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SEDIMENT TRANSPORT PATTERNS IN THE LOWER FRASER RIVER AND FRASER DELTA

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The Fraser River delivers an estimated load of 17×10^6 t of sediment to the Fraser River delta and Strait of Georgia each year (McLean and Tassone 1991). This sediment load and its distribution are important in sustaining the ecology of the delta and estuary. For example, the tidal flats of Sturgeon and Roberts banks, historically formed from Fraser River sediments, have international ecological importance, particularly as bird and fish habitat (Fraser River Estuary Management Program 1994; Vermeer and Butler 1987). These deposited sediments also provide an indicator of this environment's condition through the concentration of contaminants in the sediment (Brewer *et al.* 1998; Swain and Walton 1991, 1993, 1994). Although important for its sustenance of fish and wildlife habitat, sediment deposition presents a concern for maintaining shipping access to the lower river. Thus, since the turn of the century, there has been an ongoing program to maintain a navigable shipping channel in the estuary through the removal of sediment from the river channels by dredging (Neu 1966).

An understanding of sediment transport and its distribution is important in managing the estuary and delta. Therefore, we conducted a study to investigate net sediment transport patterns in the Fraser River Estuary and delta foreshore. The specific objectives were: (1) to establish the pattern of sand movement, for guidance in determining optimum areas for dredging and for depositing dredged sands; and (2) to determine the best sampling sites for monitoring contamination in Fraser Estuary sediments by developing knowledge of the movement and deposition areas of fine sediments. These sediments are preferred for contaminant sampling because of the greater surface area for contaminant adsorption (Karickhoff *et al.* 1978).

In this study, net sediment transport patterns were established using a technique known as a Sediment Trend Analysis (STA™). First described in McLaren and Bowles (1985), this approach measures relative changes in grain-size distribution of the existing sediments. The derived patterns of transport are, in effect, an integration of all processes responsible for the erosion, transport and deposition of sediments over the time period required to form the deposits. In addition, the analysis estimates the probability for transport of each grain size, thus describing the behaviour of the sediments in the environment.

This largely qualitative approach (it is unable to establish rates of transport or deposition) has been used elsewhere to: (1) evaluate and direct numerical models (Van Heuvel *et al*. 1993; McLaren *et al*. 1993a); (2) determine the behaviour of sediments at dredged material disposal sites (McLaren and Powys 1989); (3) predict the build-up and dispersal of contaminated sediments (McLaren *et al*. 1993b; Little and McLaren 1989); and (4) understand the sediment and process interrelationships among natural marine and coastal environments (De Meyer and Wartel 1988).

METHODS

In the pre-freshet period between February 9 and April 7, 1993, 1,488 surface sediment samples were collected from the Fraser River, from its confluence with the Pitt River (including 1 km up the Pitt River) to the 200-metre bathymetric contour in the Strait of Georgia. The northern and southern boundaries of sampling were Point Grey and Point Roberts. A Shipek Grab was used to sample the top 10 to 15 cm of surface sediment. The intertidal flats (Roberts and Sturgeon banks) were sampled with a trowel from a hovercraft. A representative sub-sample (about 100 g) from the grab was stored in a sealed plastic bag and shipped to the GeoSea (UK) office in Cambridge for grain-size analysis.

In the river, sampling was carried out on a series of transects spaced 500 m apart. On each transect, collection sites were equally spaced at about 100 m apart. Where the river was narrow, a sample was collected in the centre of the main channel and midway from the centre to the bank on either side. On the intertidal banks, samples were collected on a regular grid of 500 m spacings; in the offshore the interval was increased to 1 km.

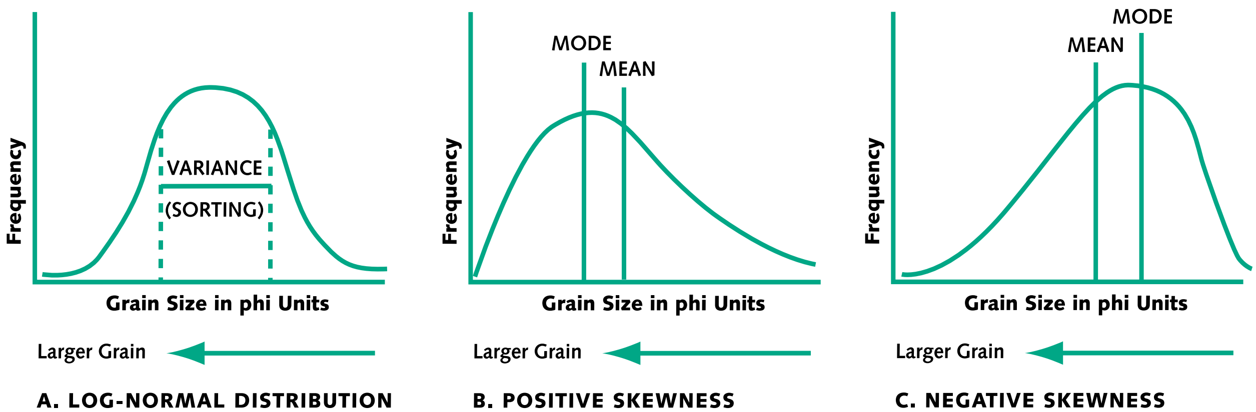
The grain-size distribution of each sample was determined by sieving sediment (ranging from -2 phi [ϕ] to 0ϕ [4 mm to 1 mm] grain-size diameter) at 0.5ϕ intervals. A Malvern laser particle-size analyzer was used to determine the particle size for the range between -0.85ϕ to 10.0ϕ (1.8 mm to 1.0 μm) grain-size diameter following a standardized technique developed by GeoSea Consulting Ltd. (McLaren and Ren 1995). Where both size fractions were present, the sieve and laser data were merged to form one complete distribution.

Sediment Trend Analysis

Details of the theory are described in McLaren and Bowles (1985) and McLaren and Ren (1995). The approach is summarized here.

The Sediment Trend Analysis examines the relationship in grain-size distribution among adjoining sediment samples. Grain sizes of most sediment deposits are characterized by a log-normal distribution, as illustrated in Figure 1a. Deviations from this distribution are caused by erosion, transport and deposition and result in skewness from the log-normal distribution (Figure 1b, 1c). The Sediment Trend Analysis model shows that, as sediment erodes, the selective removal of fine-sized particles occurs in such a manner that the grain-size distribution of the lag, or remaining deposit, is coarser, better sorted and more positively skewed (*i.e.*, the median particle size is larger than the mean) than the original deposit.

The model builds a relationship between two hypothetical sediment samples (D_1 and D_2) which are taken sequentially in a known transport direction (for example from a riverbed where D_1 is the up-current sample and D_2 is the down-current sample). The theory shows that the sediment distribution of D_2 may become



Phi units are based on a negative log scale.

Figure 1. *Illustration of grain-size distribution of sediment deposits.*

finer or coarser than D_1. If it becomes finer, the skewness of the distribution must become more negative. If D_2 is coarser than D_1, the skewness must become more positive. Over time, sediment at both sites will be sorted into more uniform particle sizes. If either of these two trends is observed, we can infer that sediment transport is occurring from D_1 to D_2. However, if D_2 is finer, better sorted and more positively skewed than D_1, transport cannot be from D_1 to D_2 and we cannot suppose that transport between the two samples has taken place. Under this scenario D_2 must be more negatively skewed than D_1 for transport to have occurred from D_1 to D_2.

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

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

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

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

To analyze for sediment transport directions over two dimensions, a grid of samples is required. Each sample is analyzed for its complete grain-size distribution and these are entered into a computer equipped with appropriate software to search for statistically acceptable trends.

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

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

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

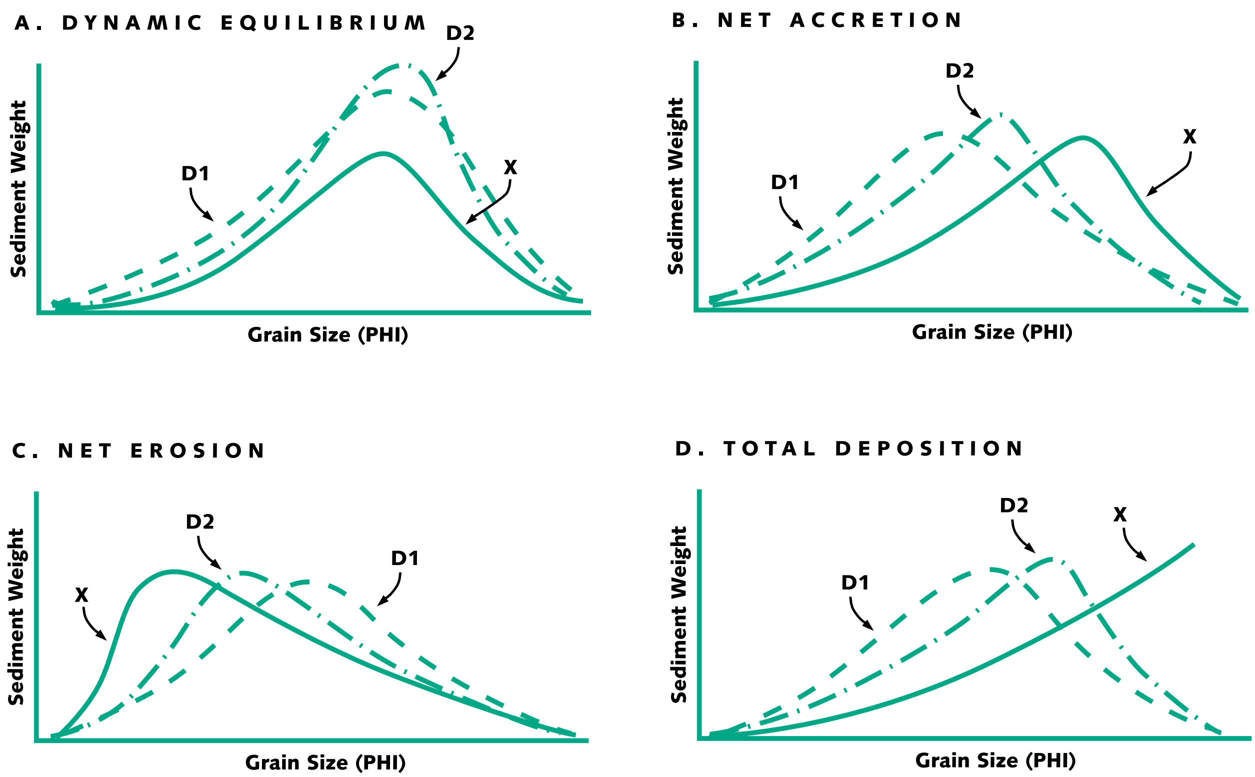


Figure 2. *Summary of interpretations given to shapes of X-distributions relative to the D_1 and D_2 deposits.*

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

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

A multiple correlation coefficient (R^2), defining the relationship among the mean, sorting and skewness in the sample sequence, was calculated. The R^2 gives a relative indication of how well the samples are related by transport. If a given sample sequence follows a transport path perfectly, R^2 will approach 1.0 (*i.e.*, the sediment samples are perfectly related by transport).

RESULTS AND DISCUSSION

Separate transport trends were established for two sediment types: sand (samples composed of 50% or more sand[1]) and mud (samples composed of 50% or more mud; mud[2] is defined as silt + clay). The sand comprises the majority of the data base (65% of the samples) and is found mainly in the river and on the tidal flats (Figure 3).

[1] ***Sand:*** *Particle Diameter from 4ϕ to 0ϕ (62.5 μm to 1 mm)*

[2] ***Mud:*** *Particle Diameter >4ϕ (<62.5 μm)*

Figure 3. Sediment types in the lower Fraser River and Delta.

A total of 175 transport lines were selected to describe the pattern of sand transport and 67 transport lines were used for describing mud transport. Details of sand and mud trends are presented in McLaren and Ren (1995). Figure 4 presents a summary of the major transport patterns detected for sand. Figure 5 presents the trends for mud.

River Sections

In the Fraser River, the derived sediment transport patterns show general net movement of both sand and mud from the upstream end of the study area to all the exits into the Strait of Georgia. This follows the classic delta morphology associated with the river. Exceptions are upstream transport, or reversals in a number of channels (Table 1). Upstream movement of sediments towards Pitt River is shown in the Coquitlam/ Pitt River area. The evidence for such movement is supplied by the formation of a "negative delta" at the south end of Pitt Lake, the result of flood tide currents that are stronger than the combined ebb stream and river flow (Thomson 1981). No specific evidence in the literature could be found to directly support any of the other reversals.

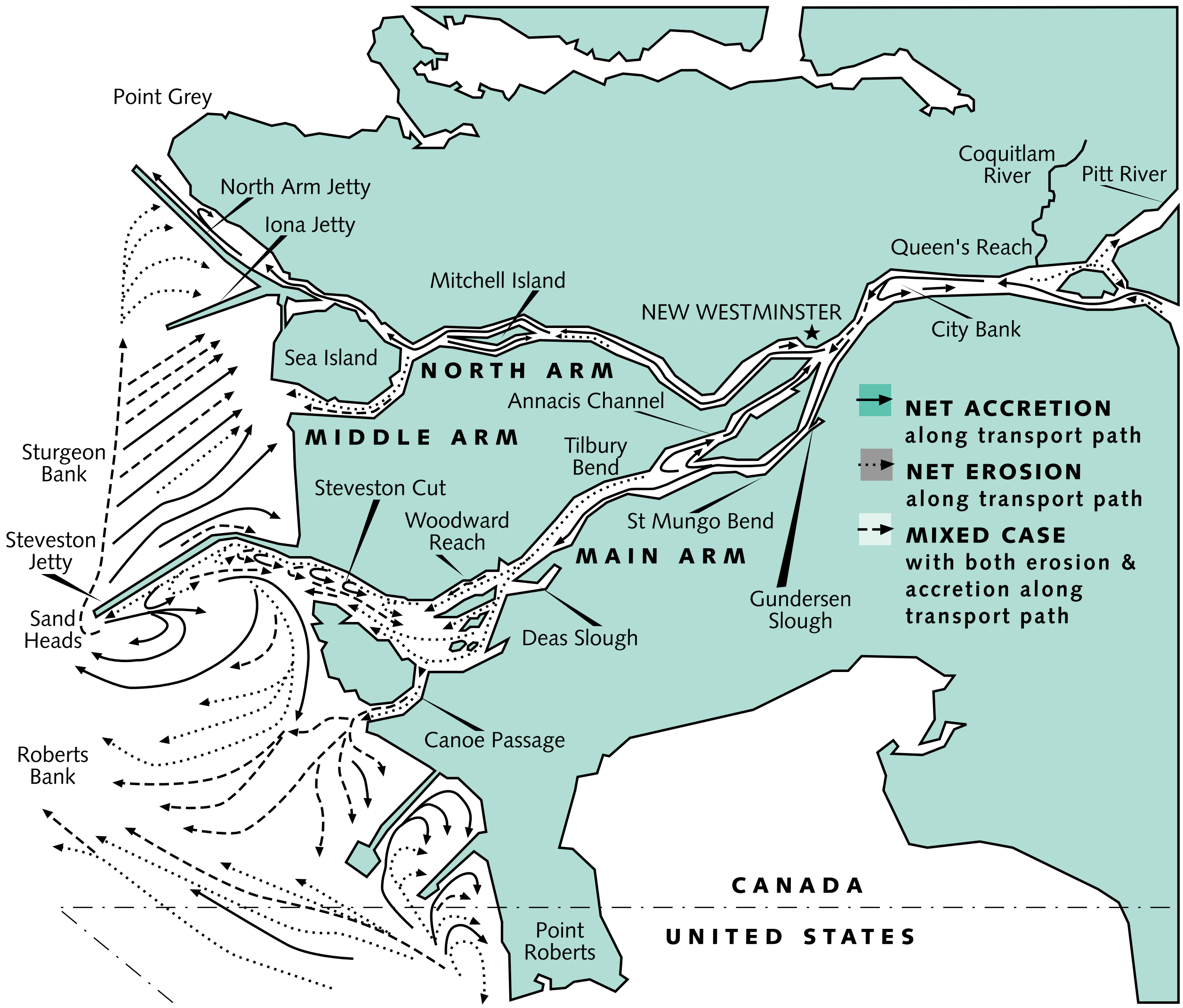


Figure 4. Sediment Transport Patterns for Sand in the lower Fraser River and Delta.

In some instances, the observed reversals coincide with areas requiring major dredging. Ferguson (1991) has identified the North Arm immediately east of Mitchell Island as one such region. Here, the South Mitchell Island upstream transport regime meets the eastern North Arm downstream transport regime, providing conditions that should increase sedimentation. In Steveston Cut, there is a flow reversal that meets the Woodward Reach transport regime. When river transport dominates over flood transport, high deposition could be expected in Steveston Cut. When the situation is reversed, the deposition would shift to Woodward Reach. Prior to the late 1960s, extensive dredging was required to address channel instability in the trifurcation area at New Westminster. In this region, downriver transport bifurcates into the North and Main Arms, but is “hampered” by an opposing flow out of Annacis Channel. Since the construction of training walls, this area is now largely self-scouring.

Only in Queen’s Reach, southeast of City Bank, did the delineation of a flow reversal fail to coincide with an area of high deposition. There is a dredge disposal site in this part of the river (Ferguson 1991) and apparently this is an area used extensively for borrow dredging (Stepchuk 1993, pers. comm.). Such activities could have two possible effects on the sediment trends. The first is that dredging and dumping have

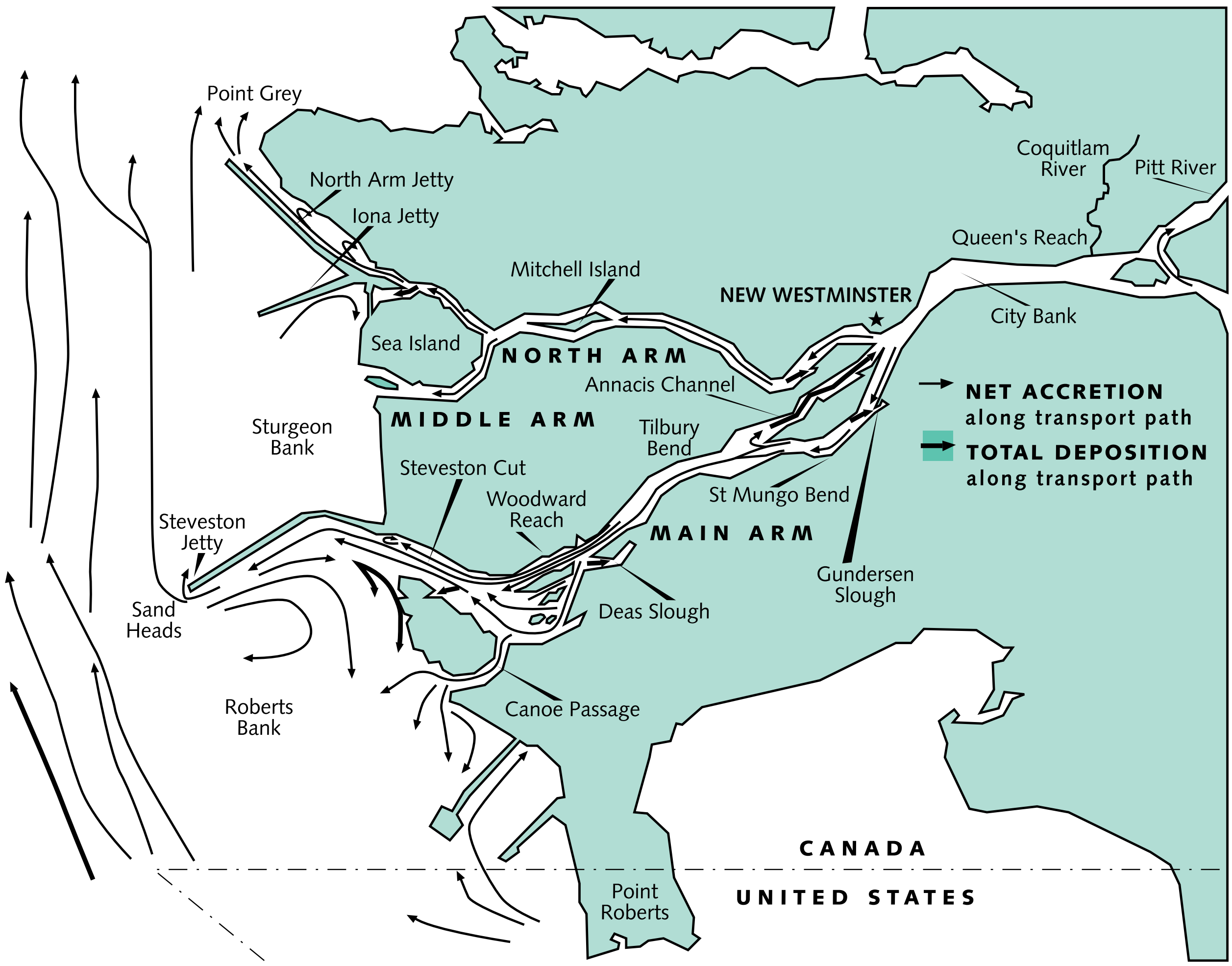


Figure 5. Sediment Transport Patterns for mud in the lower Fraser River and Delta.

Table 1. Lower Fraser River reaches demonstrating upriver sediment transport patterns as detected by the Sediment Transport Analysis. R^2 denotes the multiple correlation coefficient defining the relationship among the mean, sorting and skewness in the sample sequence. SD denotes standard deviation.

SITE	SAND			MUD		
	# of Sample transport lines	R^2 value		# of Sample transport lines	R^2 value	
		Mean	SD		Mean	SD
Coquitlam River/Pitt River	12	0.87	0.09	1	0.85	
Queen's Reach, south of City Bank	5	0.69	0.09	none		
Annacis Channel	2	0.76	0.03	2	0.94	0.04
Channel south of Mitchell Island	2	0.56	0.44	none		
Inside Steveston Cut—out to Jetty	30	0.92	0.05	none		
Deas Slough	none			1	0.87	
Gundersen Slough	none			1	1	
Cannery Channel[1]	none			2	0.86	0.007

[1] located by Steveston Cut

changed the natural sediment distributions sufficiently to produce apparent trends that are erroneous. The second is that the activities, particularly borrow dredging, have caused a transport reversal in the main channel south of City Bank. The relatively strong transport trend (mean $R^2 = 0.69$; Table 1), as detected by the sediment transport analysis used in this study, favours the second explanation.

The region of greatest conflict between known areas of sand deposition and the transport paths is in a stretch of river between Sand Heads and Woodward Reach. Seaward of Woodward Reach many of the trends were mixed, showing valid statistics for both erosion and deposition (accretion), a few were depositional and still others, particularly those adjacent to the Steveston Jetty, were erosional. In Woodward Reach, all the trends were erosional, with the exception of some mixed case trends along the right bank. The confluence of opposing transport regimes should result in areas of high deposition, as was evidenced in the North Arm east of Mitchell Island (discussed earlier). The lack of depositional trends for sand cannot easily be explained although the trends do show evidence for preferred erosion on the right bank inside of Steveston Jetty (Steveston Bend) and accretion on the left, a finding substantiated by Kostachuk and Luternauer (1987). A combination of extensive dredging in these channels as well as the presence of a dredge disposal site (PWC-3; Ferguson 1991) in Woodward Reach may have created erroneous X-distributions, despite the fact that transport trend statistics, particularly those along Steveston Jetty (mean $R^2 = 0.92$; Table 1), are excellent.

In comparison to sand, mud plays a minor role in the main river. Mud is generally found on the sides or banks of the main channels and the mud transport trends most often are associated with reversals into backwaters, such as sloughs, where total deposition (*i.e.*, once deposited, there is no further transport) is observed. Such sites have been shown to accumulate contaminants associated with fine particles (Young *et al*. 1985). The identified sloughs and backwaters have been used to assess contaminant exposure in the Fraser Estuary (Brewer *et al*. 1998; Swain and Walton 1991; 1993; 1994).

Tidal Flats

Of the four tributaries that enter the Strait of Georgia, only two, Middle Arm and Canoe Passage, have a relatively unobstructed flow onto the tidal flats. Canoe Passage accounts for 14 per cent of the total Fraser River discharge (Acres 1984; Hay and Co. 1988), and the pathways for sand produce a dendritic pattern of transport that could be considered “typical” of a meandering transport regime across a delta tidal flat. Through Canoe Passage itself, the trends for sand are indicative of high energy, erosive transport and on the delta flat nearly all the trends for sand produced a mixed case (*i.e.*, both deposition [accretion] and erosion). The statistics nearly all favour deposition, but the mix of the two cases and the eroding trends in Canoe Passage provide a signal that there may be a limited quantity of sediment reaching this area. Should sediment supply decrease in the future, the tidal flat in this area might easily change to net erosion.

Middle Arm accounts for a much smaller volume of discharge (about 3% or 4%). The amount of sand may be small as eroding trends occur inside Middle Arm; however there is accretion of mud. There appears to be no transport of sediment (sand or mud) out of the arm onto Sturgeon Bank.

The remaining two tributaries, North Arm and Main Arm, have been completely channelized across the tidal flats, with the result that the dendritic transport patterns for sand observed out of Canoe Passage cannot exist (Monahan *et al*. [1993] make a similar conclusion). In both arms, sand is carried to the extreme seaward edge of the tidal flats. In the Main Arm, which carries 70 per cent of the Fraser River discharge (Hay and Co. 1988), the sediment trends indicate three routes for sand to take. The first is a return system down the south side of Steveston Channel (on the inside of Steveston Jetty) which suggests that there is a constant recycling of sand in this region. The second route follows a clockwise gyre over northern Roberts Bank and the third transports sand northeast across Sturgeon Bank. Patterns of megaripples on Sturgeon Bank provide some support for the latter transport direction (Medley and Luternauer 1976).

There are distinct similarities in the transport of sediment on north Roberts Bank and Sturgeon Bank. For the transport pathways close to the Sand Heads source, the trends show net accretion. Farther away from source, the lines become either mixed case, or produce X-distributions indicative of net erosion. This suggests that the amount of sediment available for deposition is small. Accretion is occurring near source, but the trends soon show evidence for erosion.

There may be a fourth route for sand to be removed from the Sand Heads region, although it was not apparent from the samples obtained for the trend analysis. Evoy *et al*. (1993) described downslope slumping and gravity flow processes as a mechanism for sand to bypass the delta slope and to be deposited directly in prodelta and basinal environments, the deeper water environments associated with the Strait of Georgia. Sand lost from the river mouth in this way will no longer be available for deposition on the tidal flats.

Similar to the Main Arm distributary, sand out of the North Arm does not appear to be transported onto the delta foreshore (no sand samples were found in the sampling program). In this case, trends terminated at the Point Grey breakwater, and no further transport could be determined from the North Arm onto any of the tidal flats.

Transport pathways in Sturgeon Bank stopped at the Iona Jetty. A new transport regime started north of the Iona Jetty and extended to the North Arm Jetty. The trends in this area show net erosion that is consistent with the distance from the main source of sand at Sand Heads.

Transport pathways in southern Roberts Bank, in the vicinity of the Westshore Terminals Causeway and the Tsawwassen Ferry Terminal, appear to have no relationship with sediments derived from the Fraser River. The transport patterns show clockwise gyres with a sediment source from a northwest-trending nearshore regime. The trends for lines close to the low-water line indicate net erosion suggesting, once again, that there is little sediment available to maintain the present intertidal width.

Mud is relatively rare on the intertidal flats, being confined principally to the landward margins. Where transport trends could be determined, the derived patterns closely follow those for sand.

Delta Front and Offshore

All trends on the delta foreslope show transport to the north, parallel to the bathymetry, a finding in complete agreement with known processes. North flood currents are stronger than the ebb currents (Pickard 1956), and even surface currents affecting dispersal of the Fraser River plume favour northward transport (Thomson 1981). According to Luternauer *et al*. (1978), bottom currents on the foreslope are strong enough to transport sand-sized material and hydraulic bedforms have been observed on the sandy southwestern Roberts Banks slope. The sediment trends for these sands show net erosion which is supported by observations made in a PISCES submersible revealing erosional ledges and lag deposits (Luternauer and Finn 1983). Kostaschuk and Luternauer (1993) point out that there is no obvious source of sand replenishment and warn of slope failure. The trends indicate that the sand source must be the erosion of earlier deposits of delta foreslope sands, and it appears that such a process could have serious consequences for the stability of the Tsawwassen and Coal Port terminals. The rate of detected processes, such as erosion, cannot be determined by this analysis. As a result of this finding, a subsequent investigation was undertaken where it was found that the eroding trends may have formed in deposits disposed in the area during the construction of the Coal Port (Hay and Co. 1996).

The presence of the Fraser River and its associated plume are undoubtedly responsible for the mud deposits on the foreslope in depths greater than 50 m. It is not, however, primarily the cause for the northward direction of transport. Rather, particulate matter in the plume is carried both north and south of the outflow source at Sand Heads. On settling through the pycnocline, these particles become deposited from the transport regime that is under the influence of the dominant northward currents.

CONCLUSIONS AND RECOMMENDATIONS

In the Fraser River Estuary, the predominant pattern for sand and mud movement is from upstream to downstream; however, several reversals were detected. A close correspondence with known sites for sediment accumulation was noted.

The sediment trend analysis suggests that sand deposition over most of the intertidal flats is no longer the result of natural deltaic processes. Two of the four distributaries are channelized to the seaward edge of the intertidal flats (North and South Arms) and are restricted from meandering. Only through Canoe Passage do the trends follow the expected transport paths indicative of a delta formation. Here, as well as elsewhere on the banks, many of the trends show either a mixed case (erosion and accretion) or net erosion only, a finding that occurs when sediment supply is small. The evident paucity of sand on the tidal flats is attributed principally to channelization and removal of river sands by dredging, although the various causeways and jetties crossing the banks may also be a contributing factor. It is recommended that studies addressing the sediment budget and transport rates be undertaken to establish rates for processes observed in this study. Such studies would provide guidance regarding the impact of sediment removal on the tidal flat environment.

The evidence for a sediment return system along the inside of the Steveston Jetty (Steveston Bend) and in Steveston Cut may, in part, be caused by dredging activities in the river throughout the study area, which has lowered bed levels in recent years. In many estuaries it has been found that over-deepening increases the tidal range resulting in stronger flood currents (Jenson and Sieffert 1994). It is suggested that future engineering work along the inside of Steveston Jetty designed to decrease dredging requirements should take a landward return of sediments into account. It is not known if the same transport patterns take place during freshet.

The findings show erosion on the foreslope, which may be endangering the stability of the Roberts Bank Coal Port and Tsawwassen Ferry Terminal and are probably the result of the channelization of the Main Arm which effectively diverts sediment replenishment from this area to the Strait of Georgia. The method used in this study cannot predict the rate of erosion; thus it is recommended that the sediment transport processes be confirmed and their rates established for this area of Roberts Bank through a quantitative study.

The analysis shows that areas of total deposition for mud were observed in backwaters and sloughs in the river and at depths greater than 50 m in the foreslope. The river sites correspond to sites currently used by researchers for monitoring contaminant exposure in sediment. The results from this study confirm the suitability of using these sites for contaminant monitoring. A caveat is that dredging activities in some sloughs (Ferguson 1991) may disturb the distribution of contaminants associated with natural sedimentation.

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