CHAPTER EIGHTY FIVE

MEASUREMENTS OF BEDLOAD TRANSPORT IN THE NEARSHORE ZONE USING RADIOISOTOPIC SAND TRACERS.

by

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ABSTRACT

A field study was conducted on the North Coast of the Gulf of St. Lawrence in Eastern Canada to evaluate sediment transport processes in a coastal area that would be affected by the modification of river regimes for hydropower production. Radioactive tracers were used to evaluate the mobility of coastal sediments. Three injections were carried out using Neodynium 147 (half-life 11.1 days), at 450, 550 and 2200 m. from the shoreline at depths from 3 to 10 m. The high sensitivity of the detection system allowed to monitor the study area for 44 days. The tagged sediments responded to waves and tidal currents and were sensitive to minor changes. Comparison of the patterns of evolution of the three injections permitted to evaluate the relative mobility of bottom sediments as a function of water depth and distance from shore. Bedload transport rates were calculated but they are related to specific events such as storms within the Gulf of St. Lawrence more than to steady state conditions.

INTRODUCTION

Among the long term hydropower developments on the North Shore of the Gulf of St. Lawrence, one project would divert part of the Saint-Jean River into the Romaine River (Figure 1). This modification of the Saint-Jean River drainage basin would decrease the sediment supply to the coastal zone and aggravate coastal erosion. Coastal erosion in this area is enhanced by the directional wave attack from the South West while the coast is protected from eastern fetches by a series of coastal islands (Figures 1 and 2). A research program was initiated to evaluate sediment transport processes in the coastal area that would be most affected by the modification and regulation of river regimes. Radioactive tracers were used to define

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the mobility of coastal sediments and contribute to the study of sediment transport processes in that portion of the coastal zone of the Gulf of St. Lawrence.

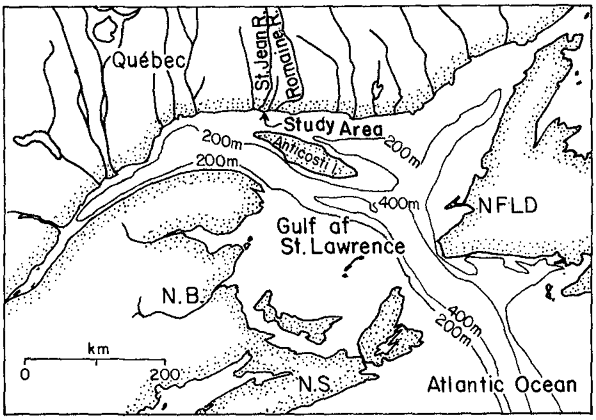

Figure 1. Location map of the study area.

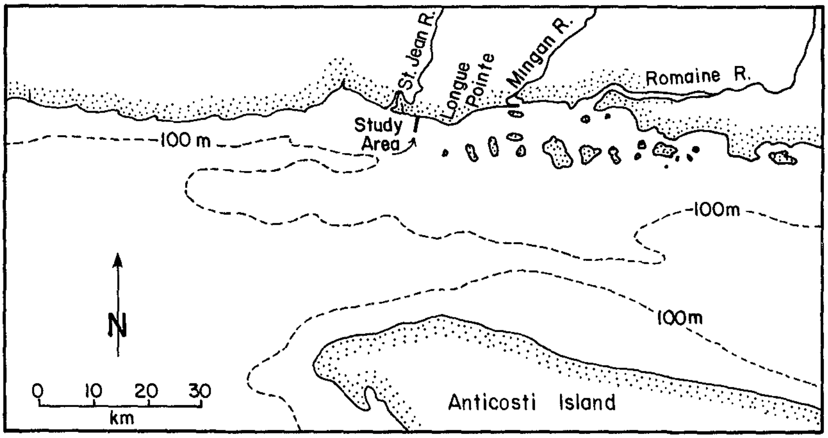

Figure 2. Regional map of the study area. This map in conjunction with figure 1 outlines that the study site is exposed to waves from SW and W and is protected from storms from other directions by Anticosti Island and a series of coastal islands. Longue Pointe is lined up with the western extremities of Anticosti Island and the coastal archipelago and it demarcates westward an erosional coastline and eastward an accretional coastline.

This paper describes the results obtained with radioactive tracers with some emphasis on the theory and methodology used, because they differ from other radioactive tracer experiments carried out in North America, namely those of Duane and his colleagues on the coast of California (Duane and James, 1980) and Lavelle and his colleagues on the New York continental shelf (Lavelle et al., 1978).

The study area is located 5 km East of the St. Jean River on the North Coast of the Gulf of St. Lawrence (Figure 2). This region is characterized by the fact that the coastline is erosional westward from Longue Pointe and accretional eastward from that point, because of the directional wave approach along that coast. The main fetch for that area is from the South-West as shown on figure 1. Figure 2 outlines with more detail that the study area is exposed to fetches from the South-West and that the window of wave propagation is quite narrow because of the protection offered by Anticosti Island and a series of coastal islands. West of Longue Pointe the present shoreline cuts through shorelines formed at higher sea levels from 1660 BP to present (Long et Drapeau, 1983). The shoreline is accretional East of Longue Pointe because of the protection offered by the coastal islands.

The study area is subjected to the combined action of waves and tidal currents. The tide is semi-diurnal and ranges between 1.7 and 2.9 m. Four Aanderaa current meters were deployed during the survey and measured reversing tidal currents of 24 to 50 cm/s during flood tides and 15 to 28 cm/s during neap tides. Long term records are not available to define yearly wave climates. During the fall of 1982, waves occasionally reached a height of 1.5 m and periods of 5 to 6 seconds in response to winds blowing from the South-West.

The nearshore zone in the study area is characterized by a shallow platform that reaches a depth of 10 m, 2.3 km offshore (figure 4). The surficial sediments are composed of well sorted 0.2 to 0.4 mm sand. Sources for these sediments are on one hand the material eroded from the coastline and on the other hand the input from the North Shore rivers (Cataliotti-Valdina et Long, 1983). Nearshore sand bars are developed on the shallow inshore platform. These bars are aligned parallel to the shoreline although they are discontinuous. Karakiewicz et al. (1983) relate the formation of this sand bar system to progressive gravity waves in the presence of tides.

BEDLOAD TRANSPORT EQUATION

The bedload transport rate Q is based on the mean velocity Vm of the mobile bedoad layer of width L, usually taken as unit width, and the thickness of the mobile layer E. This volume rate is multiplied by the density ρ of the sediment to determine the transport in terms of mass per unit time for a unit width.

$$Q = \rho \, V_m \, L \, E$$

The unknowns are then Vm and E. Vm is determined by measuring the movement of the centroid of the tracer cloud as it is done currently with radioactive as well as luminescent tracers.

The estimation of the thickness of the mobile sediment layer is more problematic. The approach used for this study was developed by Sauzay (1967) at the Université de Toulouse and used extensively in France, particularly by the Centre d'Études Nucléaires de Saclay (Tola, 1982).

Sauzay based his analysis on the principle that if the total amount of radioactive material used for injection is measured precisely and if the detections that follow the tracer injection account for all the tracer used, then a relationship exists between the amount of tracer used A, the total count of detected radiation N and the thickness of burial of the tracer E (Figure 3).

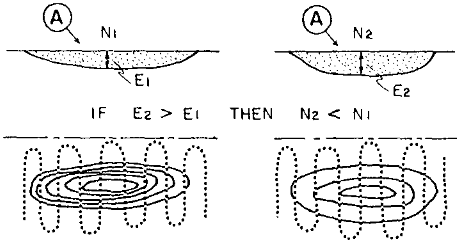

Figure 3. Schematic of the concept of count rate balance. «A» is the amount of tracer energy. «N» is the amount of tracer detected and «E» is the thickness of the tracer in the mobile sediment layer.

The probe is calibrated to conform to the penetrating power law for a point source:

$$f(z) = f_0 e^{-\alpha z} \tag{1}$$

where f_0 and α are calibration constants.

As the sand tracer is not a point source and is rather scattered within the sediment from the seafloor (depth = 0) to a maximum depth E, equation 1 is integrated.

$$f(z) = \int_0^E f_0 e^{-\alpha z} dz \tag{2}$$

The count rate recorded by the probe is also a function of the tracer concentration with depth C(z) and should also be part of the integration process.

$$f(z) = \int_0^E f\, e^{-\alpha z} C(z)dz \tag{3}$$

We analyse first a hypothetical case where the concentration of the tracer is uniform for the whole depth E, then

$$C(z) = Cm \tag{4}$$

The radiation count rate N is then easily determined by integrating equation 3 for the interval 0 to E.

$$N = Cm\, f_0 \frac{1}{\alpha} \left\{1 - e^{-\alpha E}\right\} \tag{5}$$

The initial amount of radioactivity injected A being known as well as its half-life, the remaining activity at the time of a given survey A(t) can be determined. The hypothetical uniform tracer concentration per unit Cm used in the preceeding equation can be expressed as:

$$Cm = \frac{A(t)}{E} \tag{6}$$

and by substitution of equation 6 in equation 5 we obtain:

$$N = \frac{A(t)}{E} f_0 \frac{1}{\alpha} \left\{1 - e^{-\alpha E}\right\} \tag{7}$$

Remains to be reconsidered the initial hypothesis of constant tracer concentration with depth. The distribution of radioactive tracer within the mobile sediment layer can take different configurations. Sauzay (1967) has analysed different tracer distributions as a function of depth and he has integrated these data to obtain what is termed the equivalent concentration Cc.

$$Cc = \int_0^E C(z)dz \tag{8}$$

The approach taken by Sauzay is to introduce the coefficient:

$$\beta = \frac{Cc}{Cm} \tag{9}$$

The maximum depth E is then obtained implicitely by solving the equation

$$N = \beta \frac{A(t)}{E} f_0 \frac{1}{\alpha} \left\{1 - e^{-\alpha E}\right\} \tag{10}$$

Experience has shown (Tola, 1982) that a parabolic tracer distribution is the most realistic and the use of a constant value of 1.15 for β has produced consistent results.

FIELD DEPLOYMENTS

The radioactive element used for that series of experiments on the North Shore of the Gulf of St. Lawrence is Neodynium 147 whose half-life is 11.1 days. The radioactive tracer used is made of specially prepared glass containing neodynium. This glass was radioactivated at the Centre d'Études Nucléaires de Saclay. For the purpose of this experiment, the granulometry of the glass was chosen between 0.2 and 0.4 mm to coincide with that of the natural sediment.

The radioactive tracers were injected at three locations in the study area (see Figure 4). Two injections were deployed nearshore, one on each side of a sand bar located 450 m offshore at a depth of 3 m. The third injection was located at the edge of the flat platform, 2.2 km offshore. Five hundred grams of glass radioactivated at the level of 2.9, 2.2 and 1.7 Curies were spread on the seafloor surface at each location.

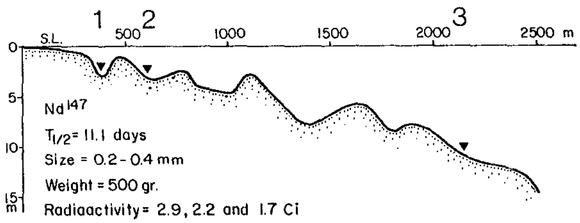

Figure 4. Seafloor profile of the study area. The location of the three injection points is indicated by black triangles. The characteristics of the tracer are summarized on the figure.

The detection equipment used was developed at the Centre d'Études Nucléaires de Saclay. It is composed of a NaI scintillation probe which is connected to two parallel systems of detectors, counters and plotters, one system working on a linear scale and the other on a logarithmic scale. This combination permits to follow with the same precision the response of the tracer at low as well as high levels of radioactivity.

The scintillation probe used is miniature as compared with the RIST probe (Duane, 1970; Lavelle et al., 1978). It is contained within a waterproof stainless steel cylinder 5.3 cm in diameter by 36 cm long that weighs only 2 kg. The probe is mounted on a sled that maintains the center of the probe at a constant height of 5 cm above the seafloor (Figure 5).

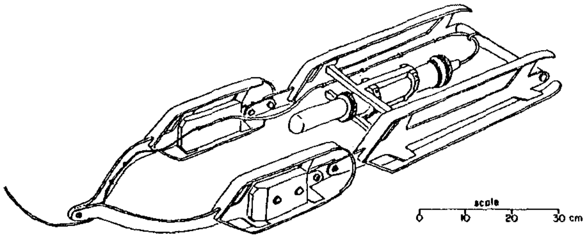

Figure 5. Drawing of the scintillation probe mounted on a sled that maintains the probe at a constant height of 5 cm above seafloor (after Anguenot, Caillot et Courtois, 1968).

It is essential that each survey completely covers the radioactive cloud as schematized on figure 3. As explained previously, the evaluation of the thickness E of the mobile sediment layer is based on the assumption that each survey detects all the tracer initially injected. The survey lines are oriented perpendicular to the direction of sediment transport and are prolongated to ascertain that the limits of the survey extend well beyond the radioactive cloud.

Radiation count rates are integrated for each transect and totalled for the whole survey. Calculations are based on a towing velocity of 1 m/sec because the probes are calibrated for radiation count rates in counts per second with reference to radioactive material uniformly covering one square meter. Sauzay (1967) has shown that towing the detection system at a constant velocity of 1 m/sec produces the same results as if count rates per second were measured at fixed grid locations. It was possible during the surveys in the Gulf of St. Lawrence to maintain a survey velocity of 1 m/sec and to correct for departures using a Trisponder system for positioning.

RESULTS

Contours of the radiation levels and locations of the centroid of the labelled zones are shown on figure 6. The contours of radiation levels outline how the initial 500 gram release of radioactive glass mixes with the indigenous sediment and spreads on the seafloor. The lowest contour is 50 counts/sec above background and the other contours are for 150, 500, 1500, 5000, 15 000, and 50 000 counts/sec. In the case of these experiments on the North Coast of the Gulf of St. Lawrence, all three injections show that the highest tracer concentration has moved and that the tracers have spread during the 44 days that the experiment lasted.

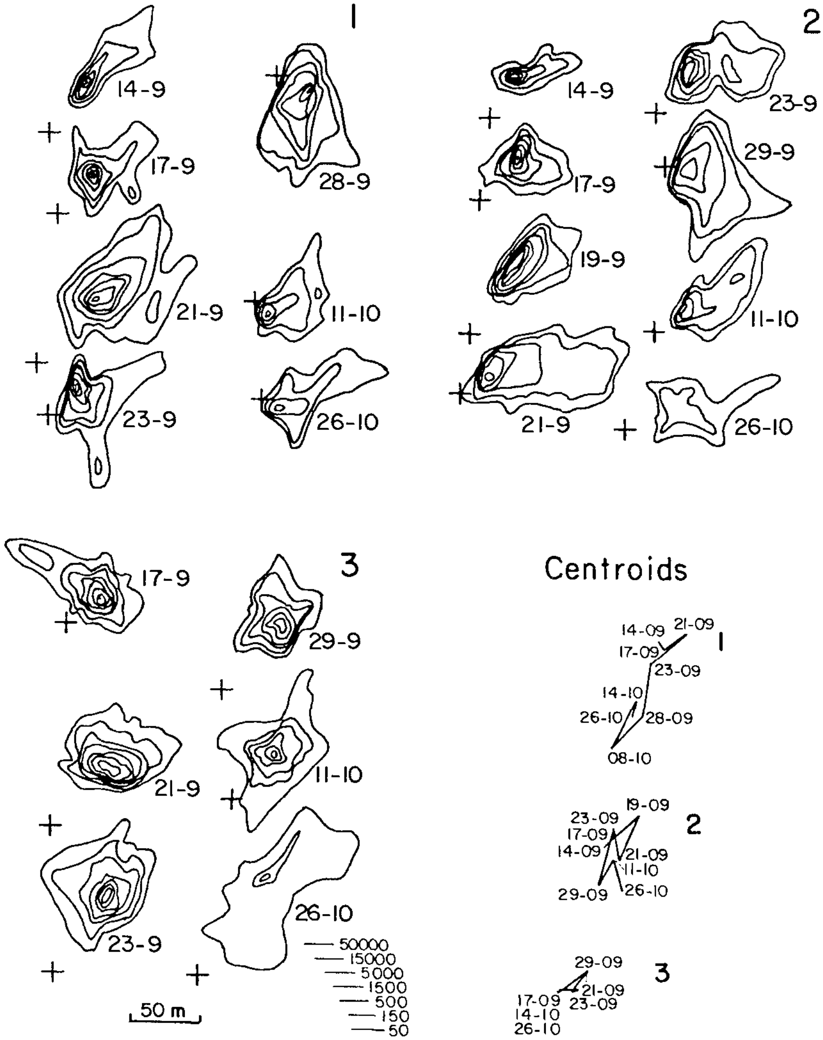

Figure 6. Evolution of tracer patterns for the three experimental sites. Each site is identified by a bold figure and each survey is identified by date-month. A cross is drawn as a fixed reference for each site to evaluate the movement of the tracer cloud. The outer countour is always 50 counts/sec and the others are 150, 500, 1500, 5000, 15000, and 50000 counts/sec. The movement of the centroids is shown in the lower right portion of the figure.

The movement of the centroid of the tagged sediments is used to calculate the mean velocity of the mobile sediment layer. It is apparent on figure 6 that the movement of the centroid, although alike, does not coincide with the highest tracer concentration.

Experiment number one was the closest to the seashore, that is 350 m from the high tide line in a slight depression on the shore side of the first sand bar (Figure 4). The first survey on September 14, two days after injection, shows that the tagged sediments have spread towards the North-East. As the sea was calm during these two days, the spreading pattern of the tagged sediments outlines the influence of the ebbing tidal currents that prevailed during and immediately following the injection of the tracer on the seafloor. The survey on 17 September outlines the influence that 0.5 m waves had on the labelled sediments. Tidal currents reached 41 cm/sec for a period of two hours between 14/9 and 17/9. The survey on 21/9 shows the result of a 30 hour storm that produced 5 to 6 second waves that reached 1 m heights. The following surveys show the evolution with time of the tagged sediments, but it should be kept in mind that the contours of radiation levels are not compensated for radioactive decay and by 26 October only 6.5 percent of the initial radioactivity was left.

The second injection site was located between the first and the second sand bar, 600 metres from the shoreline. The first survey on September 14 outlines essentially the same characteristics as for the first site that the tracer two days after injection has spread towards the North-East but is still concentrated within a 40 by 70 meters area. Comparison of surveys 19/9 and 21/9, before and after the storm mentioned previously, indicates that the movement of sediments on the seafloor has been somewhat more intense at that second location. Tidal currents were stronger: flood currents reached 20 cm/sec and ebb currents of 52 cm/sec were measured during the storm. After that storm, the tagged sediments at that location evolved in a similar manner as those of the inshore location.

The third experiment took place beyond the sand bars, 2.2 km offshore at a depth of 10 meters. The distance offshore and the greater water depth explain that the tracer was less mobile at that location. The elongation of the radioactive cloud towards the North-West is a response to flood tidal currents of 37 cm/sec. The survey 21/9, when compared with those of experiments 1 and 2 for the same date, indicates that the disturbance of the seafloor by storm waves was less intense at that third location because of the greater water depth. Tidal currents reached 41 cm/sec during the storm that preceeded that survey. The comparatively large area covered by the 50 counts/sec outside contour on 26/10 could be explained by the fact that the radioactive tracers were less dispersed at that location further offshore and could yield a uniform signal above 50 counts/sec after 44 days.

The movement of the centroid of each radioactive cloud is also shown on figure 6. As explained previously, the movement of the centroid is not identical to that of the highest tracer concentration. The figure 6 outlines the relative mobility of each cloud of radioactive sediments. Sediments from experimental site 1 were closest to shore and also the most mobile. By contrast, the centroid of the tagged sediment from experimental site 3, 2.2 km offshore, only moved back and forth a distance of some 25 m.

DISCUSSION

Bedload sediment transport rates have to be identified with the time scale of interest, be it that of waves, tides or seasonal storms. For instance, direct methods that measure grain-to-grain movement respond to all modes of excitation of the seabed and particularly to the oscillatory movement of waves. The experiments with radioactive tracers on the North Shore of the Gulf of St. Lawrence responded to tidal and storm events and they outlined that the net movement of sediments after 44 days is of comparable amplitude to the movements linked to tides and storms. Ideally, the rate of movement of the radioactive tracers would reach an asymptotic value as the tracer becomes more homogeneously integrated to the seabed. This asymptotic value would be representative of the yearly rate of transport. This «steady-state» was not reached during these experiments with Neodynium 147 on the North Shore of the Gulf of St. Lawrence: a longer half-life tracer would be needed.

Bedload sediment transport rates were calculated however for the main storm on September 20th. The centroid of the tagged sediments moved a distance of 36 m during a period of 48 hrs, that is $V_m = 0.75$ m/hr. Using the algorithm described above, the thickness of the mobile layer was determined as $E \simeq 2.95$ cm for the 19/9 survey before the storm and $E = 13.06$ cm for the 21/9 survey after the storm. A mean value of 5 cm was used for the bedload calculations. These data yielded a bedload transport rate of 60 kg/m/hr in the direction 163 degrees from North. These results are compared with calculations based on the bedload sediment transport model developed by Vincent, Young and Swift (1982). Nearbed current velocities were obtained from Aaderaa current meters fixed upsidedown on the seafloor to measure currents 50 cm above bottom. Records from these currents meters are reproduced on figure 7 and they show a very good signature from the tidal currents, but they also indicate that Savonius-type current meters are not suitable to monitor wave-dominated conditions. To obviate the problem of not having current measurements during the storm itself, current data for September 19th were used because the records show that tidal currents are not varying much from one day to the next one (see Figure 7). Calculations for different wave conditions, that is wave periods of 5 seconds and wave heights of 0.5, 0.7, 0.9, and 1.0 meter are shown on figure 7. The transport model predicts 58.3 kg/m/hr for 1 m waves which corresponds to the waves conditions that prevailed in the study area on September 20th.

The good agreement between the tracer experiment and the calculated sediment transport rate has its merits but it could be anticipated. The model developed by Vincent, Young and Swift (1982) is based on linear wave theory which implies that even the highest waves would not produce the slightest net residual transport component. In the study area, on the North Shore of the Gulf of St. Lawrence, tidal

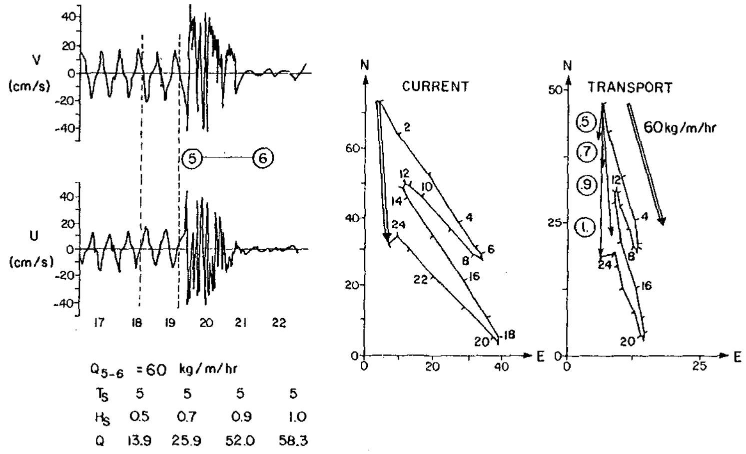

Figure 7. Experimental site 2. A time series of a portion of current meter deployment is shown on the upper left. The V(North) and U(East) components outline the semidiurnal tidal currents. A progressive current vector diagram for the diurnal tide of 19 September, delineated by dotted lines on the time series, is drawn in the center of the figure. A sediment transport progressive vector diagram appears on the right side of the figure. This diagram reproduces the progressive vector for sediment transport resulting from the combined effect of the tidal currents and 1 m high waves. Resulting transport vectors for 0.5, 0.7 and 0.9 m waves are also shown on the same diagram. A vector representing the transport rate measured with radioactive tracers (60 kg/m/hr) is also drawn at the extreme right for comparison. The results of transport calculations for different combinations of wave heights with the tidal current are tabulated on the lower left side of the figure.

currents are important and the application of a linear wave theory model reflects this phenomenon. The good agreement between the field measurements and the calculations is also interesting because the model is used at the limits of applicability. On one hand the model developed by Vincent and his colleagues uses bottom friction concepts developed by Grant and Madsen (1978) for waves in the presence of weak currents; in the present study the tidal currents are comparable to the nearbed wave orbital velocities. On the other hand the water depth versus wave height is also a limiting factor in this study that uses a linear wave theory. The latter problem is presently investigated by Boczar-Karakiewicz (1981). For many sediment tracer studies in the nearshore zone a non-linear wave model combined with nearbed currents of comparable amplitude to the bottom wave orbital velocities would provide a more realistic representation of the environmental conditions.

The rate of sediment transport (60 kg/m/hr) determined with radioactive tracers for the moderate storm conditions of September 20th are of the same order of magnitude as results obtained in other areas. Lavelle and colleagues (1978) used radioactive sediment tracers on the Long Island inner shelf and obtained sediment flux estimates of 61.2 kg/m/hr (0.17 gm/cm/sec) for winter storm conditions. The approach taken by Lavelle and colleagues to determine the sediment flux is basically different from that of the present study however, as they assumed that the points of highest tracer concentration were stationary and used an advection-diffusion equation to obtain flux estimates of the tagged sediments. Vincent, Young and Swift (1982) used their model to calculate bedload transport at a 10 m water depth 1 km from the Long Island coastline where they estimated bedload transport peaks of 316 kg/m/hr (3160 gm/cm/hr).

SUMMARY AND CONCLUSIONS

To summarize, this study shows that radioisotopic sand tracers were used successfuly in the nearshore environment of the North Coast of the Gulf of St. Lawrence. The main conclusions drawn from these experiments are:

1. The compactness and lightweight of the scintillation probe and support equipment facilitated the logistics. It was then possible to improve the precision of the surveys using a highly maneuvrable small fishing boat.
2. Radioisotopic sand tracers are very effective because they can be surveyed accurately without disturbing the sediment with which they intermix. The labelled sediments were sensitive to waves and tidal currents. It was possible to relate the evolution of the radioactive cloud patterns to specific events such as peak tidal currents and storm generated waves.
3. The use of three tracer injections permitted to evaluate the relative mobility of the seabed. Ideally, the rate of movement of the radioactive tracers would reach an asymptotic value as the tracer becomes more integrated with seabed. These experiments with Nd 147 did not last long enough to reach that steady state.
4. Estimates of sediment transport rates of 60 kg/m/hr during a storm compare with other radioisotopic sand tracer measurements particularly on the Long Island Shelf. Comparison of storm transport rates using tracers also shows a very good coherence with a linear wave analytical model.

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