the surface and becomes trapped in "lenses" immediately below the halocline at 2-8 m throughout the Sound. During the duration of the study (6 to 18 hours), the effluent only dissipated laterally. The 1% effluent zone was estimated conservatively in the study (Fig. 7). In two trials of dye injection, effluent was first found to travel north to a back-eddy during the first trial and the second time, at a different point in the tidal cycle, effluent formed a narrow band along the western shore. Effluent carried north into the back-eddy returns back down the eastern side of the channel and consequently effluent is concentrated and trapped in areas near the mill (Hatfield, 1994). The dispersion pattern changes seasonally, because of the impact of the Squamish River on currents and stratification. Stratification is strong during freshet, from May to September, but decreases in summer, resulting in a mixed layer to a depth of 10 m (Hatfield, 1994).

Port Mellon

The Howe Sound Pulp and Paper Ltd. mill (hereafter called the "Port Mellon mill") is located at Port Mellon, on the western shore of the Thornborough Channel (Fig. 7). In 1908 it commenced as a soda pulping operation, and was converted to Kraft in 1916. The production of semi-bleached pulp took effect in 1954, while fully and semi-bleached pulp production commenced from 1962 onwards (Hatfield, 1994). As a consequence, the discharge of AOX and dioxins/furans probably began around 1962. This is confirmed by MacDonald et al. (1992), as 2,3,7,8-TCDF, a known product of chlorine bleaching has been found in a sediment core near the Port Mellon mill as from 1965.

Chlorine dioxide substitution of elemental chlorine increased to 50% in 1989 and as a consequence AOX levels dropped. Primary and secondary effluent treatments were installed in September 1990, reducing the BOD, TSS and AOX dramatically (Fig. 4). The production of newsprint started in 1990 with the addition of a thermomechanical pulp machine, which mechanically grounds chips to pulp, instead of the chemical digestion in the

Kraft process. No chlorine is used in the newsprint production. In 1991 a first run of Total Chlorine Free (TFC) pulp was produced, the first in Nord America. During the intertidal sampling, only residual chips from sawmills in the Vancouver area were used.

The effluent treatment system is very similar to the one used in the Woodfibre mill, including a primary clarifier, a UNOX biobasin and two secondary clarifiers. Similar effluent cooling and pH adjustments also take place. Effluent, 65000-70000 m^3/day on average, was discharged through two surface outfalls (acidic and alkaline) into a small bay west of the mill until November 1982, when a

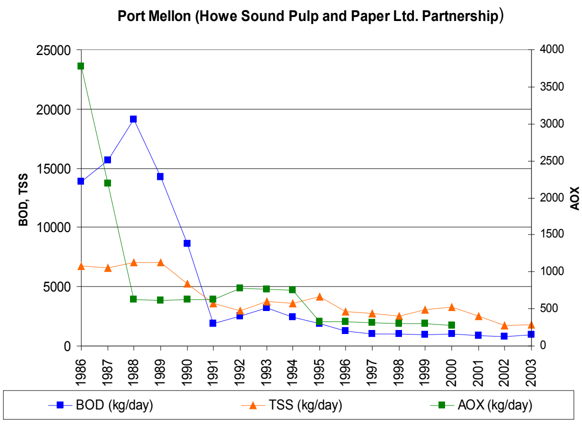

Fig. 4. Effluent discharge data for the Howe Sound Pulp and Paper partnership mill in Port Mellon. Data Source: Hatfield.

submarine diffuser was installed. The diffuser extends 277 m into the Sound and effluent is released through six diffuser ports at depths ranging from 30 to 115 m.

Spills of process chemicals and untreated effluent to the surface water near the mill also occurred in the Port Mellon mill (1989: 2 spills, 25000 l; 1990: 5 spills, > 505600 l, 1991: 3 spills, >250000 l; 1992: single spill of 400000 l) (Hatfield, 1994). A major spill of 45000 l sodium chlorate occurred in 1993, while no further spills were reported in that year (Hatfield, 1994).

A similar Plume delineation study (Hodgins and Knoll, 1990b) was conducted as in the Woodfibre mill. In contrast with the Woodfibre mill, effluent from the Port Mellon mill is released at a wide range of depth and disperses laterally along layers of equal density. Effluent extends from approximately 10 to 60 m depth overall. Effluent was never found at the surface during the Plume Delineation Study, so Hodgins and Knoll (1990b) suggest that effluent usually does not rise to the surface and intertidal areas are believed to have little contact with the effluent. Nevertheless, extrapolating the Plume Delineation Study results to summer conditions is not fully reliable, since winds and River Squamish discharge will seriously alter the surface currents (Hodgins and Knoll, 1990b).

Non-Pulp Mill Pollution Sources

Apart from the two pulp and paper mills, other pollution sources occur in Howe Sound, confounding the interpretation of the environmental effects of mill effluent. Because iron and copper mining has been conducted in the upper Howe Sound region, background metal concentrations are likely to be high. From 1905 until 1974, a copper mine was active in Britannia Beach. At its peak in 1929, it was the largest copper mine in the British Commonwealth. Acid mine drainage seeps into Britannia creek and into Howe Sound. In-situ caged experiments with Chinook smolts indicated that surface water near Britannia Creek is more toxic than deeper water (Grout, 1999). Species richness and abundance of near shore fishes were much lower near the mouth of Britannia Creek compared to uncontaminated areas (Grout, 1998). Based on a report on macro invertebrate fauna (McDaniel, 1973), only the three intertidal sites near Britannia Beach, discussed in this paper, are believed to be influenced by the acid mine drainage.

Another potential confounding factor in the interpretation of the effluent impact is the pollution present in the Squamish River. The Whistler and Squamish community effluent treatment plants discharge in the Squamish River, although a part of the sewage is discharged untreated (Shannon Bard, pers. comm., 2004).

A mercury cell chlor-alkali plant was operational during 1964-1991 in the Squamish delta area, producing caustic soda (NaOH) and hydrochloric acid for pulp mills. In the 1970's, substantial high levels of mercury were found in Howe Sound biota (Hoos and Vold, 1975). Besides mercury, alkalis, acids, sulphates, chlorine and other substances were also found (Hoos and Vold, 1975). After the installation of mercury scrubbers, mercury levels in biota dropped to below consumption guidelines (<0.5 mg/kg wet weight) (Kay, 1989).

A numerical model of the Howe Sound basin (Stronach et al., 1993) suggested that a part of the Fraser River discharge enters lower Howe Sound and Fraser sediments settle out in that area (Fig. 7). This can be regarded as another confounding factor as sewage from municipalities such as the city of Vancouver and effluent from six bleached kraft mills (Marmorek et al., 1992) were being discharged in the Fraser River. Elevated dioxin and furan concentrations were found downstream of these mills (Mah et al., 1989). The extent of the impact of pollution in the Squamish and Fraser rivers and the chlor-alkali plant on intertidal communities at the time of sampling remains to be investigated.

Probably the most important confounding factor is the presence of log booms stored near the intertidal sites. As the trees are rubbing against each other, wood fibers are released and wash ashore.

Intertidal and Subtidal Sampling

Intertidal biodiversity data collected by Bard (1998) in 1990-1993 were the source data for this paper. In total nine sites were sampled in Howe Sound. Each site was sampled at in the beginning of June. The sites were selected taking into account historical information from local fishermen, biologists, mill workers and divers (Bard, 1998). Long-term accessibility was also a factor in the site selection. None of the sites were regarded as unaffected by human activities by Bard (1998).

Each intertidal site consisted of a 3 x 3 m quadrat in the mid to low tidal zone (0.5 – 1 m tide height) of rocky shore beaches. The number of species per site was sampled using a 0.5 x 0.5 m quadrat frame, strung with strings spaced at 10 cm, forming a grid. Species were recorded under each string intersection using a plump bob. In case of overlap, only the top species was recorded. Afterwards the number of species under all rocks in the 3 x 3 m quadrat was determined. The number of species for a site was a sum of above and under rock numbers. Based on the occurrence of a species at low, intermediate or high distances of a mill outfall in 1990 and 1991, species were classified by Bard (1998) as tolerant, sensitive or intolerant to effluent exposure. The proportion of the sensitive and intolerant categories was then used to calculate a "Bioindex" for each site in all the sampling years (Bioindex=0.5 x number of sensitive species + 1 x intolerant species). The purpose of this bioindex was to identify depleted and pristine areas in relation to mill exposure (Bard, 1998).

In addition to the classification based on sensitivity to effluent, new classifications are introduced in this paper. Animals were categorized in feeding guilds, while algae were sorted according to taxonomic division (based on Integrated Taxonomy Information System database, Canadian Biodiversity Information Facility, 2004).

For each sample the number of species feeding primarily as suspension feeders, surface deposit feeders, herbivores or carnivores/omnivores was determined (Table. 1 in Appendix) (based on Kozloff, 1983; Ruppert and Barnes, 1993). Similarly, algae species were identified as being Chlorophyta, Phaeophyta or Rhodophyta (Table. 1 in Appendix) (based on Integrated Taxonomy Information System database, Canadian Biodiversity Information Facility, 2004). Insufficiently identified species were not assigned to a feeding guild or algae taxonomic group and were not included in the total number of species.

A subtidal data set consisting of grab samples, collected near both mills in 1990 by Hatfield (1994), was used to investigate the link between intertidal and subtidal diversity. Based on the number of species of these subtidal sampling stations, an interpolation was executed (see Material and Methods: GIS), estimating the number of species for each location close to the mill (Fig. 10-11).

Tracers

Because the effluent concentration was never measured directly, the exposure of each site to mill effluent, was inferred from a tracer, the dioxin/furan concentration in the sediment and crab hepatopancreas. The total toxicity of the sample is expressed in Toxicity Equivalents (TEQ), of the most toxic congener, 2,3,7,8-TCDD. TEQs were calculated by multiplying each congener by a Toxicity Eguivalent Factor (TEF) and summing for all congeners. The TEFs for fish (Van den Berg et al., 1998) were used, as the goal was to relate tracer toxicity with marine biodiversity. The dioxin/furan data set was provided by Environment Canada (Pacific and Yukon Region, Environmental

Protection Branch). Dioxin and furan TEQs for sediment grab samples were normalized by dividing the TEQ by the percent Lost in Ignition (LOI), a measure for the organic content of the sediment. This compensates for the tendency of dioxins/furans to be adsorbed to organic material. Drawbacks of the use of TEQ as a tracer are discussed later (see Discussion: Tracers).

Male Dungeness Crabs (*Cancer magister*) were collected in traps and the hepatopancreas of several animals was combined in a composite sample per site. The crab TEQ was divided by the fat content of the hepatopancreas, as dioxins and furans are highly fat soluble. Only data from 1990 are shown (Fig. 8), as this was the only year were all sites were sampled. Dungeness Crabs are known to have a limited ability to metabolize chlorinated contaminats and levels in crab tissue often mirror sediment levels (Yunker et al., 2002).

As intertidal and dioxin/furan sampling was never performed at the same sites, it was not possible to test the correlation of TEQ in crabs and sediments and intertidal community statistically. However the TEQ from neighbouring contaminant sampling sites can help to predict the exposure to mill effluent of an intertidal site. To do so, a hypothetical transect was created by drawing a line, which connected the intertidal and contaminant sampling sites in geographical order (Fig. 8). The first transect runs from the Squamish River mound to the mound of Howe Sound (Fig. 8: upper graph), while the other transect starts in Thornborough Channel and stops at the western shore of Bowen Island (Fig. 8: lower graph). Each line corresponds with the X-axis of the graphs, showing TEQ and species numbers (Fig. 8). As such, correlations between the TEQ and intertidal biodiversity along the path of the line can be observed. This replaces the traditional approach of testing statistically the correlation between diversity and contaminant levels, both measured at the same site. It was never the purpose to identify a dose-response relation for the species numbers vs. TEQ, as pulp mill effluent contains many more compounds, some even not identified to date (pers. comm. Martin Davies, Hatfield, 2004).

Due to the normalization with LOI of fat content, it was not possible to add a LC50 value to the graphs, which would give an idea of the toxicity of the measured TEQs (pers. comm. Mike Hagen, Environement Canada, 2004).

Because of the confounding influence of the acid mine drainage in Britannia Beach, this site is excluded from the hypothetical transect.

Statistics

In order to assess the differences and trends in intertidal community structure between sites and sampling years, multivariate statistics as well as linear regression were used. The dataset contained 18 samples from 7 sites compromising a total of 56 intertidal taxa. Due to the confounding influence of the mine drainage in Britannia Beach, only the site most distant from the mine (Britannia C) was included. As some of the sites were only sampled qualitatively (no abundance or species cover data), the dataset was converted to absence-presence coding prior to analysis.

At first a Two-Way Indicator Species Analysis or TWINSPAN (Hill, 1979b), was performed in PC-ORD (McCune and Mefford, 1999) to determined sample clusters. To graphically present relationships between samples, an ordination was performed in PC-ORD. Because an arch effect was evident in the Correspondence Analysis (CA), a Detrended Correspondence Analysis (DCA) was exerted on the presence-absence data set. The linear correlation of the ordination axes with the variables distance and year was calculated using Pearson Rank correlation. An Indicator Species Analysis (INSPAN) was performed to identify indicator species for the clusters obtained in TWINSPAN. The statistical significance of indicator species was tested by a Monte Carlo permutation test.

Although a regression of community parameters with the distance to the nearest mill was originally planned, this was not performed due to the inherent problems of distance as a parameter for exposure (see Discussion: Tracers). However, per site a linear regression was performed to test for significant evolutions of the total number of species, number of algae and animal species, sensitivity categories, feeding guilds and algae taxonomic groups, during the time span of 1990-1993. Sites which were sampled at least three times were tested in Statistica® (Version 4.0, Statsoft inc., 1993) using non-transformed data. Regression assumptions (no residual outliers, normal distribution of residuals) were met.

To separate the effect of an overall increase in the number of species and a relative increase of a feeding guild or algae taxonomic group, the number of species per feeding guild/algae taxonomic group was divided by the total number of animal or algae species respectively.

GIS

Intertidal and tracer data in this paper were presented using ArcMap ® version 8.3 (Environmental Systems Research Institute, Redlands, CA, USA). Digital map files were obtained from the National Topographic Database, Natural Resources Canada (NRCan) as 1:50000 map sheets (sheets 92G_05-92G_07 and 92G_10-92G_12). The exact location of the effluent diffuser and estimated effluent concentration zones were digitized from the Pre-Design Document (Hatfield, 1994). Several other layers containing scanned maps (Sediment pathways, surface currents Howe Sound) were imported in ArcMap®. The annual sedimentation in the Howe Sound basin, as modeled by Stronach et al. (1993), was digitized into a colored grid. All maps are displayed in the NAD_1983_UTM projected coordinate system (zone 10).

In order to compare trends in intertidal and subtidal communities, the number of species at several subtidal sites close to both mills was interpolated into a color coded grid (Fig. 10-11). The interpolation was performed with the Spatial Analysist ® extension for Arcmap, using the Inverse Distance Weighted algorithm (power: 2, variable search radius, search radius number of points: 12).

Results

Statistics

The five sample groups identified using TWINSPAN are presented in a tree (Fig. 5), together with the indicator species per division. The four Darrel Bay samples and the Britannia Beach sample are clustered together in group one. Samples from Porteau Cove, Lions Bay and Port Mellon A, taken in consecutive years, are scattered over several groups, suggesting an evolution in community structure. At last, group five splits of very basally in the tree and contains exclusively Tunstall Bay samples, indicating a highly different community structure of those sites.

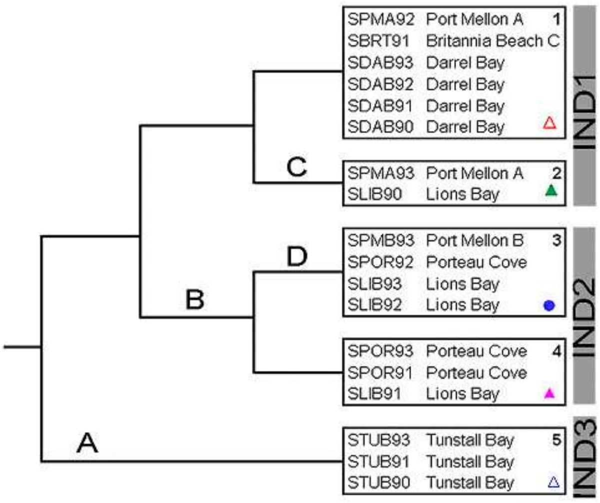

Fig. 5. TWINSPAN tree based on dataset of 18 samples and 56 species (absence-presence coding). A: *Eurystomella* sp., B: *Anoplarchus insignis*, *Enteromorpha* sp., *Ulva* sp., *Hemigrapsus* sp., *Notoacmea* sp., C: *Collisella* sp., D: *Anoplarchus purpurescens*.

The groups identified by TWINSPAN were plotted in the DCA ordination plot (Fig. 6). The first DCA axis (eigenvalue=0.478) was slightly positive correlated with distance to the closest pulp mill (R^2=0.526), while axis two (eigenvalue=0.287) was not correlated with any of the two independent variables (distance and sampling year).

Because of the limited number of observations, the INSPAN analysis was performed on three groups, each including one

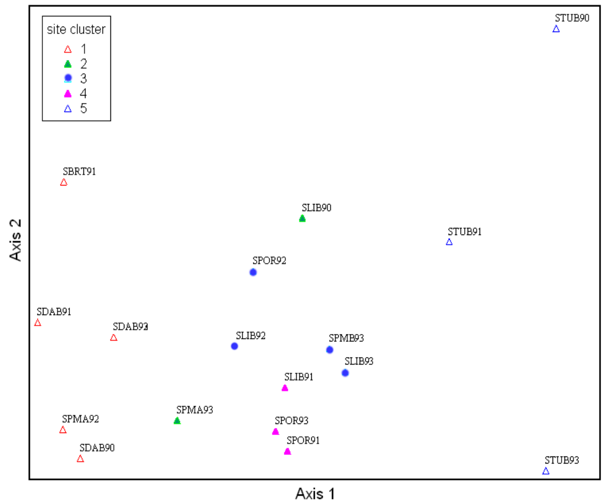

Fig. 6. DCA ordination plot.

or two TWINSPAN groups (Fig. 5). The Monte Carlo permutation test indicated no significant indicator species for group IND1 (Table. 2, in Appendix).

The lineair regression indicated no significant evolution in the total number of species, number of animal and algae species, proportion of tolerant/ sensitive/ intolerant species, Bioindex, proportion of any of the feeding guilds nor proportion of Phaeophyta or Rhodophyta. As a sole exception, the proportion of Chlorophyta decreased significantly from 1991 to 1993 in Porteau Cove ($F(1, 1)$=3267 R^2=0.999, p=0.01, B=-0.17).

Hypothetical Transect

In this section, trends in the intertidal community structure will be compared with crab and sediment TEQ, surface currents, sedimentation rate and net sediment pathways. Only crab and sediment TEQ from the most complete set (1990) are shown (Fig. 8), but three sediment sampling sites close to the Woodfibre mill (Fig. 9: HS-S) and the Port Mellon mill (Fig. 9: HS-S14, HS-S15) were sampled on a yearly base and provide data for the evolution of sediment TEQ during the sampling period.

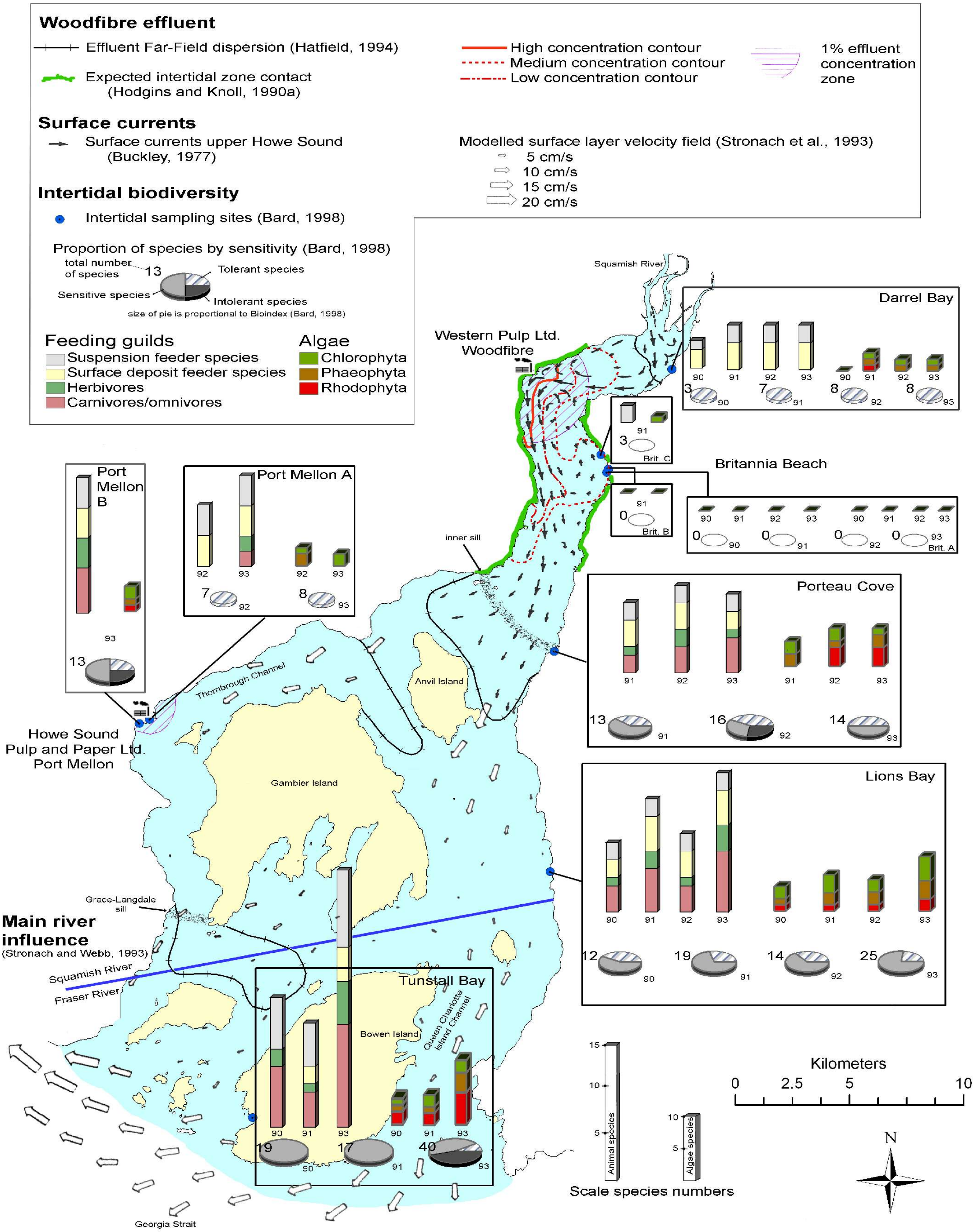

Fig. 7. Summary of oceanographic and intertidal data in Howe Sound.

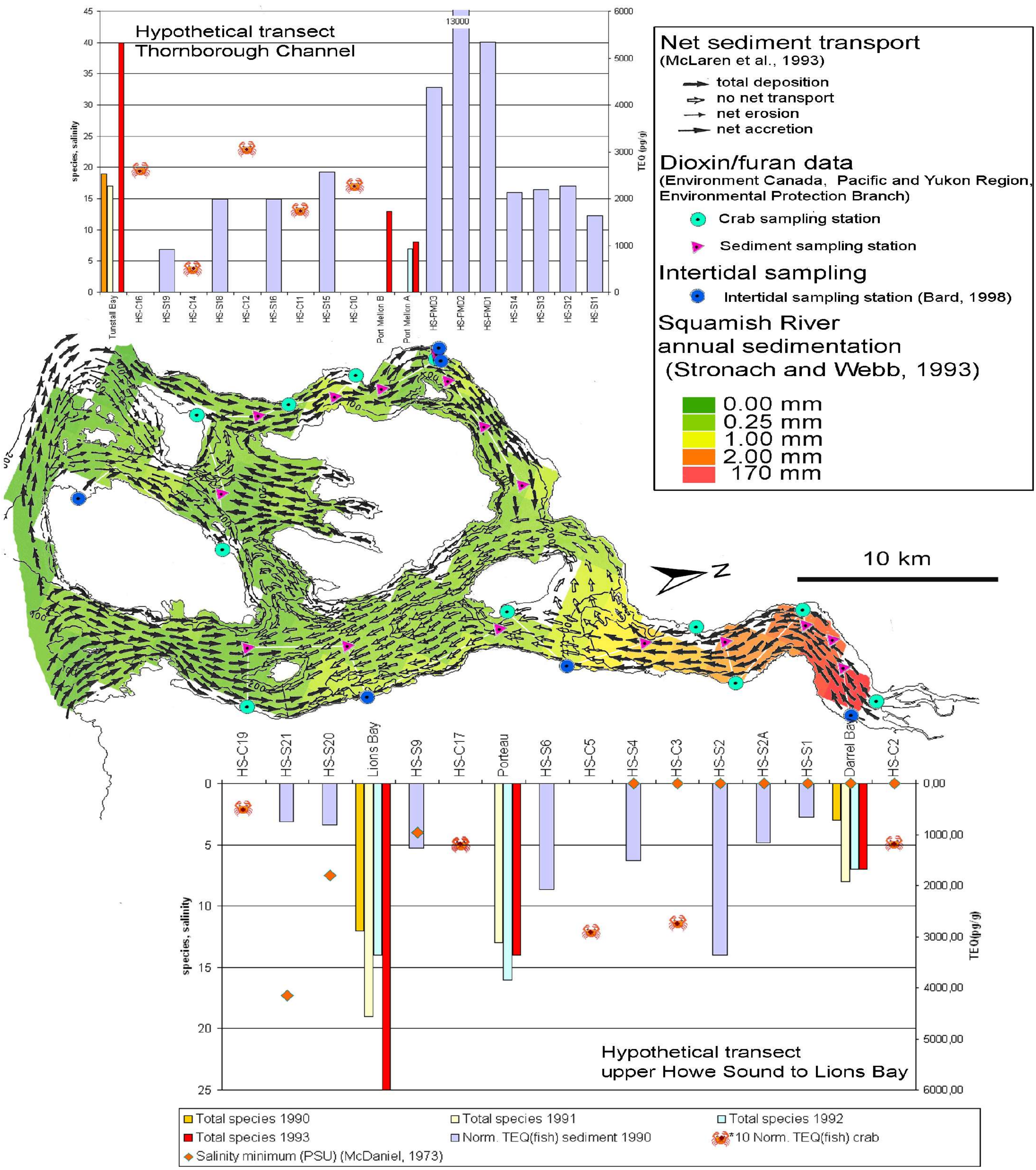

Fig. 8. Hypothetical transect and sediment data.

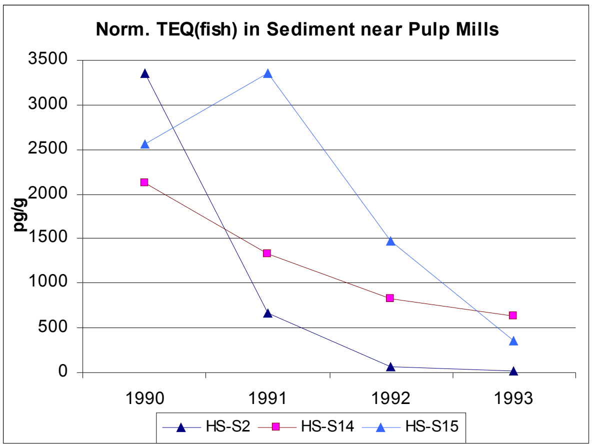

Fig. 9. TEQ(fish) in the sediment near both mills. Data source: Hatfield.

Upper Howe Sound and Lions Bay

The **Darrel Bay** site is about 3 km from the Squamish River mouth and is near a ferry terminal, transporting mill workers to the Woodfibre mill. The water was very silty and rocks were covered with silt (pers. comm. Shannon Bard, 2004). Other anthropogenic influences present were log booms in front of the site and wood fibres on the beach (pers. comm., Shannon Bard, 2004).

A sudden increase from three species in 1990 to seven or eight species in 1991-1993 was observed. In 1990, no algae were found in Darrel Bay, while in 1991 a green, brown and red algae species was found. Herbivores or carnivores/omnivores were never observed. Rockweed isopods (*Idotea wasnesenskii*) and Oregon pill bugs (*Gnorimosphaeroma oregonensis*) were very common in all sampling years. 5-10% of the rockweed (*Fucus* sp.) had orange discolorations and missed flotation bladders in 1991 (pers. comm., Shannon Bard, 2004). This discoloration might be explained by a spill of 20000 liters sodium chlorate to the surface water at the Woodfibre mill in 1989 and another spill of 2000 liters in 1990.

TEQ in sediment (Fig. 5 and Fig. 8: HS-S1) is low, but might be biased because of the very high annual deposition of Squamish River sediments in the area (170 mm a^{-1}), which buries contaminants (see Discussion: Confounding Factors). Crab TEQ is low (Fig. 5: HS-C2), but relatively higher than in other sites with similar sediment TEQ values (Fig. 5: sediment HS-S21 and crab HS-C19). The surface current pattern of the Squamish River predicts a low impact of the effluent and seasonally (freshet) very low surface salinities exist (till 0 PSU) because of the river discharge (McDaniel , 1973). Hodgins and Knoll (1990a) suggest no intertidal contact of the effluent and the site is outside of the Estimated Far-Field dispersion of the effluent (Hatfield, 1994).

Close to the Woodfibre mill, TEQ levels in crabs and sediment rise, but the site closest to the mill, Britannia Beach, is not discussed further, due to the very strong confounding influence of the acid mine drainage. Southward, the next intertidal site is **Porteau Cove,** which is situated inside a marine park. The bottom of rocks and the ground was covered with grey silty mud and brown, fibrous seaweed (*Pilayella littoralis*) (pers. comm. Shannon Bard, 2004). Log booms or wood fibres were not present at the site (pers. comm. Shannon Bard, 2004).

A significant decrease of the proportion of green algae (Chlorophyta) between 1991 and 1993 was found ($F(1, 1)=3267$ $R^2=0.999$, $p=0.01$, $B=-0.17$). In 1991, two out of the four algae species were green algae, but the proportion of green algae dropped to one out of six in 1993. Red algae were absent in 1990, but three species were observed in 1991 and 1993. Oregon pill bugs (*Gnorimosphaeroma oregonensis*) were present in all years, while rockweed isopods (*Idotea wasnesenskii*) were only observed in 1992 and 1993.

Sediment and crab TEQs are higher in Porteau Cove than in Darrel Bay, but the average number of species is higher in Porteau Cove (Fig. 7). Seasonally, very low surface salinities (till approx. 3 PSU) exist (McDaniel, 1973). The site lies well within the Estimated Far-Field dispersion of the effluent, but no intertidal contact of the effluent was suggested (Fig. 7). No net sediment transport takes place close to the site and the annual sedimentation is very low (0.26 mm a^{-1}) (Fig. 8).

The **Lions Bay** site was situated in front of a local residents' house and was relatively undisturbed. Except for the 1992 sampling, which was done in less detail (pers. comm. Shannon Bard, 2004), the biodiversity seems to increase from 12 species in 1990, to 25 in 1993, making this site the second most diverse in Howe Sound. However, the number of suspension feeders remained constant at two. The purple sea star (*Pisaster ochraceus*) was observed only at Lions Bay and Tunstall Bay. Wood fibers were never found on the beach (pers. comm., Shannon Bard, 2004).

Sediment and crab TEQ near the Lions Bay site are the lowest in Howe Sound. It is unclear which mill has the most impact on the site, as both mills are approx. 22 km away (shortest distance over water). The Lions Bay site is located at the point were Squamish and Fraser river surface currents (Fig. 7) and net sediment pathways seem to collide (Fig. 8). Low salinities (less than 17 PSU) occur during freshet (May-September). The Effluent Dispersion Study (Hodgins and Knoll, 1990a), suggests no intertidal contact and the site is outside of the Estimate Far-Field dispersion of the effluent-area (Fig. 7).

Thornborough Channel

The hypothetical transect in lower Howe Sound compromizes only three intertidal sites, of whom the Tunstall Bay site is distant from any contaminant sampling site. The two **Port Mellon** sites are adjacent to the mill. High quantities of fibers were present on the Port Mellon beach; log booms were tied up in front of both Port Mellon sites at the time of sampling and refuse logs were washed up on the beach (Shannon Bard, pers. comm., 2004). Sediment samples close to the chip dock, deep sea dock and rail slip (Fig. 8: HS-PMD1-PMD3, respectively), all very close to the intertidal sampling site, showed very high TEQ levels. TEQ levels at the nearby sediment sampling sites HS-S14 and HS-S15, have only dropped slowly compared to the site near the Woodfibre mill, HS-S2 (Fig. 3), consequently significant quantities of dioxins/furans were believed to be present in the sediment in 1993. The surface currents in Thornborough Channel are southwestward (Fig. 7), but net sediment pathways are believed to be in the opposite direction (Fig. 7).

The **Port Mellon A** site**,** closest to the Port Mellon mill, was relatively silty, probably due to a creek, discharging on the beach (pers comm. Shannon Bard, 2004). A large part of the intertidal quadrat was covered with a mass of fibrous algae (*Rhizoclonium* sp.) (pers. comm. Shannon Bard, 2004). Oregon pill bugs (*Gnorimosphaeroma oregonensis*) were observed in 1992 and 1993, while rockweed isopods (*Idotea wasnesenskii*) were absent in both years. Much of the rockweed (Fucus sp.) was discolored in 1992 and rockweed was absent in 1993. A spill of 45000 l sodium chlorate to the surface water near the mill in 1993 (Hatfield, 1994), might have induced the discoloration and disappearance of the rockweed, which is sensitive to chlorate (Rosemarin, 1994) (see Discussion: Species).

A few hundred meters farther away from the mill, the **Port Mellon B** site contained 13 species in 1993. At least two representatives per feeding guild were present as well as the three algae taxonomic groups (Fig. 7). Oregon pill bugs (*Gnorimosphaeroma oregonensis*) were found. Two fish species were present, the High Cockscomb (*Anoplarchus purpurescens*) and the Slender Cockscomb (*Anoplarchus insignis*). The brown algae species *Polysiphonia hendryi* and rockweed (*Fucus* sp.), were observed in low quantities at the site.

The **Tunstall Bay** site is the most diverse site in Howe Sound and the number of species increased from 19 in 1990 to 40 in 1993. The intertidal sampling in 1991 was done less extensively, because of prevailing weather conditions, which explains the low species number in that year (Shannon Bard, pers. comm., 2004). The total number of animal and algae species increased from 1991 to 1993, but the relative proportions of each feeding guild and algae taxonomic group remained unchanged. In contrast with other Howe Sound sites, Oregon pill bugs (*Gnorimosphaeroma oregonensis*) and rockweed isopods (*Idotea wasnesenskii*) were found only in very low numbers in 1993. The polychaetae *Serpula vermicularis*, the sea urchin *Strongylocentrotus droebachiensis* and the gastropod *Littorina* sp., were observed only in 1993.

Compared to 1990, six additional species of algae were observed in 1993: two brown algae (*Leathesia difformis* and *Sargassum muticum*) and four species of red algae (*Mastocarpus* sp., *Porphyra* sp., *Prionitis* sp., *Pterosiphonia bipinnata*). The purple sea star (*Pisaster ochraceus*) was present every year.

The magnitude of the effluent exposure at the Tunstall Bay site is unclear as no dioxin/furan sampling sites are nearby, but is probably low till very low according to the Estimate Far-Field dispersion of the effluent (Fig. 7) (Hatfield, 1994).

Subtidal Diversity

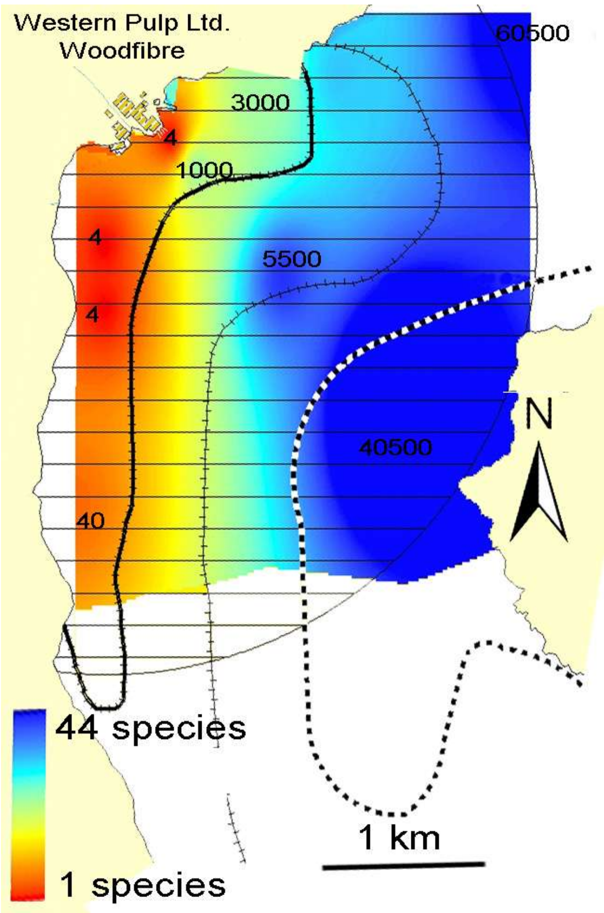

Fig. 10. Subtidal abundance and species diversity near the Western Pulp Ltd. mill at Woodfibre. Data source: Hatfield (1994). Hatched circle is 1% effluent dilution area (Hatfield, 1994). Dotted line indicate the effluent dispersion pattern (see Fig. 7).

For the Woodfibre mill the number of subtidal species is well correlated with effluent dispersion patterns (Fig. 10). Immediately near the submarine diffuser and along the western shore, the lowest species numbers are found. The number of species seems to be highly correlated with the total abundance.

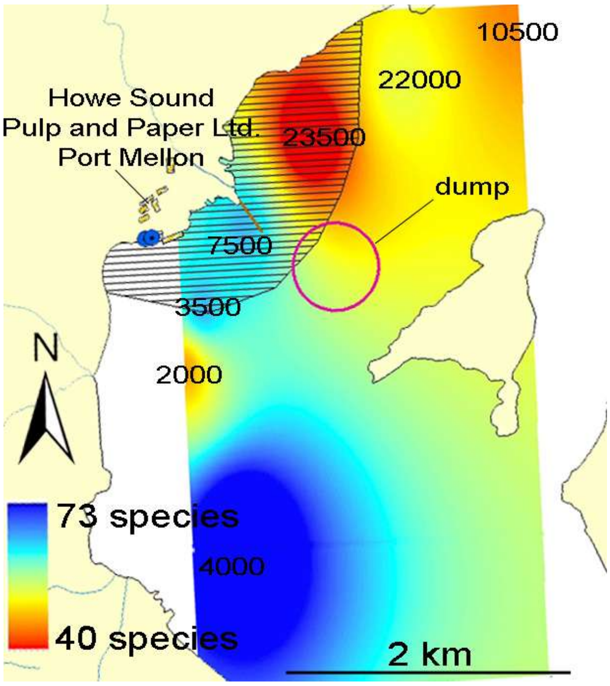

Fig. 11. Subtidal abundance and species diversity near the Howe Sound Pulp and Paper Ltd. mill at Woodfibre. Data source: Hatfield (1994). Hatched circle is 1% effluent dilution area (Hatfield, 1994).

A similar correlation between total abundance and number of species, is observed near the Port Mellon mill (Fig. 11). However, species numbers are higher in the immediate vicinity of the diffuser and south of the mill. As no detailed effluent dispersion data were available, no relationship between effluent dispersion and subtidal diversity could be examined. In general the number of species is higher near the Port Mellon mill and the abundance exhibits less variance.

Discussion

Hypothetical transect

Upper Howe Sound and Lions Bay

The most relevant feature of Howe Sound is the Squamish River discharge. Waldichuk (1962) suggests that the upper Howe Sound basin can be regarded as an estuary (Waldichuk, 1962), and consequently has some features unique to estuaries: very low surface salinities and sediment deposits, which can influence intertidal biota and confound the assessment of the mills' impact.

Although no intertidal contact was expected at **Darrel Bay**, based on the Plume Delineation Study, the site did exhibit a sudden increase in the number of algae species in 1991. But even after this increase, the number of species in Darrel Bay is low compared to the Porteau Cove site which has similar sediment TEQ levels. However, TEQ levels at the Darrel Bay site are biased due to the burial of the contaminants with Squamish River sediment (see Confounding Factors).

The low diversity intertidal community with only suspension and deposit feeding animals can be a result of effluent impact and the estuarine character of the site. Other factors might also influence intertidal diversity: wood fibers from log booms and siltation. While magnitude of effluent impact on the Darrel Bay site cannot be proven indisputably, chemical spills at the Woodfibre mill to the surface water seem to have an impact on the site. Discoloration of Rockweed, a brown algae, seems to be highly correlated with a sodium chlorate spill in the nearby Woodfibre mill (see Discussion: Species).

Nothing can objectively be said regarding mill impact on the **Britannia Beach** site, due to the major confounding factor of acid mine drainage. However, future sampling on this site is useful to observe the recolonisation of intertidal substratum after the planned installation of a water treatment plant on the Britannia Creek (Shannon Bard, pers. comm., 2004).

No intertidal contact was suggested for the **Porteau Cove** site, but in 1992 three species of red algae appeared and the proportion of green algae decreased significantly from 1991 to 1993. Because of seasonally low surface salinities, the only apparent confounding factor, this site has a moderate estuarine character.

The TEQ in crabs and the sediment near **Lions Bay** were the lowest in Howe Sound. No intertidal contact was expected by the Plume Delineation Study, and the site is outside of the Estimated Far-Field dispersion of the effluent. Nevertheless, species numbers more than doubled at the site from 1990 to 1993. The change in community structure can also be observed in the TWINSPAN tree, as each Lions Bay-sample is found in a different TWINSPAN group (Fig. 5).

The geographic order of the sites along the transect from upper Howe Sound to Lions Bay coincides with the clustering of these sites in the TWINSPAN and ordination analysis: the Britannia site clusters with the Darrel Bay sites in group one, while the Porteau Cove and Lions Bay sites cluster together in TWINSPAN group three and four.

Looking at all sites along the transect, some trends in the number of species can be observed. The Darrel Bay and the Porteau Cove site show a substantial change in the number of algae species. Also red algae species are suddenly found at both sites. However, this increase in algae species numbers did occurred in 1991 in Darrel Bay and in 1992 in Porteau Cove. However, at both sites the number of algae species didn't change anymore in later years, despite a further drop in the levels of BOD, AOX and toxicity.

The Lions Bay site on the other hand, exhibits a more gradual and continuous increase in diversity. As stated earlier, it is not known which mill has the most impact on the Lions Bay site. At the Port Mellon mill, however, the levels of BOD, AOX en TSS did not dropped from 1991 to 1993. The increase in intertidal diversity can be due to drop of AOX, BOD and TSS at the Woodfibre mill, but other factors might as well have an influence.

Thornborough Channel

For the Port Mellon mill, it is difficult to assess intertidal exposure based on crab and sediment TEQ, because effluent is mostly trapped under the halocline. The Plume Delineation Study even suggests no intertidal contact at all (Hodgins and Knoll, 1990b). Besides the two sites near the Port Mellon

mill, no further sampling was done in Thornborough Channel.
In the TWINSPAN tree and the DCA plot, the two Port Mellon A samples and the Port Mellon B sample are each in a different group, indicating a temporal evolution in the A site and a substantial difference between the B and A site.

The **Port Mellon A** site has substantially lower diversity than the B-site. This might be because it is closer to the mill and hence more vulnerable to physical disturbance by mill activities and spills. The impact of these spills is demonstrated by the low cover and discoloration of Rockweed in 1993 (*Fucus* sp.), which seems to be very well correlated with a spill of 45000 liters sodium chlorate in the same year, as no significant changes in the effluent from 1992 to 1993 were recorded for the Port Mellon mill. On the other hand, carnivores/omnivores and herbivores were observed in 1993, but not in 1992. This increase can not be linked clearly to a process change in the Port Mellon mill.

Species numbers at the **Port Mellon B** site are higher and two fish species were observed at the site. This might be explained by the local effect of spills, having a greater influence on the A-site, as the Port Mellon B site is a few hunderd meters further away from the mill.

As effluent is expected to stay under the halocline (Hodgins and Knoll, 1990b), the low species numbers in the two Port Mellon sites are probably more indicators for physical disturbance of mill activities (fibers, log booms, ships) and spills, as suggested by Hatfield (1994). Future sampling of this site is very useful to monitor intertidal recovery, but not really to assess the impact of the effluent itself.

The species composition of the **Tunstall Bay** site is quite distinct from the other Howe Sound sites, which is indicated by the TWINSPAN, ordination and INSPAN analysis. Additionally, there is a major increase in number of species, which doubled from 1990 to 1993. So in spite of the site being outside of Estimate Far-Field effluent dispersion area, a clear temporal trend is observed. This trend in intertidal biodiversity might be linked to changes in the Port Mellon mill effluent from 1990 to 1993, but cannot be proven.

In the Pre-Design document the Western shore of Bowen Island, hence Tunstall Bay, is proposed as a reference site. Ultimately the EEM program didn't use the Bowen Island area, but Toba Inlet, north of Howe Sound, because it was also a fjord, but no pulp mills discharged in the water body (Hatfield, 1996).
As the Tunstall Bay site has no estuarine influence, the species number in absence of any pollution, is expected to be higher than any other Howe Sound site (see Discussion: Species).

Subtidal

The subtidal study conducted near both mills in 1990 (Hatfield, 1994), using a grab sampler, demonstrated that density, number of taxa and species richness (number of taxa per number of individuals) decreased near the diffuser of the **Woodfibre mill**. The number of subtidal species is low at the western shore for at least 3 km south of the mill.

Assuming that effluent from the **Port Mellon mill** has the same impact on subtidal biota as Woodfibre effluent, the Port Mellon effluent appears to disperse north-eastward. Unfortunately, a correlation between intertidal and subtidal diversity was difficult to verify, as only two intertidal sites were sampled in 1993-1993, remote from the subtidal sites.

Species

In the assessment of intertidal effluent impact, it should be taken into account that an estuarine gradient exists in upper Howe Sound. Neglecting this feature might overestimate the effluent impact as estuaries have lower species numbers. This is explained by the “paradox of estuaries”: few species can thrive at the borderline between fresh and salt water (Chapman and Wang, 2001). Only species tolerant to a wide range of salinities and seasonal siltation are found in estuaries.

Thus, even in the absence of any pollution the maximum number of species in the Darrel Bay and Porteau Cove site will never be the same as in the Tunstall Bay site. Chapman and Wang (2001) even suggest that faunal distribution is primary controlled by salinity and only secondary by other factors as substrate and anthropogenic impact. Typically, estuarine benthic communities have low biodiversity, small body size, short life cycle and low competitive ability (Chapman and Wang, 2001).

Apart from the estuarine gradient, the effluent of the two pulp mills also creates a gradient of pollution. According to the paradigm of Pearson and Rosenberg (1978), benthic organisms respond in three (non-linear) consecutive stages to decreasing pollution: 1) increase of abundance, 2) increase of diversity, 3) shift in dominant species from pollution tolerant to pollution sensitive. Also distribution among feeding guilds is expected to become more divers, as pollution impact decreases (Word, 1978).

The classification of animal species in feeding guilds provided new insights in the data. Suspension feeders and surface deposit feeders were observed at all sites, while carnivores and omnivores were not found at Darrel Bay and Britannia Beach. This observation is probably due to the existence of an estuarine gradient, as well as a pollution gradient.

The division of algae species in three taxonomic groups allowed to identity trends for each group. For **brown algae** (Phaeophyta), a striking correlation between sodium chlorate spills and rockweed (*Fucus* sp.) discoloration was observed at the Darrel Bay site. Similarly at Port Mellon A, rockweed was discolored in 1992 and disappeared in 1993. Another brown seaweed (*Pilayella littoralis*), also disappeared in 1993. Rosemarin et al. (1994) demonstrated experimentally the toxicity of chlorate on brown algae. A first effect observed was the inhibition of the apical growth and flotation bladders. This is confirmed in the Howe Sound data, as some rockweed missed flotation bladders (pers. comm. Shannon Bard, 2004). Higher concentrations of chlorate induced discoloration in rockweed. This is believed to be due to the oxidation of polyphenolics, compounds naturally produced by *Fucus*-species (Rosemarin, 1994).

The toxicity of chlorate is due to the fact that it is an analogue of nitrate (Rosemarin, 1994). During nitrogen starvation, chlorate is being taken up and converted to the toxic compound chlorite (ClO_2^-), by the enzyme nitrate reductase (Rosemarin, 1994). As a consequence, high nitrogen concentrations render chlorate less toxic. Chlorate is highly soluble, non-persistent and does not adsorp to sediment particles or bioaccumulate in biota (Van Wijk and Hutchinson, 1995). So it can be assumed that only sites close to both mills will be affected by chlorate spills. Red and green algae were not sensitive to chlorate (Rosemarin, 1994).

Red algae were observed each year at Tunstall Bay and Lions Bay, but never at Port Mellon A and only one species in 1991 at Darrel Bay. The occurrence of red algae shows a temporal variation at some sites, but no immediate trend can be observed. For instance, no red algae were observed in 1991 at Porteau Cove, while at Darrel Bay, close to the Woodfibre mill, red algae were found only in 1991.

Green algae were observed at all sites, except in 1990 at Darrel Bay. The proportion of green algae dropped significantly in Porteau Cove, but a clear reason cannot be given

The INSPAN analysis proposed no indicator species for the low diversity sites in group IND1. This might be explained by the fact that the Darrel Bay site and the Port Mellon A site have low species numbers, due to a different reason. Estuarine conditions in the Darrel Bay site, compared to physical disturbance and spills for the Port Mellon A site.

The isopod Oregon pill bug (*Gnorimosphaeroma oregonensis*) was the only indicator species of group IND2. According to Kozloff (1983), Oregon pill bugs are an indicator for lower salinities. Salinities are indeed lower at Darrel Bay, but the Port Mellon A site has a moderate salinity.

Oregon pill bugs and rockweed isopods (*Ideotea wosnesenskii*) are abundant were rocks lie on gravely substratum and decaying seaweeds accumulate under rocks (Kozloff, 1983). Rockweed isopods were never observed at Port Mellon A and at Tunstall Bay. The absence of the species can be explained by the higher salinities at these sites. On the other hand, species might have disappeared because of physical disturbance at Port Mellon A and because of competition from other species at Tunstall Bay.

Seven indicator species for the Tunstall Bay site (IND3) were pointed out by the INSPAN analysis, suggesting the distinctness of this site. The suspension feeding polychaetae *Serpula vermicularis* , only observed at the Tunstall Bay site, is an indicator for low physical disturbance, high salinities (35 PSU) and a moderately exposed habitat (Hill, 2003). The absence of this species at all other Howe Sound sites can be attribuated to the low salinities at those sites.

The sensitivity of species for mill impact, as described by Bard (1998), was mostly confirmed: intolerant and sensitive species are indicator species for the Tunstall Bay site, which has very low effluent impact. The purple sea star (*Pisaster ochraceus*) and the red algae (*Caulacanthus ustulatus)* are indicator species for the Tunstall bay sites, but were deemed tolerant to mill effluent by Bard (1998). The red algae species was observed only in Tunstall Bay, while the purple sea star was also found in Lions Bay; both sites are 22 km from the nearest mill. For the other indicator species of the Tunstall Bay sites, no information on sensitivity or salinity preferences was available, complicating the assessment of effluent impact based on intertidal biota.

Confounding Factors

Tracers

Tracers for effluent exposure in the marine environment are problematic (pers. comm., Martin Davies, Hatfield, 2004). The absence of a quantitative parameter "exposure to effluent" for each site renders the interpretation of intertidal biodiversity data in Howe Sound difficult. This is the main reason why a regression with community parameters (number of species, number of suspension feeders,…) versus a tracer was not executed, as none of the tracers (TEQ, AOX,…) neither distance to the closest mill are objective measurements for intertidal exposure to effluent (see further). Each tracer has its own drawback. The major drawback of TEQ as a tracer is the fact that it was measured in subtidal sediment and crab sampling sites, but never in the intertidal area.

Distance to the nearest mill was not used as a tracer for exposure to effluent, because there is only one distance per site (to the closest mill), while it can reasonably be expected that the Lions Bay and Tunstall Bay sites are impacted by both mills. Additionally, effluent dispersion is influenced in a complex way by currents, confounding the correlation between intertidal exposure of a site and distance to the nearest mill. The fact that in the DCA-plot the first axis is correlated with distance is deceptive and is mainly due to the high biodiversity of the four Tunstall bay samples (22 km from nearest mill) and the very low biodiversity of the Britannia Beach and Darrel Bay samples. As discussed before, the diversity of these sites is the result of effluent exposure and salinity regime.

As the effluent of the Port Mellon mill remains trapped near the surface while it dissipates, contaminant contribution to the sediments is likely to occur over a large and diffuse area (Hatfield, 1994). The Port Mellon A and B sites are "in the shadow" of the effluent plume and experience only very little effluent exposure (Shannon Bard, pers. comm., 2004). The relatively high diversity of the Port Mellon B site demonstrates this. As a consequence, the exposure of a site to effluent from the Port Mellon mill is poorly correlated with the distance to the mill.

Drawbacks of TEQ as a tracer

The use of dioxin and furan levels in crabs and sediment, summarized in the TEQ, has several drawbacks. A first drawback is that only TEQ from 1990 was available for the whole Howe Sound region. In later years dioxins/furans were not measured at all sites. Another problem is the fact that organic contaminants are concentrated in the sediment because of the chemistry of seawater, as salinities in the deeper layers in Howe Sound are equal to seawater. Two major effects of salinity on the fate of contaminants are suggested by Chapman and Wang (2001). Firstly, higher salinities will "salt out" hydrophobic organic chemicals in the effluent, which is essentially freshwater, to the sediment phase. Secondly, dissolved organic matter, which has organic contaminants adsorbed to its surface, will be removed from the water column, through the floculation effect. Both processes actively remove contaminants from the water column and concentrate contaminants in and on top of the sediment. In this way they will no more be available for intertidal biota, but all the more for subtidal biota.

Sedimentation, which occurs mainly in the upper basin, tends to complicate the relation between TEQ and intertidal exposure to effluent even more, burying contaminants with sediment. Despite the problems with TEQ, the sediment concentrations of contaminants were found to be consistent with the Plume delineation study (Hodgins and Knoll, 1990a, 1990b).

Log booms, found near the Darrel Bay and Port Mellon site, have a deleterious effect on intertidal communities, as they produce lots of fibers that wash up on near by beaches. However, this confounding effect of the log booms can add a new application to intertidal monitoring: assessing the effect of log booming on Howe Sound shores.

Future

Recovery of the intertidal area

When the deep diffusers were installed, they lowered the impact on intertidal communities (Kay, 1989). In the same way the secondary effluent treatment is expected to improve intertidal habitat quality, but eutrofication, resulting from the effluent treatment, might introduce a new problem (Ferguson and McPhee, 1991). During secondary treatment biosolids are produced, aggregates of organic matter and bacteria (Hatfield, 1994). As a consequence, the observed diversity is the result of an inhibition because of effluent toxicity and stimulation by eutrofication.

It is unclear whether intertidal communities recover faster than subtidal biota, after a drop in effluent toxicity. Simultaneous subtidal and intertidal sampling could help clarify this relation. However, this seems reasonable for the rocky intertidal area, since rocks cannot retain contaminants. Yunker et al. (2002) observed a faster response in the dioxin/furan composition of crabs, compared to sediment, after major mill process changes.

Historic contaminants will still be in the sediment during the sampling of 2004, as for dioxins/furans a half life of ten years in the sediments is suggested (MacDonald et al., 1992). The sediment can be a continuous source of contaminants in regions with net erosion (Yunker et al., 2002), in addition to bioturbation. These regions are however limited to the Howe Sound mouth west of Bowen island (Fig. 8). Recolonization of a site is also highly dependent on the presence of larvae. Based on the planktonic drift of their larvae in Howe Sound, intertidal fishes are believed to have low recovery potential in case of environmental impact (Ferguson and McPhee, 1991).

So a general increase in intertidal diversity is expected, due to further process changes in both mills from 1993 to 2004. However, as pollution decreases, each site shall attain its maximum diversity, which is determined primarily by the presence of an estuarine gradient. Gradually the pollution gradient will disappear and only the estuarine gradient will remain.

Recommendations for future sampling

Regarding the future campaigns of 2004 some recommendations are given, based on the data analysis presented in this paper. To sample the complete gradient of pollution, the addition of some additional intertidal sites would be useful. Recommended sites in order of priority are: 1) in Thornborough Channel, north and south of the Port Mellon mill, 2) close to Woodfibre mill, 3) on the western shore of upper Howe Sound. Rocky beaches with minimum anthropogenic disturbance and no nearby creeks or freshwater influence on the beach should be selected.

Useful observations are: surface water salinity at the site, wave exposure, sediment loads of the water. The substratum under rocks should be registered carefully as rocks on top of gravel or bedrock will have a different fauna underneath. Regarding the quadrat study, the number of species as well as the abundance should be recorded. Discoloration of algae or any other abnormalities should be documented.

In addition to the intertidal species treated in this paper, changes in diatom (Rosemarin, 1994) and amphipod species composition (pers. comm. Martin Davies, Hatfield, 2004) are believed to be good indicators of effluent impact, although field identification is challenging. But, while interpreting the newly collected data, the presence of an estuarine gradient should not be neglected.

Conclusion

A GIS approach, combined with multivariate statistical analyses proved very useful in the assessment of pulp mill pollution in Howe Sound, because GIS allowed to visualize the two gradients existing in Howe Sound: a pollution gradient, result of the effluent discharges, and an estuarine gradient; the latter mainly in upper Howe Sound. Pollution assessments looking at a gradient were found to be more realistic in estuaries, than studies using reference sites (Chapman and Wang, 2001).

The classification of animal species in feeding guilds and algae species in taxonomic groups, turned out to be a powerful way of interpreting the intertidal data. But because of the limited size of the available data set, only one significant trend in the proportion of feeding guilds or algae taxonomic groups could be demonstrated. The general trend at all sites seems to be an increase in species diversity. At the Darrel Bay and Porteau Cove site, sudden increases in the number of species happened, but not synchronically. No further increases were observed at these sites in later years. At the Lions Bay and Tunstall Bay sites, a gradual increase in species numbers was observed.

The main challenges in the interpretation of the data were the presence of an estuarine gradient and the absence of a good tracer, which would allow to quantify intertidal exposure accurately. Any interpretation of intertidal data in Howe Sound should take into account currents, historical pollution, effluent discharge data and estuarine characteristics in order to correctly assess the true impact of pulp mill effluent on intertidal biota.

The continuation of this intertidal monitoring is certainly useful to evaluate future pollution abatement programs, and to create a long term data set. Contaminant measurements are only a snapshot, but benthic diversity is the result of long term habitat quality improvements. The intertidal area is the nursery ground for many subtidal species and therefore an intertidal-subtidal link is always present. Additionally, intertidal monitoring is the only sampling tool that can assess the effect of spills on intertidal biodiversity.

As conclusion, it can be stated that intertidal monitoring is a valuable addition to the current practice of taking subtidal grab samples.

Interpretation of the data, collected in 2004, can be done in a similar way as in this paper, using GIS to visually present the intertidal diversity, categorized in feeding guilds and algae taxonomic groups. The main challenge in the interpretation of the newly collected data, will be trying to correlate the observed biodiversity with the process changes at both mills during ten years.

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Appendix

				Sensitivity and Bioindex, adapted from Bard (1998)					Feeding guilds					Algae taxonomic group		
Site	Distance nearest mill (m)	Year	Total numer of species	% tolerant species	% sensitive species	% intolerant species	Bioindex	Suspension feeders	Surface deposit feeders	Herbivores	Carnivores/ Omnivores	Animal species	Green algae (Chlorophyta)	Brown algae (Phaeophyta)	Red algae (Rhodophyta)	Algae species
Brit. Beach A	5400	1990	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brit. Beach A	5400	1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brit. Beach A	5400	1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brit. Beach A	5400	1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brit. Beach C	4700	1991	3	0	0	0	0	2	0	0	0	2	1	0	0	1
Brit.Beach B	5500	1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Darrel Bay	5900	1990	3	100	0	0	0	1	2	0	0	3	0	0	0	0
Darrel Bay	5900	1991	8	100	0	0	0	2	3	0	0	5	1	1	1	3
Darrel Bay	5900	1992	7	100	0	0	0	2	3	0	0	5	1	1	0	2
Darrel Bay	5900	1993	7	100	0	0	0	2	3	0	0	5	1	1	0	2
Lions Bay	22400	1990	12	43	57	0	29	2	2	1	3	8	2	1	1	4
Lions Bay	22400	1991	19	30	70	0	35	2	4	2	5	13	3	2	1	6
Lions Bay	22400	1992	14	37	63	0	32	2	3	1	3	9	2	2	1	5
Lions Bay	22400	1993	25	23	77	0	38	2	4	3	7	16	4	3	2	9
Port Mellon A	1000	1992	7	100	0	0	0	2	2	0	0	4	1	2	0	3
Port Mellon A	1000	1993	8	100	0	0	0	2	2	1	1	6	2	0	0	2
Port Mellon B	1000	1993	13	25	50	25	50	2	2	2	3	9	2	1	1	4
Porteau	13000	1991	13	40	60	0	30	2	2	1	4	9	2	2	0	4
Porteau	13000	1992	16	43	29	28	43	2	3	2	3	10	2	1	3	6
Porteau	13000	1993	14	50	50	0	25	2	3	1	2	8	1	2	3	6
Tunstall Bay	22000	1990	19	0	100	0	50	6	0	2	7	15	1	1	2	4
Tunstall Bay	22000	1991	17	0	100	0	50	5	2	1	4	12	2	1	2	5
Tunstall Bay	22000	1993	40	8	46	46	69	9	4	5	12	30	2	3	5	10

Table 1. Summary of the intertidal source data. Bard (1998).

Group	Scientific name	Taxonomy	Sensitivity	Observed IV	Mean	Stdv.	p*
IND2	*Gnorimosphaeroma oregonensis*	Crustacea, Isopoda, Sphaeromatidae	T*	45,3	37,8	3,87	0,05
IND3	*Halosydna brevisetosa*	Annelida, Polychaeta, Polynoidae	S	54,9	22,2	9,94	0,04
IND3	*Serpula vermicularis*	Annelida, Polychaeta, Serpulidae	S	100	21,9	9,81	0
IND3	*Mopalia* sp.	Mollusca, Polyplacophora, Mopaliidae	S	66,7	19	9,92	0,01
IND3	*Pododesmus macrochisma*	Mollusca, Bivalvia, Anomiidae	S	100	21,9	9,81	0
IND3	*Eurystomella* sp.	Bryozoa, Cheilostomata, Eurystomellidae	I	100	21,9	9,81	0
IND3	*Pisaster ochraceus*	Echinodermata, Asteroidea, Asteriidae	T	78,9	25,1	11,9	0,01
IND3	*Caulacanthus ustulatus*	Rhodophytha, Gigartinales, Rhabdoniaceae	T*	100	21,9	9,81	0

Table 2. Indicator species generated by INSPAN Monte Carlo permutation test. IV=Indicator Value. Sensitivity adapted from Bard (1998).