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# The Role of the Salt-Wedge in Sediment Resuspension and Deposition: Fraser River Estuary, Canada

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**ABSTRACT**

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The Fraser River estuary is a high-energy, salt-wedge system on the west coast of Canada. Results from channel surveys indicate that resuspension and deposition of sandy bed-material are affected by the salt-wedge. As the tide rises, the salt-wedge migrates into the channel and rapid deposition of suspended bed-material occurs. This is related to interference in the pattern of sediment exchange between the flow and the bed and reduced turbulence in the upper layer. During falling tides the salt-wedge moves seaward and resuspension begins as the tip of the wedge passes, in response to enhanced turbulence in this region. Resuspension is then sustained by accelerating downstream flows.

**ADDITIONAL INDEX WORDS:** *Salt-wedge estuary, bed-material, resuspension, deposition, salt-wedge, turbulence.*

## INTRODUCTION

Suspended sediment in estuarine channels is transported as wash load and bed-material load. Wash load is fine sediment transported entirely in suspension and is not found in appreciable quantities on the bed. Bed-material load is bottom sediment that is coarser and is transported episodically through resuspension. Although wash load may be volumetrically important, bed-material transport controls channel morphology and is crucial to many aspects of estuarine management.

The erosion, transport and deposition of suspended bed-material in estuaries is controlled by a variety of factors including the composition of bottom sediment, river conditions, tides, waves, meteorological conditions and density stratification. Although the effects of a number of these controls are reasonably well-documented (*e.g.* ALLEN *et al.*, 1980; MILLIMAN, 1980; GELFENBAUM, 1983), less is known about the role of density stratification, especially in highly stratified, salt-wedge channels. The Main Channel of the Fraser River estuary, Canada (Figure 1) is a mesotidal, sand-rich, salt-wedge estuary (MILLIMAN, 1980) and the purpose of this paper is to examine the role of the salt-wedge in bed-material resuspension and deposition within the channel.

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## SETTING

The Fraser is a sand-bed river, with a mean annual discharge near the mouth of 3,400 $m^3s^{-1}$ (WATER SURVEY OF CANADA, 1985), that drains 250,000 $km^2$ of southern British Columbia into the Strait of Georgia. The drainage basin is very rugged, comprising sections of the perhumid Coast Mountains, the subhumid Interior Plateau, and the western flanks of the Cariboo Mountains and part of the Rocky Mountains (CHURCH *et al.*, 1987). Mean daily discharges and total daily suspended loads for 1985 at Mission, the closest station to the estuary where flow and suspended sediment conditions are continuously monitored (74 km upstream of Sand Heads), follow the typical annual pattern (*e.g.*, MILLIMAN 1980) (Figure 2). Discharge is low in winter between January and March and the spring snow-melt freshet begins in mid-April. This produces a rapid rise in discharge that peaks on June 6. Discharge falls gradually during the summer to mid Octo-

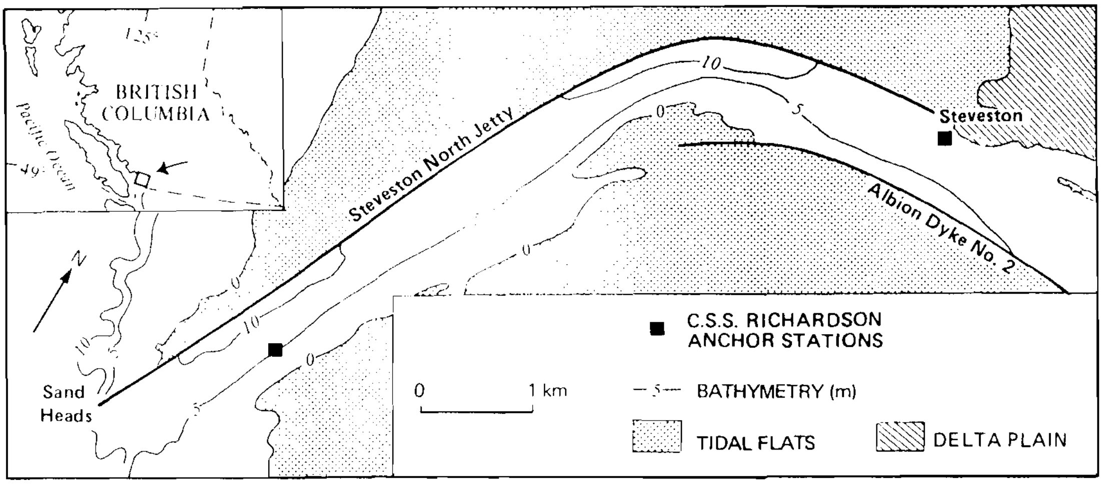


Figure 1. Outer Main Channel of the Fraser River estuary, showing locations of sampling stations near Steveston and Sand Heads.

ber, rises slightly in November and declines to winter lows by December. The suspended load follows a similar pattern during rising spring discharges, but the load peak occurs on May 28, 9 days earlier than the discharge peak. Loads drop off very rapidly after May 28 and by the end of July are near pre-freshet values. This pattern in suspended load occurs because the supply of easily eroded, fine sediment that collects near river banks over the winter is quickly exhausted early in the discharge season (CHURCH *et al.*, 1987).

Tides in the estuary are mixed, semi-diurnal with a mean range at Sand Heads of almost 3 m, decreasing landward and with increasing river discharge (AGES and WOOLARD, 1976). The tide, in concert with river discharge, controls the position of the salt-wedge (HODGINS *et al.*, 1977). During low river discharges the wedge intrudes over 30 km upstream of Sand Heads at high tide, but during high discharges the maximum high tide intrusion is less than 7 km (WARD, 1976). Density stratification increases and the salt-wedge is better defined as river discharge increases (HODGINS *et al.*, 1977).

## METHODS

Field data were collected during three one-week cruises (April 22-28, May 20-26 and June 16-20, 1985) on the *C.S.S. Richardson*. Sampling was carried out over 3 rising and 2 falling tides as the vesesl was anchored at stations near Sand Heads and upstream at Steveston (Figure 1). Vertical profiles were taken, at 1 or 2 m depth intervals and hourly time intervals, of suspended sediment (using a pump sampler and USP-61 river sampler), water temperature and salinity (using a YS1 Model 33 S-C-T meter) and current speed and direction (using an NBA Controls DNC 3 current meter). Water temperature and salinity were used to calculate density. Suspended sediment samples were collected in 0.5 l and 20 l volumes. A Shipek sampler was used for bottom sampling.

Shear velocity ($u_*$), a parameter that is considered a good indicator of the ability of a flow to suspend bed-material, was calculated from velocity profiles (BLATT *et al.*, 1980, p.113). Suspended sediment concentrations were determined using pre-weighed 0.45 $\mu$n filters. Velocity and sediment concentration profiles were used to calculate suspended load. Grain size distributions of suspended sediment were assessed using the bottom-withdrawal method for high-concentration 0.5 l samples taken at low tide, and sieve and sedigraph methods for samples obtained from 20 l samples (McCAVE, 1979). Sieves provided grain size distributions of bottom samples. The method of moments was used for grain size statistics. Grain size classification

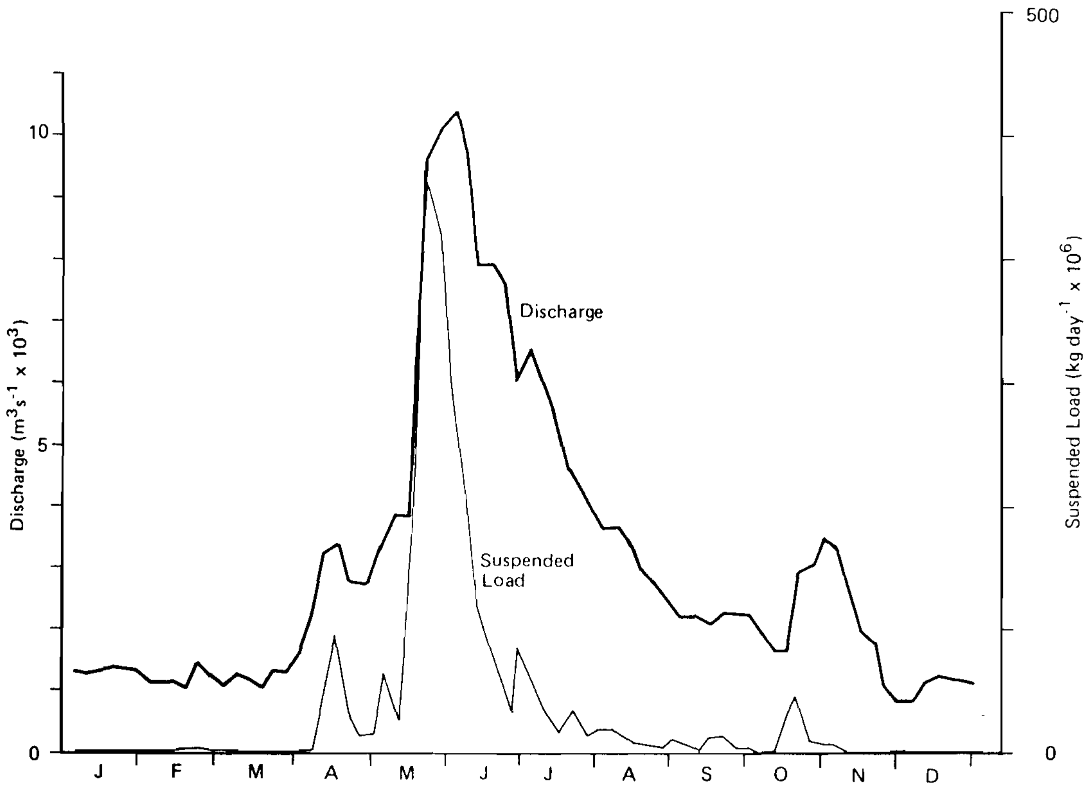


Figure 2. Mean daily discharge and daily suspended sediment load for the Fraser River at Mission during 1985 (data from Water Survey of Canada, 1985).

follows the Udden-Wentworth scale (*e.g.* BLATT *et al.*, 1980, p.57).

## BED-MATERIAL RESUSPENSION

The distinction between wash and suspended bed-material loads is made on the basis of grain sizes of sediment on the bed and in suspension (*e.g.* DYER, 1986). For the sampling station at Mission, CHURCH *et al.* (1987) found that wash load consisted of sediment finer than 0.125 mm (very fine sand) and suspended bed-material load of material coarser than 0.125 mm. The bed samples we obtained from the estuary (Figure 3) are composed of poorly sorted, positively skewed fine sand at Steveston and positively skewed, moderately well sorted medium sand downstream. These results are virtually identical to samples collected during an extensive survey in the estuary by PRETIOUS (1956), indicating our samples are representative of long-term bed composition. There is very little material finer than 0.062 mm in our samples (2 to 9%) but a significant portion of the bed-material (13 to 24%) consists of sediment finer than 0.125 mm. In addition, our analyses of sediment in suspension during high tides (discussed below), plus those of MILLIMAN (1980) for the estuary, show that all material in suspension is less than 0.062 mm at high tide. The following discussion, then, uses 0.062 mm, the boundary between silt-clay and sand, to separate wash and suspended bed-material loads in the estuary. Thus, the amount of bed-material in suspension is represented by the % sand in suspension. The effect of the salt-wedge on bed-material resuspension is apparent during both rising and falling tides.

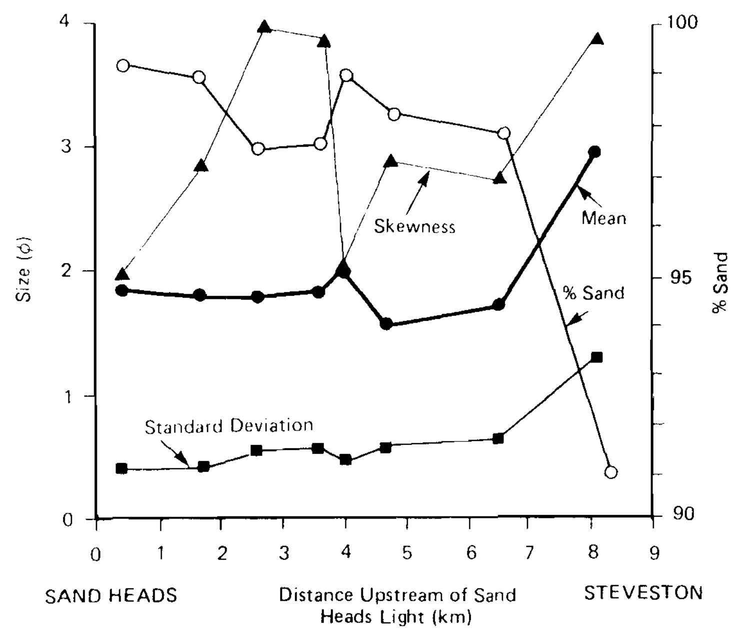


Figure 3. Grain size characteristics of bottom samples for May 24, 1985.

**Rising Tides**

At low tide in June (0800 hrs), shear velocities are similar at Steveston and Sand Heads but sediment concentrations, loads and size are slightly higher at Sand Heads, probably because of the slightly higher river discharge on June 11. The salt-wedge appears at Sand Heads at about one-third flood (1000 hrs), but does not appear at Steveston (Figure 4). At Steveston, velocity, concentrations, load, mean grain size and % sand remain relatively constant during the first third of the flood cycle then decline as high tide approaches (1600 hrs) (Figures 4, 5). At Sand Heads the initial decline in sediment transport is much more rapid, corresponding with the appearance of the salt-wedge. Particularly dramatic is the decline in bed-material in suspension (% sand) as the flow becomes stratified. This is likely related to loss of contact of the dominant downstream flow with the bed and the reduction of turbulence in the upper layer.

As the salt-wedge intrudes into the channel the fresh water flow is lifted above the bed. In unstratified flows the transport of suspended bed-material load is intermittent, with constant exchanges of sediment between the bed and water column (MIDDLETON and SOUTHARD, 1984). The salt-wedge cuts off this pattern of exchange and material that is deposited is not replaced. The net result is a decrease in sediment concentration and grain size in the upper layer, with transport restricted to wash load.

In turbulent flows there are velocity fluctuations produced by eddies generated at the bed (MIDDLETON and SOUTHARD, 1984). It is the vertical component of these velocity fluctuations that is responsible for keeping sediment in suspension. However, when flow is stratified and density decreases upward turbulence must work against buoyant forces, resulting in a decrease in turbulent energy (TRITTON, 1977, p.286) and, presumably, a decrease in suspended sediment capacity. In stratified flows the ratio of turbulent to buoyant forces is provided by the interfacial Froude number F′:

$$F' = u/(\gamma g h')^{0.5} \qquad (1)$$

where u is the upper layer flow velocity, $\gamma$ is the density ratio:

$$\gamma = 1 - (\rho_f/\rho_s) \qquad (2)$$

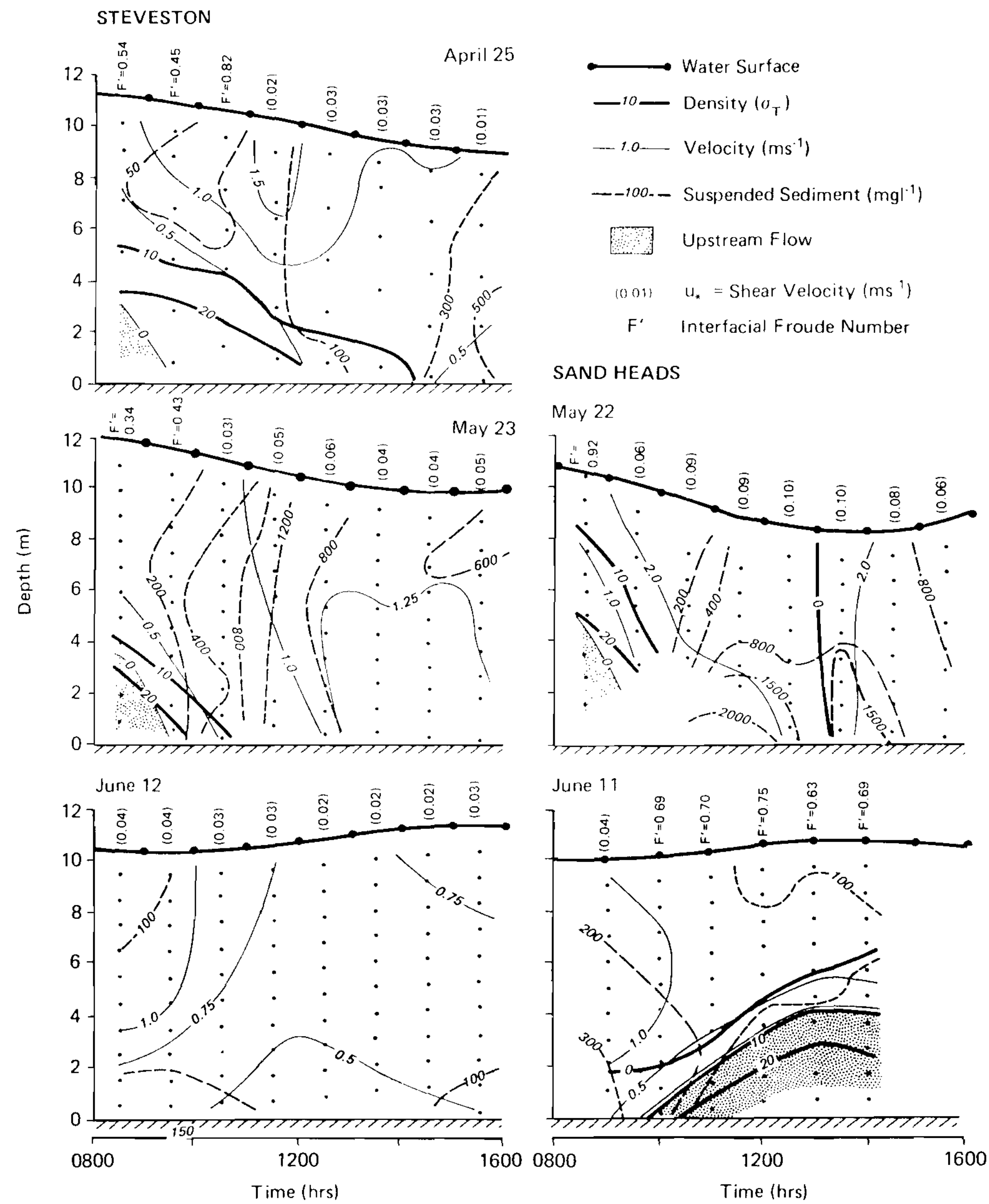


Figure 4. Temporal variations in water density, velocity, suspended sediment concentration, interfacial Froude Number and shear velocity for the two stations. Water surface position was determined with an echosounder. Dots representing sampling points.

where $\rho_f$ is the density of fresh water, $\rho_s$ is the density of sea water, g is the acceleration due to gravity and h′ is the depth of the density interface (WRIGHT and COLEMAN, 1971). Values of F′ less than 1 indicate a dominance of buoyancy and a suppression of turbulence. The

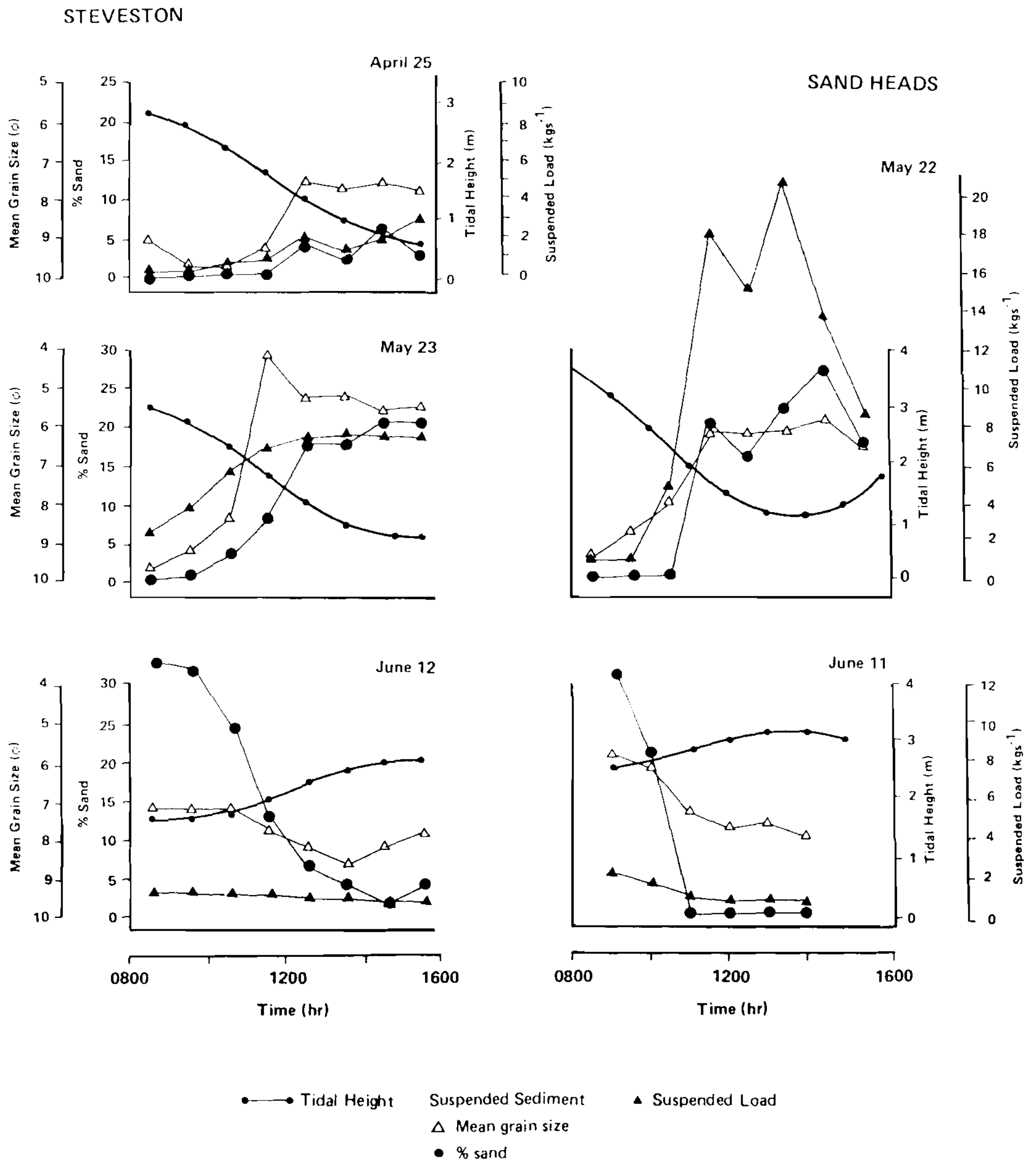


Figure 5. Temporal variations in tidal height, suspended load, mean grain size and % sand. Tidal elevations are based on predictions supplied by the Institute of Ocean Sciences, Sidney, B.C. Suspended loads are net values per unit width of channel. Mean grain size and % sand are from 20 l. pump samples taken 2 m from the surface in stratified conditions, 2 m from the bed in unstratified conditions.

stratified flows in the Fraser during all survey periods have values of F′ less than one (Figure 4), suggesting that rapid deposition of bed-material load may be related to a reduction in upper layer turbulence.

## Falling Tides

At high tide in April and May (0800 hours) the salt-wedge is positioned in the channel and sediment concentrations are extremely low, mean grain sizes are extremely fine and there is no bed-material in suspension (Figure 4, 5). As the tide falls the wedge is flushed out of the channel. In April, the wedge persists in the channel much longer than in May (1400 hrs) and although surface velocities are high as the tide falls, velocities near the bed, and hence shear velocities, are low. As the wedge tip passes the anchor station and shear velocity increases there is entrainment of bed-material and associated increases in concentration, load, mean grain size and % sand (Figure 4, 5: 1200-1400 hrs). As the flow decelerates slightly toward low tide (1600 hrs) in April, sediment concentrations continue to increase probably because flow conditions have not reached their sediment-transporting limit and continue to erode bed-material (Figure 4).

During May, high river discharges force the salt-wedge out of the channel much more rapidly than in April (Figure 4: 1000-1200 hrs) and maximum shear velocities occur near mid-tide and decline towards low tide at both Steveston and Sand Heads (Figure 4). Shear velocities are also considerably higher in May than April because of higher river discharge, and are higher at Sand Heads than Steveston in May because of the slightly larger tidal range. As the tide falls in May and the salt-wedge tip passes the anchor stations, sediment concentrations, loads, mean grain size and bed-material entrainment increase rapidly towards mid-tide (1200 hrs). They then remain relatively constant as low tide approaches (1600 hrs), following the pattern of shear velocity (Figures 4 and 5).

It is apparent from these results that initial bed-material entrainment corresponds with the passage of the salt-wedge tip and that this is sustained afterward by increasing shear velocity in the accelerating current. WARD (1976) investigated the behaviour of the salt-wedge in the Fraser and found that intense turbulence was generated at the wedge tip as it migrated down the channel. Sediment entrainment is strongly controlled by near-bed turbulence (MIDDLETON and SOUTHARD, 1984) suggesting that turbulent fluctuations associated with the wedge tip may produce enhanced conditions for bed erosion.

It must be pointed out that the much higher suspended concentrations and loads in May relative to April also reflect the passage of the pulse of mobile sediment that characterizes the early freshet period in the Fraser, rather than being entirely resuspended bed-material. The April data collection preceded the rise in suspended load in the river, but the May data were collected immediately prior to the peak in load (Figure 2).

## DISCUSSION

Most of the recent reviews of estuarine sedimentation (*e.g.* DYER, 1986; NICHOLS and BIGGS, 1985) include a conceptual model of salt-wedge sedimentary process, citing the microtidal Mississippi as an example. In this model sediment transport is accomplished primarily by river flow. As it meets the tip of the salt-wedge the river water rises, leaving its bed-load behind. The coarser fraction of the suspended load settles through the halocline at the wedge tip, while the finer component continues downstream over the intrusion. The model, however, is based on research that has focussed on the river mouth area (*e.g.* WRIGHT and COLEMAN, 1971, 1974; WRIGHT, 1971) rather than on zones within the confines of the channel. Salt-wedge dynamics beyond the river mouth, however, are affected by effluent expansion, thinning and deceleration and as such differ significantly from channel dynamics (WRIGHT, 1971). Quantitative evidence for suspended sediment behaviour in salt-wedge estuarine channels is lacking. This study provides some insight into sediment suspension processes in salt-wedge channels, but more research is required to adequately test and refine the salt-wedge sedimentary model. Of particular importance are the relationships between the salt-wedge and flow turbulence.

## CONCLUSIONS

The following conclusions can be drawn about the role of the salt-wedge in bed-material resuspension and deposition in the Fraser Estuary.

(1) The estuary bed is composed almost entirely of sand, which represents the bed-material load.

(2) During rising tides the salt-wedge migrates into the channel, producing rapid deposition of suspended bed-material. This appears to be related to interference in the pattern of sedi-

ment exchange between the flow and the bed and reduced turbulence in the upper layer.
(3) As the tide falls, the salt-wedge moves seaward and bed-material resuspension begins as the tip of the wedge passes, in response to increased turbulence in this region. Resuspension is then sustained by accelerating downstream flows. These effects are enhanced by high river discharge.

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## LITERATURE CITED

ALLEN, G.P.; SALOMON, J.C.; BASSOULET, P.; DU PENHOAT, Y., and DE GRANDPRE, C., 1980. Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sedimentary Geology*, 26, 69-90.

AGES, A. and WOOLARD, A.L., 1976. *Tides in the Fraser Estuary*. Pacific Marine Science Report 76-5, Institute of Ocean Sciences, Sidney, British Columbia, 100p.

BLATT, H.; MIDDLETON, G.V., and MURRAY, R.G., 1980. *Origin of Sedimentary Rocks*. Englewood Cliffs, NJ: Prentice-Hall, 782p.

CHURCH, M.A.; McLEAN, D.G.; KOSTASCHUK, R.A., and TASSONE, B., 1987. *Sediment Transport in Lower Fraser River: Field Guide*. Field Guide for the International Association of Hydrological Sciences, August 19, 1987, at the 19th General Assembly, International Union of Geodesy and Geophysics, Vancouver, Canada.

DYER, K.R., 1986. *Coastal and Estuarine Sediment Dynamics*. Toronto: Wiley, 342p.

GELFENBAUM, G., 1983. Suspended sediment response to semidiurnal and fortnightly variations in a mesotidal estuary: Columbia River, U.S.A. *Marine Geology*, 52, 39-57.

HODGINS, D.O.; OSBORN, T.R., and QUICK, M.C., 1977. Numerical model of stratified estuary flows. *American Society of Civil Engineers, Journal of the Waterways, Port, Coastal and Ocean Division*, WW1, 25-42.

McCAVE, I.N., 1979. Suspended Sediment. *In:* K.R. Dyer (Ed.), *Estuarine Hydrography and Sedimentation*. Cambridge: Cambridge University Press, pp. 131-185.

MIDDLETON, G.V. and SOUTHARD, J.B., 1984. *Mechanics of Sediment Movement*. Society of Economic Paleontologists and Mineralogists, Short Course Number 3, 401p.

MILLIMAN, J.D., 1980. Sedimentation in the Fraser River and its estuary. *Estuarine and Coastal Marine Science*, 10, 609-633.

NICHOLS, M.M. and BIGGS, R.B., 1985. Estuaries. *In:* R.A. Davis (Ed.), *Coastal Sedimentary Environments*. New York: Springer/Verlag, pp. 77-173.

PRETIOUS, E.S., 1956. Bed-load measurement in the Main Arm of the Fraser River estuary. *Fraser River Model Report FRM-229*, Canada Department of Public Works, 21p.

TRITTON, D.J., 1977. *Physical Fluid Dynamics*. Toronto: Van Nostrand Reinhold, 362p.

WARD, P.R.B., 1976. Seasonal salinity changes in the Fraser River estuary. *Canadian Journal of Civil Engineering*, 3, 342-348.

WATER SURVEY OF CANADA, 1985. *Sediment Data: British Columbia*. Environment Canada, Inland Waters/Lands Directorate, Water Resources Branch, Ottawa.

WRIGHT, L.D., 1971. Hydrography of South Pass, Mississippi River. *American Society of Civil Engineers, Journal of the Waterways, Harbors and Coastal Engineering Division* 97, WW3, 491-504.

WRIGHT, L.D. and COLEMAN, J.M., 1971. Effluent expansion and interfacial mixing in the presence of a salt-wedge, Mississippi River delta. *Journal of Geophysical Research*, 76, 8649-8661.

WRIGHT, L.D. and COLEMAN, J.M., 1974. Mississippi river mouth processes: effluent dynamics and morphologic development. *Journal of Geology*, 82, 751-778.

## □ RÉSUMÉ □

L'estuaire de la Fraser River est situé sur la côte ouest du Canada, en milieu de forte énergie et comporte un coin salé. Les résultats des campagnes dans l'estuaire indiquent que les processus de remise en suspension et de dépôt du matériel sableux du fond sont affectés par le coin salé. Au cours de la marée montante, le coin salé migre dans le chenal et il se produit un dépôt rapide du matériel en suspension. Ce phénomène est lié à l'interférence entre le courant et le fond sur la répartition des échanges de sédiments et à la turbulence réduite de la tranche d'eau supérieure. A marée descendante, le coin salé se déplace vers la mer et la remise en suspension commence, en réponse à l'élévation de la turbulence, avec le déplacement de la pointe du coin salé.—*Catherine Bressolier, EPHE, Montrouge, France.*

## □ ZUSAMMENFASSUNG □

Das Fraser River Ästuar an der Westküste Kanadas ist ein "high energy" System, in dem sich ein Salzkeil mit der Tide hin und her bewegt. Die Ergebnisse von Peilungen zeigen, daß die Resuspensionen und Ablagerung von sandigem Bettmaterial durch den Salzkeil beeinflußt werden. Mit dem Tidestieg gelangt der Salzkeil in das Rinnensystem und als Folge davon kommt es zu schnellen Ablagerungen von suspendiertem Bettmaterial. Dieser Vorgang ergibt sich aus Interferenzen in der Verteilung des Sedimentaustausches zwischen der Strömung und der Gewässersohle. Vermindert werder dadurch auch Turbolenzen in höheren Wasserschichten. Während des Tidefalls bewegt sich der Salzkeil seewärts und Resuspensionen beginnen infolge der Erhöhung der Turbolenzen unter der Kuppe des ablaufenden Salzkeils. Die Resuspensionen werden durch die Beschleunigung der seewärtigen Strömung aufrechterhalten.—*Reinhard Dieckmann, WSA Bremerhaven, West Germany.*

□ RESUMEN □

El estuario del rio Fraser es un sistema de alta energia, parcialmente estratificado en la costa Oeste del Canadá. Los resultados de la toma de datos en el canal indican que la resuspensión y sedimentación de los materiales arenosos del fondo está afectada por la cuña de agua salada. A medida que sube la marea, la cuña salada emigra hacia aguas arriba del canal, produciéndose una sedimentación rápida del material de fondo en suspensión. Este proceso está relacionado con la interferencia en el intercambio de sedimentos entre el flujo y el fondo, al disminuir la turbulencia en la capa superior. Durante la bajada de la marea, la cuña salada se mueve hacia el mar y la resuspensión comienza a medida que el extremo de la cuña se desplaza, en respuesta al incremento de turbulencia en esa región. La resuspensión se mantiene en tonces debido al flujo descendente acelerado.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*