CHAPTER 120

TIDAL SEDIMENTATION IN GROS-CACOUNA HARBOR

by

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ABSTRACT

The harbor of Gros-Cacouna on the South shore of the St.Lawrence Estuary has been silting at the rate of 31 cm/yr. since it was dredged at the depth of 14 meters in 1968. Measurements of temperature, salinity, turbidity, current speed and direction were carried out as well as bottom sampling and reflection seismic profiling. A model of suspended sediment transport combines the tidal volumes and the current profiles at the harbor entrance.

During a period of high turbidity (Spring) in the St.Lawrence Estuary, 54.2 tons of suspended sediments entered the harbor during the flood phase, while 41.1 tons were carried out during the ebb phase of a semi-diurnal tide, leaving 13.1 tons of sediments in the harbor. The transfer coefficient is 0.24 indicating that one quarter of the suspended sediment load settles in the harbor during one tidal cycle. In September, the turbidity is low in the Estuary and the suspended sediment budget in the harbor is 4 times smaller but the ratio of deposited sediments versus the total quantity of sediments transported in suspension is the same.

INTRODUCTION

The harbor of Gros-Cacouna is located on the south shore of the St.Lawrence Estuary at latitude 47°55'42" North and longitude 69°31'12" West, 230 kilometers downstream Quebec city (Fig. 1).

The St.Lawrence Estuary is 20 km wide and 70 meters deep off Gros-Cacouna. Water temperature varies between 10°C and freezing.

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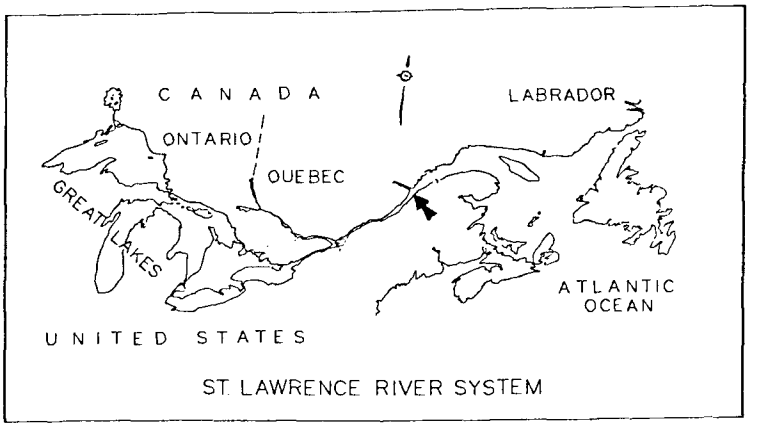

FIGURE 1 The location of Gros-Cacouna harbor on south shore of St.Lawrence River system is shown by an arrow.

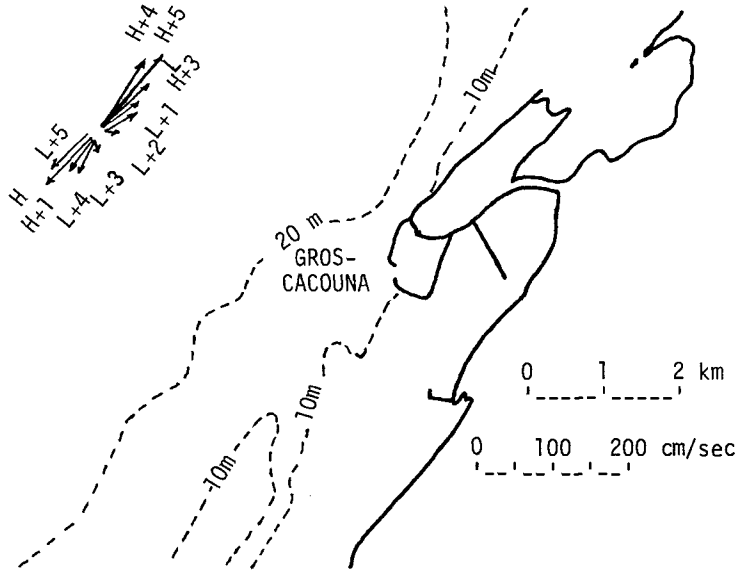

FIGURE 2 Location of Gros-Cacouna harbor at the southern end of Gros-Cacouna Island and rose of offshore tidal currents (H: high tide, L: low tide, H+1: one hour after high tide, etc). (Canadian Hydrographic Service,1939).

The harbor is often surrounded by drifting ice in winter. Salinity varies seasonally and also with depth and ranges between 20 °/oo and 29°/oo. The limited fetch across the Estuary and the presence of islands along the southern coast prevent the formation of large waves. During the windiest month (January), 4 meter waves are expectable 5% of the time and only if the Estuary is not ice covered.

Tide is mixed, dominantly semi-diurnal, and ranges from 3.7 m. (neap) to 5.7 m (spring). The difference between day and night tide reaches one meter at some phases of the lunar month.

Tidal currents in the St.Lawrence Estuary are strong and reverse with the semi-diurnal tide. Off Gros-Cacouna the surface currents reach 130 cm/sec during the ebbing tide and 100 cm/sec during the flood (fig. 2). The circulation is typically estuarine; the water column is stratified and the two layers are flowing in opposite directions most of the time, as observed outside the harbor during this survey as well as some 3 km offshore by d'Anglejan and Ingramm (1976).

The rubble-mound jetties of Gros-Cacouna harbor were built in 1966. They enclose an area of 5.3×10^5 m^2. A 2×10^5 m^2 basin was dredged at a depth of 14 meters in 1968 (fig. 3). As the harbor was not yet complemented with wharves in 1976, it was an ideal hydraulic model where experiments could be carried out at the 1:1 scale.

Previous studies (E.R.S.L., 1973) indicated that the suspended sediment concentration was relatively high (10 to 19 mg/l) in the harbor and that siltation was progressing rapidly in the basin dredged in 1968. By contrast, essentially no sediment transport is taking place in the intertidal zone in this area. A small wharf at Cacouna Village did not retain sediments on either side since it was built 30 years ago.

FIELD INVESTIGATIONS AND METHODS

The suspended sediment load varies considerably in the St.Lawrence Estuary and is related to the fresh water run off of the St.Lawrence drainage Basin although that run off is regulated to 1.7: 1 (Neu,1976). Two cruises were organized to survey the harbor during periods of high turbidity (31 May - 4 June 1976) and low turbidity (30 August - 3 September 1976).

Precise measurements of temperature, salinity, turbidity, current speed and direction were carried out at the entrance and both inside and outside the harbor. Bottom samples were taken as well as continuous reflection seismic profiles to gain a thorough understanding of the harbor sedimentation dynamics. The precision of measurements was ±0.02°C for temperature, ± 0.02 mmhos/cm for conductivity and ± 25 cm for depth. Shipborne current measurements permitted to obtain continuous profiles of current speed and direction versus depth.

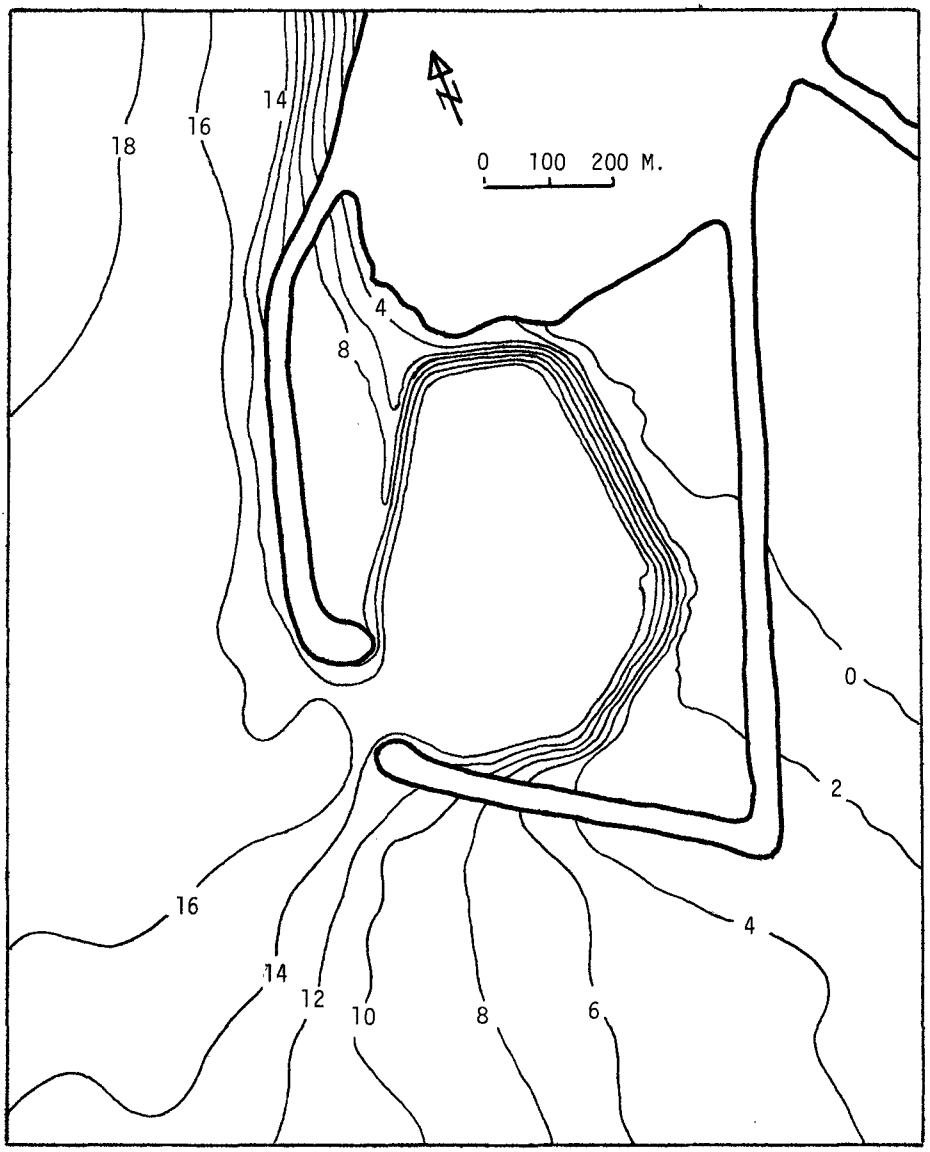

FIGURE 3 Bathymetry of Gros-Cacouna harbor (depth contours in meters). The depth contours at two-meter intervals outline the basin dredged at a depth of 14 meters.

The concentration of suspended sediment particles was determined with a turbidimeter during the May-June cruise. Calibration of the instrument specificly for that cruise showed that the transmissivity for a 10 cm beam was linear within a range from 10 mg/l to 100 mg/l. During the August-September survey the suspended sediment concentration was too low to use a turbidimeter and the concentration of suspended sediments was determined by filtration of 250 ml water samples on 0.45 micron filters.

TIDAL CIRCULATION IN THE HARBOR ENTRANCE

The variation of current speeds and directions as a function of depth and time is shown in the upper portion of figure 4 for the day-time tide of September 1st, 1976. At high tide (09:00 hrs) water is flowing out of the harbor through the upper half of the entrance and inward at the bottom. The flow pattern evolves through the tidal cycle and at low tide (15:00 hrs) it has reversed and water flows inward through the upper half and flows out at the bottom of the entrance. This two-layer flow across the harbor entrance reflects the main features of the tide-induced circulation in the Estuary. The circulation of water masses across the harbor entrance more than compensates for changes of water levels due to the propagation of the tide in the harbor.

SEDIMENTATION RATE IN GROS-CACOUNA HARBOR

Continuous reflection seismic profiles were surveyed at the completion of the dredging of the harbor basin in 1968 and were repeated along the same base lines in 1971 and 1972 and during this survey, in 1976. Bottom samples were taken to determine the nature of the sediments deposited on the bottom of the basin since 1968. These data were used to determine the rate of sedimentation in the harbor. The results appear on table 1.

TABLE 1

SEDIMENTATION IN GROS-CACOUNA HARBOR
(2×10^5 m^2 basin dredged in 1968)

	Volume ($\times 10^3 m^3$)	Weight ($\times 10^3$ tons)	Sedimentation rate (cm/yr)
1968-72:	314.7	535	39
1972-76:	248.8	423	31
1968-76:	563.5	958	35

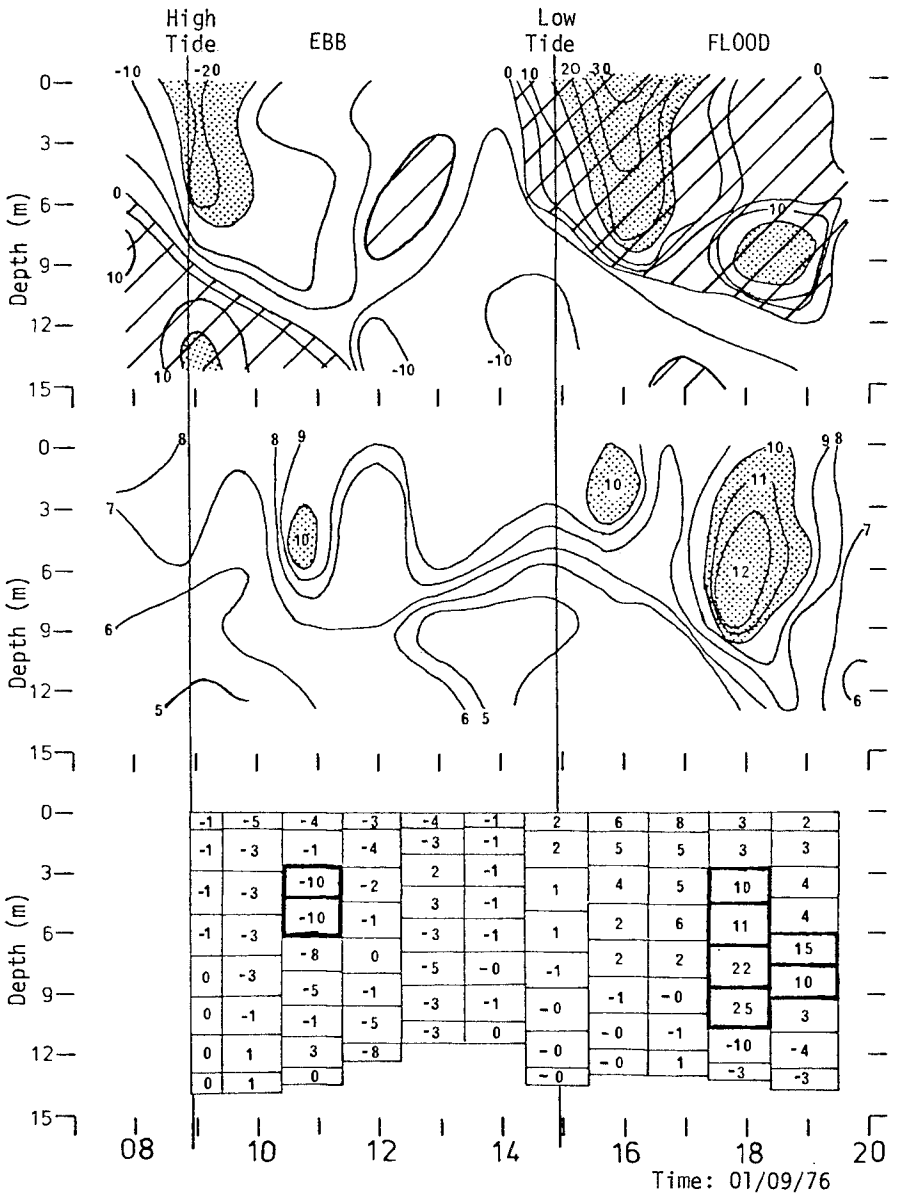

FIGURE 4 Top: Current speed profiles (cm/sec) as a function of time (ebb and flood) at the harbor entrance. Inflowing currents are positive and are outlined by inclined lines. Middle: Suspended sediment concentration (mg/l); inflow is positive. Bottom: Suspended sediment transport in hundreds of kilograms (+:inflow) corresponding to current velocities and suspended sediment concentrations shown above.

The texture of these sediments ranges from sand to clay-size particles. On the basis of textural analyses of the sediments deposited in the basin, the total suspended load is estimated to be in the order of 268 x 10^3 tons (Fortin et Drapeau, 1979).

TRANSPORT MODEL FOR SUSPENDED SEDIMENTS

The tide being the dominant phenemenon, the objective of the model is to determine the net quantity of sediments that remain inside the harbor at the end of a tidal cycle. The problem is simplified by the fact that no rivers flow in the harbor, the jetties are impermeable and the harbor has only one entrance.

Firstly the flow pattern at the entrance is determined and secondly the measurements of suspended sediment concentration are used to calculate the transport of sediments based on the flow pattern.

Flow at the harbor entrance

The proposed model is empirical and integrates two types of data: 1) tidal volumes of the harbor, that is the net quantity of water flowing through the harbor entrance calculated on the basis of changes of water level during given time intervals, and 2) current velocity profiles measured at the harbor entrance for the same time intervals.

The net volume of water (W_i) either entering or flowing out of the harbor during a specific time interval (ΔT_i) is the product of the change of height (ΔH_i) of the water level during that time interval by the area of the water surface of the harbor (A_i):

$$W_i = \Delta H_i A_i \qquad (1)$$

To be significant in terms of sediment transport, it is essential at the end of the tidal cycle analysed that exactly the same volume of water flows in and out the harbor that is:

$$\Sigma W_i = 0 \qquad (2)$$

Current speed and direction profiles were monitored at the harbor entrance with a shipborne current meter and recorded at 8 to 10 depths depending on the height of the tide. These current measurements are transformed into a matrix of current vectors [$V_{i,d}$] perpendicular to the entrance of the harbor. The vectors are positive (+) for inflow.

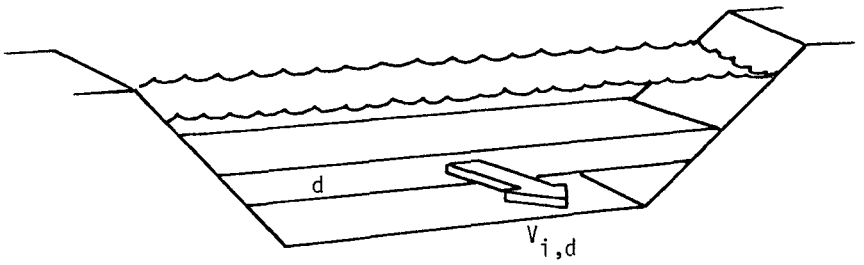

FIGURE 5

The cross-sectional area of the harbor entrance is divided into a given number (d) of horizontal layers corresponding to each current measurement. L_d is the cross-sectional area of each horizontal layer (see fig. 5).

During a given time interval ΔT_i, the volume of water ($Q_{i,d}$) flowing through one layer is:

$$Q_{i,d} = V_{i,d} L_d \Delta T_i \quad (3)$$

and the net flow of water through the entrance during the interval ΔT_i is:

$$Q_i = (\sum^{d} V_{i,d} L_d) \Delta T_i \quad (4)$$

In theory Q_i and W_i are equal. In practice hundreds of current measurements would be necessary to make Q_i consistently equal to W_i. This difficulty is overcome by calibrating the current vectors ($V_{i,d}$). A correction factor (C_i) is determined for each series (i) of measurements:

$$C_i = \frac{W_i}{Q_i} \quad (5)$$

This correction factor is used to generate a calibrated matrix of current vectors $[V^*_{i,d}]$

$$V^*_{i,d} = C_i V_{i,d} \quad (6)$$

These corrected current vectors are introduced in equations (3) and (4)

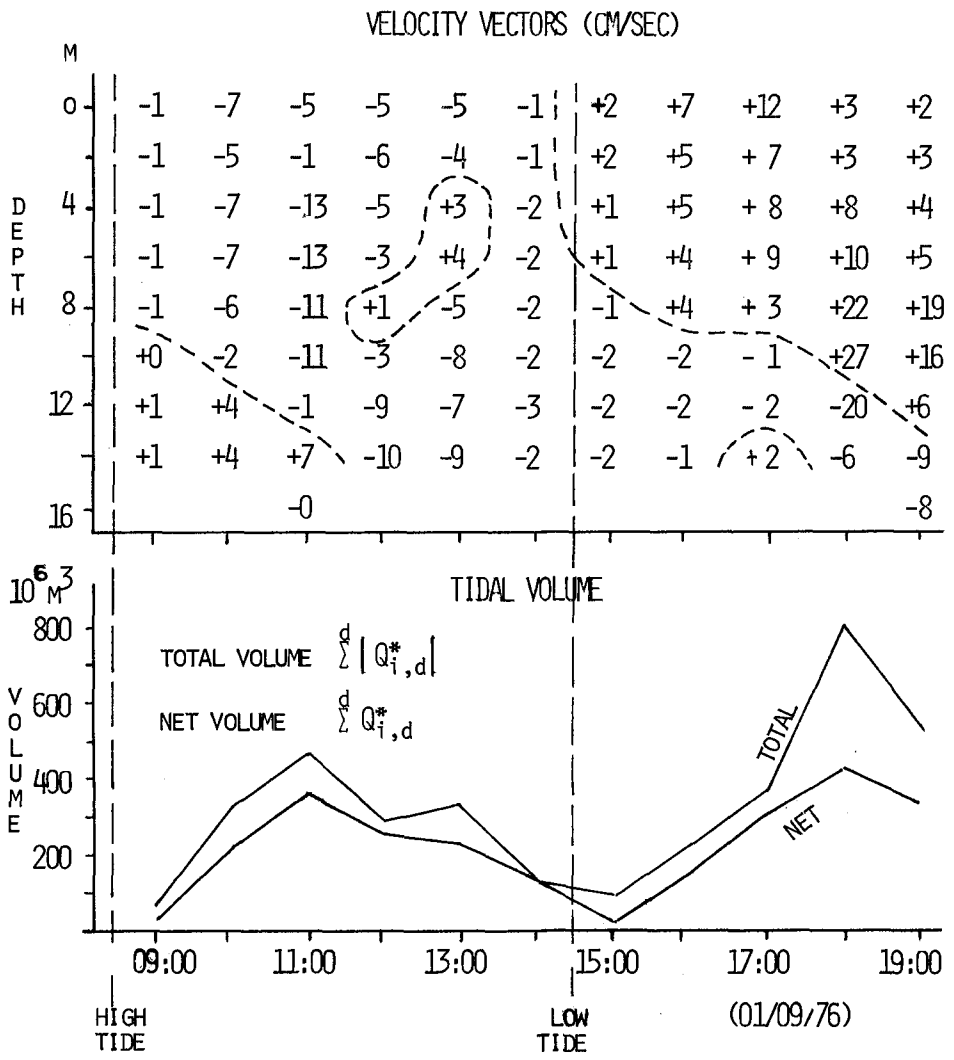

FIGURE 6 Top: Current vectors perpendicular to the cross-sectional area of the harbor entrance and calibrated according to the tidal volume of the harbor. Bottom: Diagram showing the net and the total volume of water flowing through the entrance of the harbor at different phases of the tide.

$$Q^*_{i,d} = V^*_{i,d} L_d \Delta T_i \quad (7)$$

$$Q^*_i = (\sum^d V^*_{i,d} L_d) \Delta T_i \quad (8)$$

These calibrated data fulfill the requirement that at the end of a tidal cycle, that is when the water level reaches the same height as at the beginning of the tidal cycle:

$$\Sigma Q^*_i = 0 \quad (9)$$

As already mentionned, the validity of the model is based on equation (9). The model has to be in accordance with the fact that tide in the harbor is a purely harmonic phenomenon.

The matrix of calibrated current vectors $[V^*_{i,d}]$ for September is tabulated on figure 6. It schematizes the circulation at the entrance of the harbor. The flow pattern has the same characteristics as those shown on the upper portion of fig. 4, except that the individual velocities are calibrated to fulfill the requirements of equation (9). The matrix outlines the two-layer circulation and its evolution with the progression of the tide. Only at station 33 is the whole water column flowing in the same direction. During all other time intervals the flow is bi-directional, that is, more water than necessary to compensate for the tide flows through the entrance of the harbor. The difference between the total flow ($\sum^d |Q^*_{i,d}|$) and the net flow ($\sum^d Q^*_{i,d}$) is outlined on the lower half of figure 6. Summation of these data indicates that 1.57 time the water necessary to compensate for the tidal volume of the harbor did flow through the entrance during that tidal cycle.

Transport of suspended sediments

Calculations for the transport of suspended sediments are based on the calibrated flow matrix $[Q^*_{i,d}]$ and the suspended sediment concentration measurements ($F_{i,d}$). The quantity of sediments ($S_{i,d}$) transported through one layer during a given time interval (i) is:

$$S_{i,d} = Q^*_{i,d} F_{i,d} \quad (10)$$

The net suspended sediment transport through the entrance during a given time interval is:

$$S_i = \sum^d Q^*_{i,d} F_{i,d} \quad (11)$$

The net suspended sediment transport during one tidal cycle is:

$$S = \Sigma S_i \quad (12)$$

TABLE 2

SUSPENDED SEDIMENT TRANSPORT, 1 JUNE 1976

Time (EDT)	Flow ($\times 10^3$ m^3)	Transport (kg)	Total Transport (kg)	Net Transport (kg)
High tide				
07:36-08:06	-200.7	-5,193		
08:06-08:35	-238.	-6,259		
08:35-09:00	-193.4	-4,532		
09:00-09:30	-246.5	-6,192		
09:30-10:00	-218.5	-6,195	-41,060	
10:00-10:24	-140.6	-3,894		
10:24-11:00	-147.8	-4,077		
11:00-11:27	- 95.9	-2,415		
11:27-11:58	- 71.1	-2,303		
11:58-12:27	0	458		13,138
Low tide				
12:27-12:58	46.3	2,146		
12:58-13:30	74.0	2,578		
13:30-13:56	102.4	3,782		
13:56-14:27	197.2	7,815		
14:27-14:59	201.8	8,820		
14:59-15:28	192.8	7,048	54,198	
15:28-15:57	208.0	7,344		
15:57-16:26	184,7	6,023		
16:26-16:56	143,3	4,375		
16:56-17:27	132.2	4,155		
17:27-18:00	67.7	- 346		

TABLE 3

SUSPENDED SEDIMENT TRANSPORT, 1 SEPT. 1976

High tide				
08:55-09:25	- 32.2	- 275		
09:25-10:27	-225.5	-1,624		
10:27-11:24	-385.1	-3,628		
11:24-12:23	-278.7	-2,422	-10,346	
12:23-13:23	-219.2	-1,716		
13:23-14:25	-111.6	- 681		3,466
Low tide				
14:25-15:26	13.8	350		
15:26-16:24	169.0	1,680	13,812	
16:24-17:24	317.5	2,487		
17:24-18:26	430.7	5,971		
18:26-19:37	322.1	3,324		

The results of these calculations for each time interval (S_i) and for the net transport during a tidal cycle (S) are shown on Table 2 for the June survey and on Table 3 for the September survey.

TRANSFER COEFFICIENT

Table 2 shows that during the tide studied in June, 54.2 tons of suspended sediments were transported inside the harbor during the flood of the tide while 41.1 tons were carried out durind the ebb; leaving 13.1 tons in the harbor. This survey coincided with a period of high turbidity in the Estuary. The second survey (September) was carried out during a period of low turbidity and the suspended sediment transport rates were lower, as shown on Table 3. The net transport for a comparable tidal cycle was only 13.8 tons, that is 4 times less than in June. The proportion of sediments that remainded in the harbor at the end of a tidal cycle is the same in both cases however. The term "transfer coefficient" is used to describe that characteristic.

Transfer coefficient:

June:	13138/54198	= 0.24
September :	3466/13812	= 0.25

The transfer coefficient bears some analogy with the "equilibrium concentration" defined by Mehta and Partheniades (1974) to discuss the depositional properties of estuarine sediments. The equilibrium concentration is a parameter defined experimentally while the transfer coefficient is empirical and would need further investigation.

COMPARISON OF SUSPENDED LOAD TRANSPORT WITH MEASURED SILTATION

The total accumulation of sediments in the harbor basin is in the order 95.8×10^4 tons over a period of 8 years, that is an average sedimentation of 164 tons per tidal cycle. A large proportion of these sediments is too coarse to be transported in suspension and the average transport in suspension is estimated to be 45.8 tons per tidal cycle (Fortin and Drapeau, 1979). That quantity of sediments is much higher than what was measured during June (13.1 tons) and September (3.5 tons) surveys.

The suspended sediment concentration most reach higher values in Gros-Cacouna area than those observed in June 1976 (24-48 mg/l). Although the turbidity maximum of the St.Lawrence Estuary is further upstream, the suspended sediment longitudinal gradient is 1.5 mg/l per kilometer in April-May in Gros-Cacouna area (Poulet and Chanut, 1979). High concentrations of suspended sediments are then susceptible to reach Gros-

Cacouna harbor and produce high siltation rates during these periods of high turbidity.

Differences in ranges of successive tides (1 meter at neap tides) can lengthen the residence of water masses in the harbor and favor the deposition of suspended sediments. The importance of this phenomenon is difficult to evaluate however at the present stage of the investigations.

SUSPENDED SEDIMENT TRANSPORT MECHANISMS

Distribution of suspended sediments

Figure 4 shows simultaneously the currents, the suspended sediment concentration and the transport of sediments across the entrance of the harbor during a tidal cycle. The suspended sediments are concentrated in streams in the upper half of the water column. This phenomenon has also been observed outside the harbor (Fortin, 1978). D'Anglejan and Ingram (1976) have sampled mid-depth concentration maxima once each semi-diurnal tidal cycle at seven stations surveyed in the Middle St.Lawrence Estuary. They relate these maxima to both the turning time of tidal currents from ebb to flood and the intensity of cross-channel flow.

Floculation

Floculation of fine sediment particles is playing an important role in Gros-Cacouna harbor. On the basis of a settling velocity of 0.5 mm/sec determined by Migniot (1977) for the muds of many estuaries, the floculated suspended sediments could fall a distance of 7 meters (centrum of harbor depth) in 4 hours. If macro-flocs are formed, the settling velocity could be higher. Such mechanisms must be particularly efficient in Gros-Cacouna harbor considering the high rate of sedimentation.

Tidal volume

The concept of tidal basins as used by Renger and Partenscky (1974) and Renger (1978) is useful to evaluate the importance of tidal movements in the nearshore zone. The nearshore zone can be divided according to natural tidal basins or into more arbitrary cells. As shown on figure 7 a cell of width A, the size of the harbor, is delineated perpendicularly to the coast. The change of tidal volume of that cell is calculated for different heights of the tide. If the cross-sectional area A is considered, less water is flowing through that cross-section because of the presence of the harbor that prevents the free movement of water.

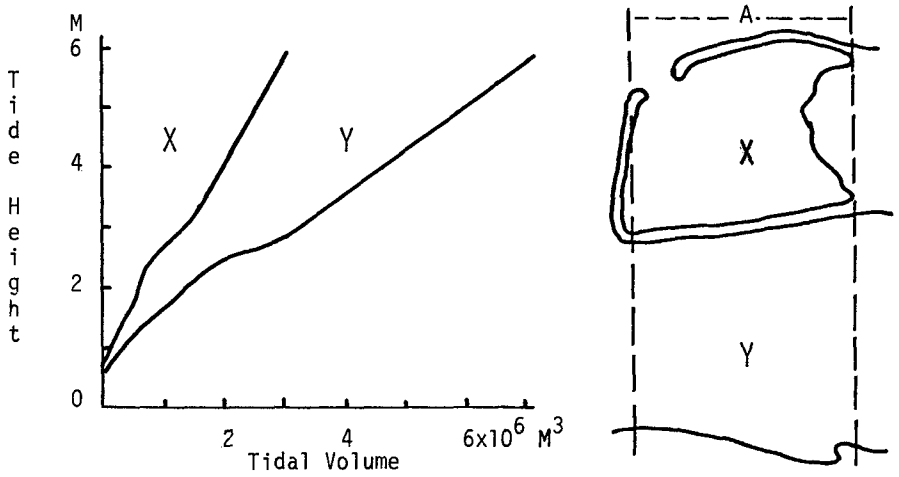

FIGURE 7

The diagram on figure 7shows the volume of water flowing in the harbor as well as the total volume of water that would otherwise flow through the cross-sectional area A. Less than half the initial volume of water is now flowing over the harbor area. It disrupts the hydraulic equilibrium that used to prevail. Although water is flowing faster at the very entrance of the harbor, the water mass is more tranquil and sedimentation is favored.

ACKNOWLEDGEMENT

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