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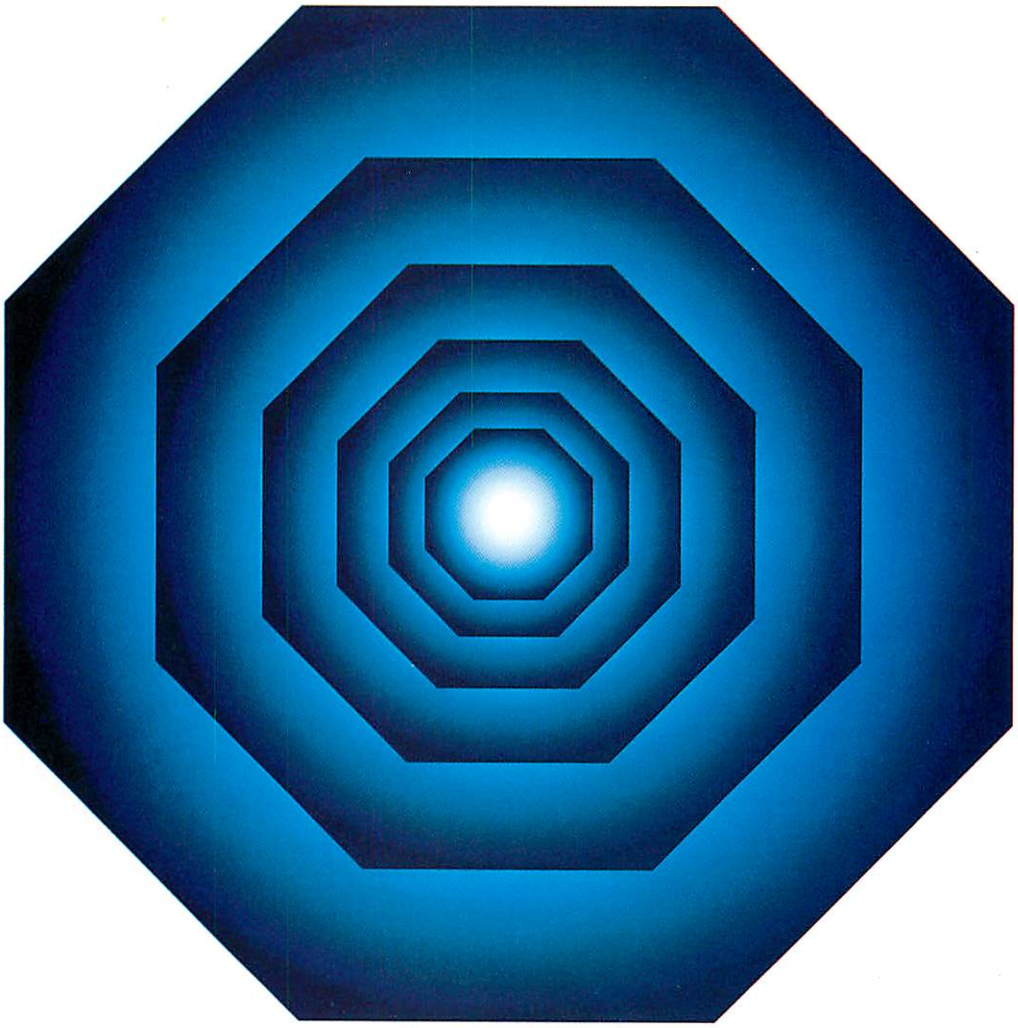

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Alteration of fish habitat by natural and industrial sedimentation in macro tidal estuaries British Columbia, Canada

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Abstract

Anomalous patterns of sediment composition in the intertidal zone of estuaries on the west coast of Canada (British Columbia (B.C.)) help identify potential changes to the estuarine ecosystem owing to the sedimentation of fine-grained material from both natural and industrial sources. Jetties and causeways, located on the largest tidal flats in B.C. at the Fraser River estuary, were found to 1) redirect the riverine suspended silt source in an offshore direction, 2) focus on-shore wave energy, and 3) cause a shift in sediment composition from mud to sand within the high intertidal zone of an intercauseway region. At a smaller B.C. estuary, Bonsall Creek, the deposition of gel-mud resulting from the discharge of particulate material from a water treatment settling pond likely affected the distribution and abundance of vascular plants and epibenthic and infaunal invertebrates within a tidal channel. Empirical data on the thickness of gel-mud deposits, loadings data, and a GIS analysis of tidal channels were used to compute possible deposition rates and area of impact. Estimated deposition rates at the landward head of the impacted tidal channel were significantly higher than maximum sedimentation rates estimated at two major estuaries: the Fraser River and Squamish River estuaries. Changes in sediment input, as well as modifications of estuarine geomorphology, can result in imbalanced sediment budgets for specific parts of an estuary. Changes in the capacity of an estuary to process and distribute sediment may therefore be a useful measure for ecosystem alterations and thus, general fish habitat management.

Key words:Fraser River estuary; Tidal sedimentation; Fish habitat; Squamish River estuary

1. Introduction

In this paper, we describe results from ecological studies of macrotidal estuarine environments from two settings in British Columbia (B.C.), Canada. This applied research was conducted to investigate potential alterations in sedimentation characteristics as a result of anthropogenic changes in sediment loadings and dispersal patterns of suspended particulate material. This research is necessary to determine if changes in sedimentation characteristics can lead to the harmful alteration, destruction, and disruption of fish habitat (HADD), which identify unauthorized activities under the habitat provisions of the Canadian Fisheries Act (Levings, 1999). Our research has focused on the habitats of detrital feeding invertebrates that are important as food for young salmon (Oncorhynchus spp). The young salmon live in estuaries after migrating downstream from the river where they hatched. At high tide the salmon move into the shallow waters over the mud and sandflats, where they feed and obtain refuge from predators before continuing their migration to the open Pacific Ocean. The tidal flats that we studied are located in the Strait of Georgia (Figure 1), a macrotidal environment with mixed semidurnal tides of up to 5 m range. This is a relatively small (surface area 6800 km2) enclosed coastal sea, with moderate wave energy (maximum fetch is about 200 km). However, seas with significant wave heights up to 2.5 m and periods of 7-8 s occur on occasion (Thomson, 1981).

Anomalous patterns of sediment properties of tidal flats in B.C. estuaries can help identify ecosystem alterations occurring in estuarine environments (Levings, 1980; Barrie and Currie, 2000). Changes in sediment input, as well as modifications of estuarine geomorphology, can result in imbalanced sediment budgets for specific parts of an estuary.

"Ifthe complex interactions (between morphology, tidal range, tidal prism and friction) can produce a condition of equal work per unit area of the estuary bed, then preferential erosion or deposition in any particular section is restricted,

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and an equilibrium can become established" (Dyer, 1986, p. 245). Scientific research on changes to this equilibrium state is necessary to determine if shifts in sedimentary processes and properties result in the harmful alteration and disruption of fish habitat. At present surrogates of ecosystem performance are being used by environmental managers, primarily those based on area (ha) of unvegetated vs. vegetated habitat, combined with qualitative measures of slope and substrate (Levings, 1999).

Whatever the prevailing sedimentation field of a particular estuary, sediment sources in equilibrium with the distribution of wave and current energy are necessary to maintain tidal flat ecosystems and detrital food webs supporting fish.

Although specific data from a range of estuaries are not available, it appears most estuaries in B.C. are characterized by relatively low annual sedimentation rates. Because of the highly mountainous and recently glaciated terrain in B.C., there are hundreds of streams and rivers that drain into the Pacific Ocean. Most of these catchment basins are characterized by granitic rock with a thin layer of sediment.

Except during high discharge periods (freshet), the concentrations of bedload and washload in rivers are relatively small and the water is not turbid. There are a number of estuaries located at the mouths of rivers that drain through sandy soils, glacial till, or have extant glaciers in their basin. These latter estuaries are typically characterized by higher sedimentation rates and have received the most attention from sedimentologists (e.g. Milliman, 1980; Williams and Hamilton, 1995; Amos et al., 1997; and Gibson and Hickin, 1997).

2. Disruption at the Fraser River estuary by structures changing longshore drift, wave reflection, and local sediment supply

The Fraser River (mean annual flow 3600 m3 s-1) drains a catchment basin of about 233,000 km2 and enters the sea near the city of Vancouver, B.C., at the southeast portion of the Strait of Georgia. The river is turbid, with an annual sediment load of approximately 17.3 x 106 t (65% mud, 35% sand) leading to the development of the largest estuarine sand and mudflats on the west coast of Canada. There are two large intertidal banks at the river mouth: Sturgeon Bank (83 km2) and Roberts Bank (141 km2). A more complete description of the Fraser River estuary is given in Barrie and Currie (2000) and Levings (1998).

Causeways built normal to the shoreline on Sturgeon Bank were found to have several effects on the intertidal sediment ecosystem. Firstly, wave energy became focused between two causeways built for river channelization and the deflection of sewage effluent (Figure 1). The focusing of wave energy was determined by the presence of unstable sand waves up to one metre in height in the intercauseway area, especially close to the most northerly causeway. These sand waves were mapped using aerial photography and verified by direct observation (Levings, 1980). Secondly, the causeways disrupted the longshore transport of fine sediments arising from the river mouth. Sand was the dominant sediment within the intercauseway region of Sturgeon Bank, in contrast to natural gradation from sand (at lower elevations) to mud (at higher elevations) observed elsewhere on the Banks (Levings and Coustalin, 1975).

Amos et al. (1997) showed that unconsolidated sand on the central sector of Sturgeon Bank had higher erosion rates relative to mud, including mud with a biological matrix such as algae. A reduction in the abundance of benthic invertebrates serving as salmon food was observed in the intercauseway beach region which did not support brackish marsh vegetation or the restoration of productivity using marsh transplanting technology (Pomeroy et al., 1981).

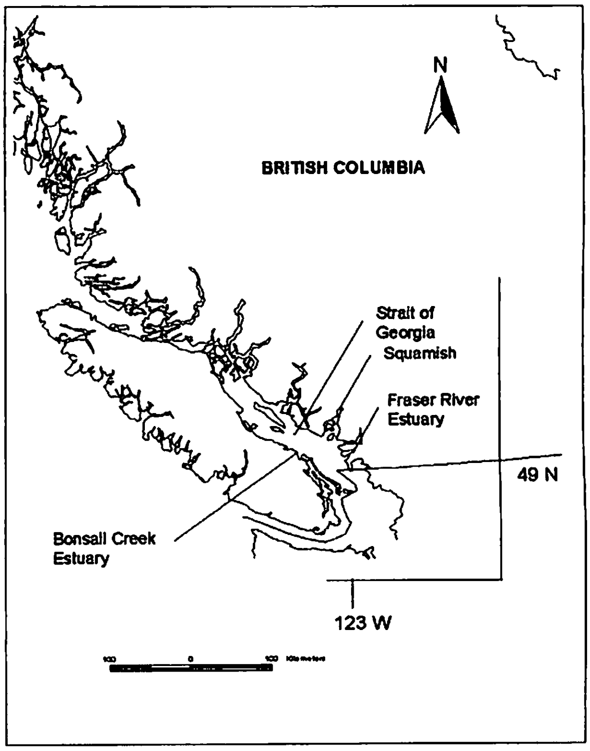

Fig. 1. Map of the British Columbia coast showing the Strait of Georgia and location of estuaries mentioned in the text. Fraser River estuary, Point Grey, Bonsall Creek estuary, Squamish River estuary.

On Roberts Bank, reduced accretion at a 82 ha upper intertidal salt marsh dominated by halophytes (Distichlis stricta and Salicornia validus (Hillaby and Barrett, 1976)) was attributed to causeway effects. On the marsh's southern flank, construction of a ferry terminal causeway in 1960 led to the cessation of northward longshore transport of sand and gravel from English Bluff, an escarpment on the southern edge of Roberts Bank (Canect, 1988). On its northern flank, a causeway for a deep sea terminal built in 1968 reduced mud supply for the marsh's building processes (Hillaby and Barrett, 1976; Canect, 1988) (Figure 2b). A dike was also built to reduce the potential flooding of farms landward of the salt marsh and original plans called for almost complete isolation of the marsh from tidal flooding. However culverts were installed through the dike as a mitigation measure (Hillaby and Barrett, 1976). This deep-sea terminal causeway has also had major effects on the sand flats and eelgrass habitats in the lower intertidal zone on Roberts Bank. The structure blocked the flow of fresh water and associated suspended sediment arising from the Fraser River and resulted in the deposition of mud on the estuarine side (Figure 2b). Although this data set is limited to 3 stations on the northern estuarine side of the deep-sea port causeway, observations made during concurrent studies have revealed the mud-dominated regions exist on the estuarine tidal flats relative to the intercauseway region. The intercauseway region on Roberts Bank experienced a shift in sediment composition from mud to sand and a decrease in turbidity promoting the rapid expansion and colonization of two eelgrass beds (Zostera marina, Z. japonica) (Tarbotton and Harrison, 1996). The disruption of the dispersal patterns of sand dispersion from the Fraser River channel to Roberts Bank has also affected subtidal environments, causing instability on the delta front (Barrie and Currie, 2000).

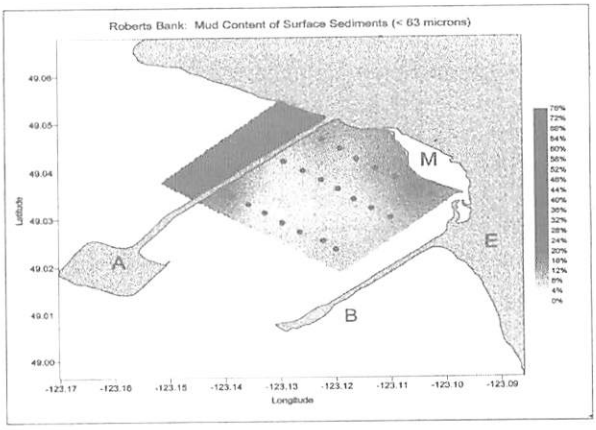

Fig. 2b. Map of the Fraser River estuary estuary, Roberts Bank, showing the effect of a causeway built for deep-sea terminals (A) on distribution of mud and sand on the intertidal flats (October 1997). Locations of a ferry terminal causeway, a sand feeder bluff on an escarpment, and a salt marsh are shown as B, E, and M respectively.

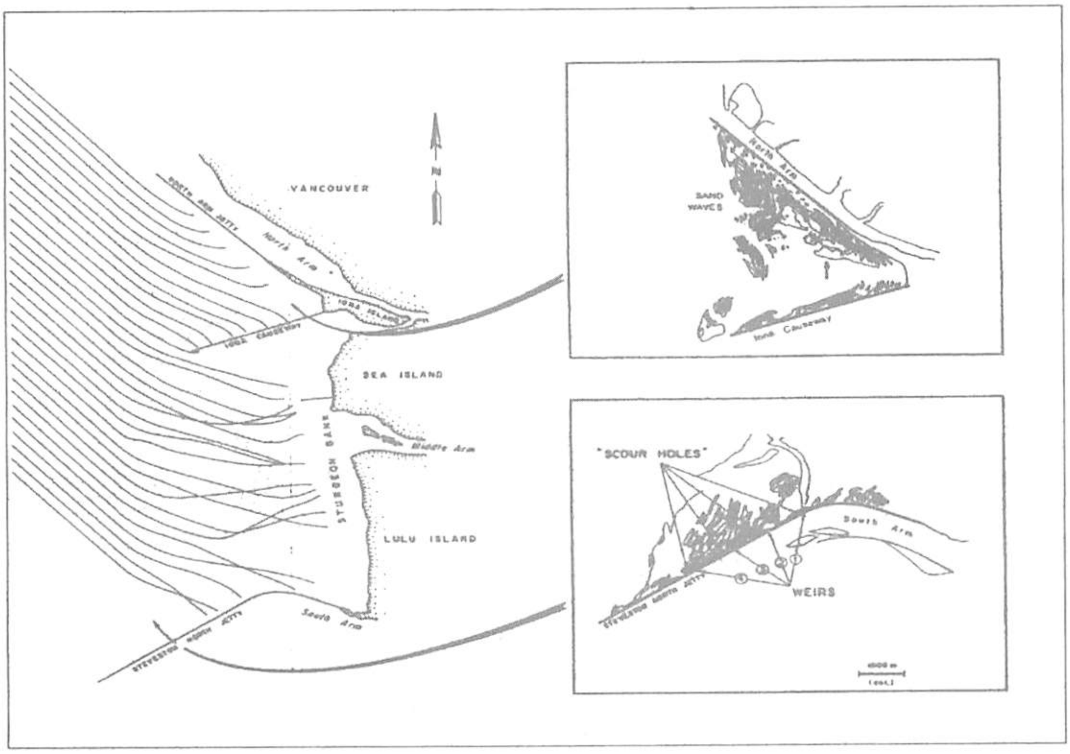

Fig. 2a. Map of the Fraser River estuary showing the intercauseway area on Sturgeon Bank where wave focusing has led to a modified sedimentary environment (from Levings, 1980).

3. Disruption by diversion of sediment from the Cowichan River to the Bonsall Creek estuary

Bonsall Creek is a small non-turbid river (catchment basin area 13 km2) which discharges onto an estuarine sand-mud flat on Stuart Channel, on the southwest coast of the Strait of Georgia (Figure 1). A pulp mill diverts water from the nearby Cowichan River (catchment basin area 123 km2) into a water treatment plant. The intake for the diversion system is approximately 11 km upstream from the mouth. A settling pond connected with the treatment plant captures sediment from the plant and the pond introduces fine sediments to the Bonsall Creek estuary. This diversion has been occurring since 1957 and up until 1998 approximately 885 t sediment y -1 was moved from the Cowichan River to the Bonsall Creek estuary. Although recent improvements in engineering practices at the pulp mill have resulted in lower sediment loadings (annual average 44.7 t y-1), heavy sediment discharges have occurred on occasion (e.g. 749 kg d-1; in November,1998) (Levings et al., 2001).

3.1. Sedimentation rates near the outfall

In order to calculate an estimate of the sedimentation rate of the sediment loadings into an affected tidal channel (landward end of transect AA5, Fig. 2c), flow and concentration data (e.g. suspended solids, mg L-1) are required. Since these data were not initially available, we computed approximate deposition rates using available data on the amount of sediment flushed from the pond annually (kg yr-1) and an estimate of the affected area (m2). We assumed these sediments would be deposited in the first 800 m of the tidal channel where transect AA was located, as predicted from a regression model relating distance from the outfall and sediment grain size (Figure 4). From a GIS presentation of the morphology of the tidal channel (see Levings et al., 2001), we estimated that the total minimum surface area affected in the channel would be about 2 ha.

The average depth that a corer could be pushed into the sediment was about 52 cm on Transects A and AA, compared to approximately 36 cm on the other transects located north of the affected area. These data indicate that a thicker layer of fine sediments was deposited on the former transects. GIS analysis of the area where the corer could be pushed at least 50 cm into the gel-mud layer was estimated between 7 and 9 ha of the Bonsall Creek estuary (Figure 3).

Assuming a bulk density of 1150 kg m-3 for deposited gel-mud or 1500 kg m-3 for consolidated muds (Sutherland et al., 1998), the predicted average sedimentation rates, or deposition heights, in the first 800 m of the affected channel would have been between approximately 3.8 and 2.9 cm yr-1, respectively. Because the sediments are coagulated by the addition of alum in the settling ponds the material would likely settle in the form of a gel-mud, as confirmed by our direct observations at Station AA5. These estimated sedimentation rates are higher than those from the intertidal zone of the two B.C. estuaries where data are available. At

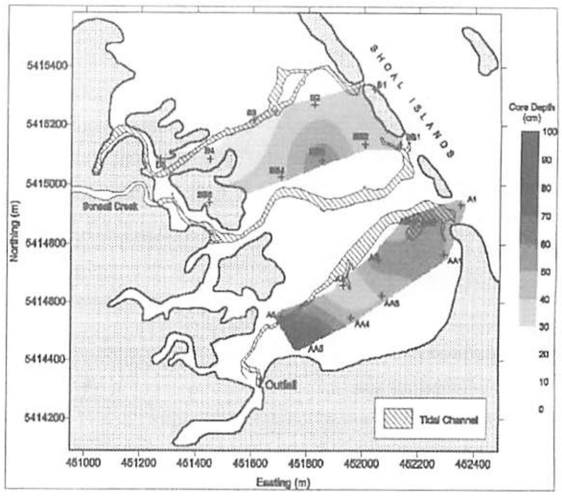

Fig. 3. Contoured data on core penetration depth at four sampling transects close to the settling pond outfall on Bonsall Creek estuary (from Levings et al., 2001). The contouring program only extrapolated 25 m from the sampling stations and therefore is highly conservative for area affected.

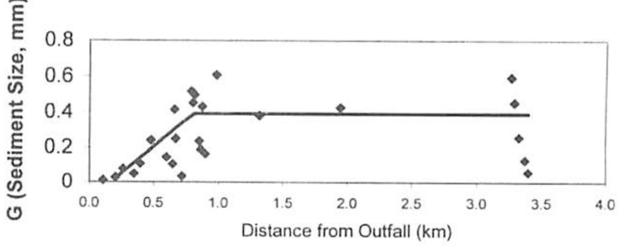

Fig. 4. Best fit regression model relating sediment grain size (as expressed by geometric mean particle size of sediment passing through a 2-mm sieve) to distance from the outfall at the Bonsall Creek estuary (from Levings et al., 2001).

the Fraser River estuary, Williams and Hamilton (1995) estimated a maximum sedimentation rate of 2.1 cm yr-1 (range 0.3 to 2.1 cm yr-1) in a marsh on Sturgeon Bank. At the Squamish River estuary Pomeroy (1977) estimated an annual average rate of 1.5 cm yr-1 in the intertidal zone.

Using the same calculations with the most recent (1998-1999) annual average loadings data (see Levings et al., 2001) of about 44.7 tonnes yr-1, the annual sedimentation rate would be approximately 0.2 cm yr-1. This rate is well within the natural range expected in the intertidal zone of B.C. estuaries (see above) and falls within the natural changes in bed elevation owing to suspension/deposition from tidal action (Whitehouse and Mitchener, 1998). Even with worst case daily loadings (e.g. November 23 1998; 749 kg d-1), daily sedimentation rates would be very low (<1 mm d-1) over the estimated depositional area of the channel (800 m).

However there could be very significant build-up of sediments in strongly depositional areas such as bends and corners that could occur over time. In addition, the habitat in the first few m2 downstream of the culvert would be severely affected - for example the 10 m2 immediately below the culvert would be subjected to sedimentation of approximately 4.0 cm d-1, which could cause catastrophic burial of invertebrates. Before the sediment loading from the outfall was reduced in 1998, our preliminary data showed polychaete worms were less abundant near the outfall (Figure 5a), but amphipods were not (Figure 5b). More research is needed on the sensitivity of invertebrates to the gel-mud, especially as direct effects such as gill clogging or failure of larval settlement may be interacting with toxic effects from aluminum. The latter would be especially significant in the fresh water at the outfall. Effects of uncontaminated sediment on adult invertebrates have been documented in a few local studies. For example, Chang and Levings (1978)

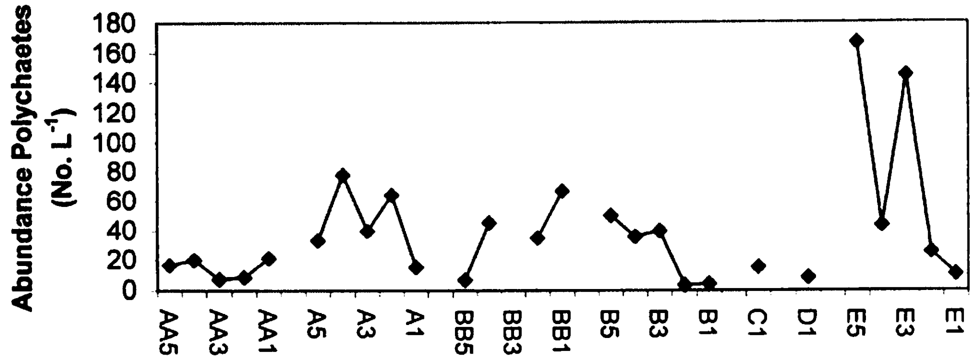

Fig. 5a. Abundance (number L-1) of polychaetes at varying distances from the outfall along transects at Bonsall Creek estuary (see Figure 4), sampled from cores at low tide (from Levings et al., 2001). Transects C, D, and E are to the north of the estuary and are not shown on Figure 3.

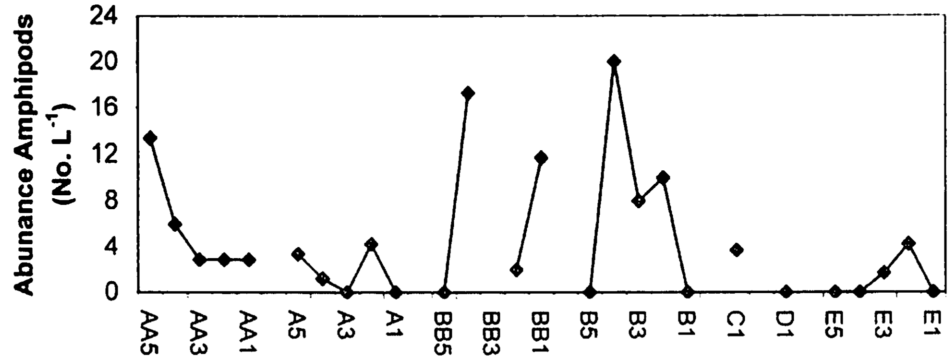

Fig. 5b. Abundance (number L-1) of amphipods at stations at varying distance from the outfall along at Bonsall Creek estuary (see Figure 4), sampled from cores at low tide (from Levings et al., 2001). Transects C, D, and E are to the north of the estuary and are not shown on Figure 3.

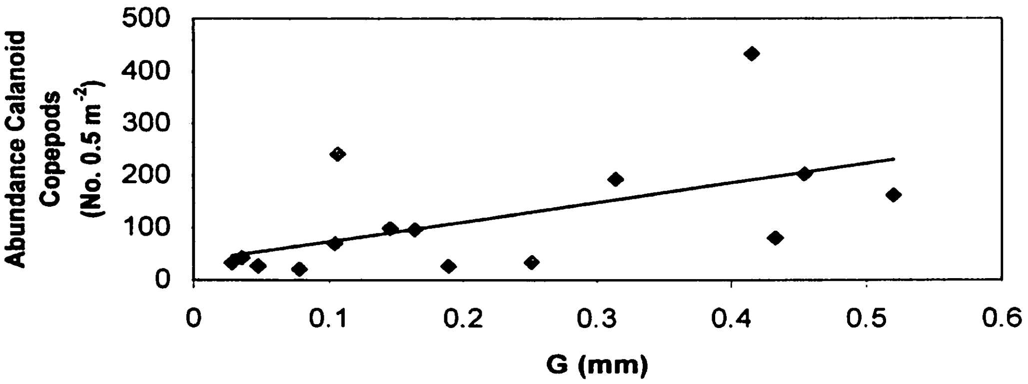

Fig. 5c. Abundance of calanoid copepods (number 0.5 m-2) sampled by an epibenthic sled at high tide in relation to sediment grain size (as expressed by geometric mean particle size of sediment passing through a 2-mm sieve). Data are from transects AA, A, B, and BB on the Bonsall Creek estuary (see Figure 3).

observed that cockles (Clinocardium nuttalli) were immobilized by 10 cm of sand in laboratory experiments.

Levings et al. (1978) found somewhat similar results with other species of invertebrates, in a field study on the Fraser River estuary mudflats.

3.2. *Effects of suspended sediment in the water column*

At high tide, crustaceans such as calanoid copepods, which feed in the water column or near the bottom, move over the tidal flats from offshore. Their abundance was inversely related to proximity to the outfall (Figure 5c), possibly because they were avoiding elevated high suspended sediment (SS) concentrations. We have no data on levels of SS, but speculate they may have been higher than normal on the landward end of transect AA because of levels discharged, wave erosion, or particle saltation. Increased suspended sediment has been shown to reduce the feeding rate of copepods in several studies (e.g. Butler, 1995).

Alternatively the relationship may reflect distance from deeper water, the main habitat of calanoid copepods, as the fine sediments were generally located at sites closer to the shoreline.

3.3. *Change in vegetation communities*

Direct comparisons of the vegetation communities adjacent to the affected channel identified by air photo interpretation of 1998 images were obtained with baseline 1981 data given in Campbell et al. (1982). However, a new transition vegetation community was identified that may not have been present in the 1981 data (Levings et al., 2001). This new community, dominated by seashore saltgrass (Distichlis spicata), may have developed in response to sediment accretion, probably in the intertidal areas between tidal channels (e.g. north side of transects A and AA, Figure 3), where glasswort (Salicornia virginica) was previously dominant. Both of these salt marsh plants are important in food webs supporting fish in British Columbia estuaries (e.g. Hillaby and Barrett, 1976).

3.4. *Changes in the competency of the Bonsall Creek estuary*

It is clear the equilibrium between sediment input from the Bonsall Creek watershed and its subsequent dispersal by natural hydrological and oceanographic processes have been disrupted by the introduction of sediment from the Cowichan River. In an unmodified estuary there is a dynamic balance between freshwater inflow and sediment loading from the watershed - these factors shape the estuary (Dyer, 1986) and the organisms living in it. The Bonsall Creek estuary's competency for sediment flux has been overwhelmed by sediment from another watershed, which could have been up to 39,825 t between 1953 and 1998. We have no data on the loadings of natural sediment from Bonsall Creek; further data are needed to determine if sediment loading from the settling pond was within natural variability - but our data suggest it is not. It should also be noted that the estuary's competency has been compromised by the construction of an agricultural dyke in the earlier 1900s, which reduced the surface area of the estuary available for dispersion. The sediment diversion

Table 1. Proposed table of scores to measure loss of ecological integrity based on changes in rate and directions of sediment dispersion, Bonsall Creek and Fraser River estuaries.

Integrity measure/site	Bonsall creek estuary	Fraser river estuary
Lateral sediment dispersion from the river mouth is blocked	No (-)	Yes (+)
Salt marsh to riparian succession is blocked	Yes (+)	Yes (+)
Sediment from watershed outside natural range	Yes (+)	No (-)
Sediment movement alongshore from marine supra tidal feeder sources is blocked	No (-)	Yes (+)
Sediment can move onshore from marine subtidal feeder sources	Unknown	Unknown
Delta front is unstable subtidally	No (-)	Yes (+)
> 50 % of delta inside dikes	Yes (+)	Yes (+)
Total scores toward loss of cological integrity	3	5

and morphological change in the estuary are likely why our study and McClaren (1996) observed unusual patterns of sediment dispersal over the Bonsall Creek mudflats.

Reduced competency may also contribute to sedimentation in the affected tidal channel by moving material discharged from the settling pond outfall back into the affected tidal channel after it has been discharged seaward.

4. Summary of fish habitat disruption and sedimentology

Our studies strongly suggest that fish habitat disruption can occur when sediment dynamics are modified by industrial activity and rates and patterns are forced outside their normal ranges. A proposed scoring scheme that might be used to evaluate the ecological integrity based on changes in estuarine competency in a semi-quantitative sense is shown in Table 1. Observations that estuarine sediment dynamics have been forced out of equilibrium conditions by anthropogenic activities might be a useful operational definition of harmful alternation, disruption, and destruction of fish habitat in estuaries. In this scheme, Bonsall Creek estuary has had fewer (loss score 3) of its functional attributes removed compared to the Fraser River estuary (loss score 5). Biological integrity features such as presence of exotic species, areas of low productivity, eutrophication, etc., could be added to the scheme in future work. As described, a variety of engineering works can change the natural equilibria and reduce the competency of the estuary to prograde and process sediment for ecosystem maintenance.

Causeways and dikes on the Fraser River estuary are examples of structures that can change sediment movement pathways after initial deposition from the river. The diversion of sediment from one catchment basin to another, as shown by the example at Bonsall Creek, is clearly a major ecological disruption with both near and far-field effects.

Acknowledgements

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