CHAPTER 234

DISPERSION MODEL OF DREDGE SPOIL DUMPED IN COASTAL WATERS

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Abstract

This model is specifically conceived to work in estuarine environments characterized by strong tidal currents. It operates on a microcomputer and it is conceived to work with minimal input. The model determines the velocity and radius of the dense sediment cloud, formed by the release of sediments from a scow, during its downfall in the water column. These parameters are used to determine the proportion of sediments settling at the point of impact. Sediments maintained in suspension by the high level of turbulence following impact on the bottom form a density current that spreads out radially. The performance of the model was verified by a series of experiments carried out in the St Lawrence Estuary to monitor the disposal of dredged spoil from a 400 m^3 scow.

1. INTRODUCTION

The present model was initially developed for the Canadian Ministry of Fisheries and Oceans to evaluate the impact of dredged sediments dumped from a scow in different marine biotopes. Prerequisites were that the model works with minimal input and runs on a microcomputer. Another requirement was that the model would be efficient in estuarine environments characterized by strong tidal currents.

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The bulk of sediments released from a scow reach the sea floor at the dumping site and only a small percentage remains in the water column. Gordon (1974) estimates that more than 95 per cent of sediments released from a scow reach the sea floor and observations by Tavolaro (1984) lead to similar conclusions. The present model describes the behavior of the dredged sediments that reach the sea floor at the dump site and a companion model is used to determine the fate of sediments dispersed in the water column.

Different mathematical models have been developed to describe the dispersal of dredged sediments. A model was developed by Edge and Dysart (1972), in which the dumped material is assumed to behave as a dense liquid moving in a lighter one. Koh and Chang (1973) used similar concepts to develop a model that deals with each of the three phases of dredged material dispersal and can handle continuous discharge of sediments as well as dumps from a scow. However, this model is not particularly suited for coastal environments and it is much more complex than the model described in this paper. Bokuniewicz et al. (1978) developed a mathematical model that determines potential and kinetic energy of dumped sediments. Based on the energy budget of the dumped sediments, the authors determine the maximum distance reached by the density current that spreads on the sea floor after the dumped sediments impact on the bottom.

Field measurements to develop this model were carried out in in Canada, in the Lower St. Lawrence Estuary. Measurements took place at Rivière-du-Loup and Rimouski where the tidal range varies between 5 and 6 m. and the dump sites are located in 10 m. and 20 m. water depth respectively.

2. MODEL DESCRIPTION

The dispersal of dredged sediments released from a scow follows three stages (Fig. 1). Upon release, the dredged material descends rapidly through the water column as a well-developed high density jet; subsequently, when the dredged material hits the bottom, part of the sediment load settles at the site of impact; and finally, the high level of turbulence generated by the impact maintains a cloud of sediments in suspension that forms a density current which spreads out radially.

2.1 Descent of sediments through the water column

A series of flume experiments conducted by Krishnappan (1975) have shown that the fall of dumped sediments can be treated in two distinct phases, an entrainment phase when sediments leave the scow followed by a settling phase that develops only when the water depth is sufficient (which is not the case in coastal waters) for the vertical downward velocity to become the same as the settling velocity of sediment particles. During the entrainment phase, the size of the

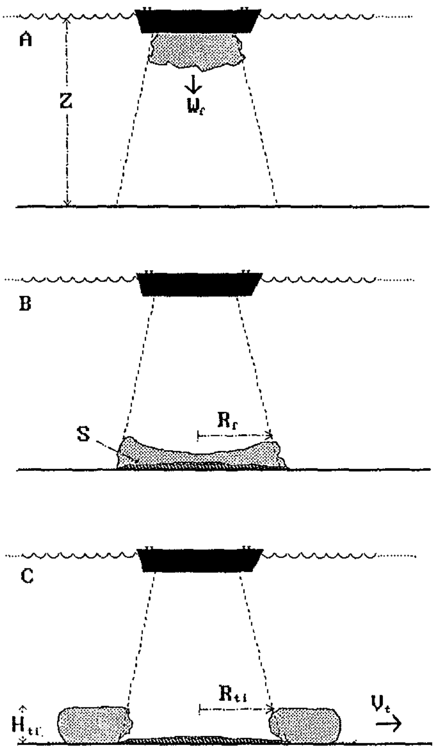

Figure 1. A) The dump load leaves the scow as a massive cloud of sediments that expands during its fall as water is incorporated.
B) At impact on sea floor a portion of the dumped sediments settle on the sea floor and the remainder is maintained in suspension by the high level of turbulence generated by the impact and forms a density current.
C) The density current expands radially taking the shape of a tore. For modeling purposes, the initial radius of the tore is taken to be that of the falling sediment cloud at the moment of impact.

sediment cloud, that forms when the scow opens, grows owing to the incorporation of external fluid while the vertical downward velocity diminishes (Fig. 1a). Flume measurements and dimensional analysis have lead Krishnappan to formulate the downward velocity (W_f) as well as the radius (R_f) of the sediment cloud as a function of water depth:

$$R_f = \alpha_k Z \tag{1}$$

$$W_f = \beta_k F^{1/2}/Z \tag{2}$$

where Z is the water depth, F is the negative buoyancy of sediments and α_k and β_k are variables whose values are functions of the sediment grain size determined experimentally by Krishnappan.

2.2 Settling of sediments at point of impact

No systematic formulation is presently available to determine the exact proportion of the total sediment load that settles on sea floor at the point of impact. The parameters that determine the settling of dumped sediments at the point of impact are: 1) the sediment grain size and 2) the impact velocity on the sea floor, which is related to water depth. It stands to reason that coarser sediments will have a greater tendency to settle at the point of impact than finer ones. Velocity of the mass of dumped sediments at the moment of impact provides the energy necessary to generate a level of turbulence sufficiently high to bring sediments into suspension. For instance, if the water depth is sufficient to allow sediments to reach their inherent settling velocity, all sediments would settle naturally on the sea floor without further movement, no energy being left to generate turbulence and maintain sediments in suspension.

The proportion of sediments settling directly at the point of impact is defined as follows in the present model:

$$S = 1\text{-}C(W_{fi} - W_s)/W_{fi} \tag{3}$$

where W_{fi} is the downfall velocity of the mass of dumped sediments at the moment of impact and W_s is the natural settling velocity of sediment particles (Fig. 1b). C is a constant; its present value is set at 0.5. This equation determines the "excess energy" available to generate a density current. As explained above, if W_f diminishes to the point that $W_f = W_s$, Then $S = 1$ and no sediments are left to form a density current.

According to field measurements carried out by Gordon (1974), 80 per cent of the dumped sediment load settles within a 30 m. radius from the point of impact. Other workers (Bokuniewicz et al., 1978; Tavolaro, 1984; Truitt, 1986) observed that a large proportion of dumped sediments settle at the point of impact, but no specific correlation is established with sediment grain size and water depth.

2.3 Formation of a density current

Truitt (1988) summarized observations of many workers explaining that dredged sediments form density currents that spread on the sea floor following impact on bottom. Profiles of dredged sediment dispersion, measured by Gordon (1974) and also by Malherbe (1990), on a larger scale, outline this phenomenon.

The principle of conservation of mass is used to determine the transfer from a massive sediment fall before impact on the bottom to the formation of a density current (Fig. 1). The cloud of sediments formed by the content of the scow falling through the water column has a radius R_{fm} (cf. eq. 1) and a downward velocity W_{fm} (cf. eq. 2) when it hits the sea floor. The vertical flux is defined as:

$$\text{Flux} = \pi R_{fm}^2 W_{fm} \tag{4}$$

The density current generated by the impact on the sea floor expands radially and it takes the shape of a tore (Bokuniewicz et al., 1978). If R_{ti} is the initial radius of the tore, H_{ti} is the initial height, and V_{ti} is the initial velocity, the initial flux of the density current expanding radially on the sea floor is:

$$\text{Flux} = 2\pi R_{ti} H_{ti} V_{ti} \tag{5}$$

The initial radius R_{ti} of the density current is that of the sediment cloud when it impacts on the sea floor (Fig. 1b and 1c):

$$R_{ti} = R_{fm} \tag{6}$$

Using the principle of conservation of mass to equate equations 4 and 5, we can write:

$$\pi R_{fm}{}^2 W_{fm} = 2\pi R_{ti} H_{ti} V_{ti} \tag{7}$$

and:

$$R_{fm} W_{fm} = 2 H_{ti} V_{ti} \tag{8}$$

This equation contains two unknowns; the initial height (H_{ti}) and the initial velocity (V_{ti}) of the density current.

2.3.1 Velocity of the density current

Density currents are studied principally to interpret sedimentary facies (Middleton and Southard, 1984). For instance, Keulegan (1957) and Middleton (1966a,b) produced density currents experimentally by releasing brines and suspensions of spherical beads into horizontal channels. Experimental results agree to define the velocity of the density current as follows. The difference density D_t of the density current is defined as:

$$D_t = p_s / p \tag{9}$$

where p_s is the excess density of the density current and p is the density of water; and:

$$V_t = Fr(D_t g H_t)^{1/2} \tag{10}$$

where V_t is the velocity of the density current, Fr is the densimetric Froude number, D_t is the difference density of the density current, and H_t is the height of the density current. Middleton (1966a) has found experimentally that the densimetric Froude number for density currents generated by sediments into suspension flowing on a horizontal bottom has a constant value of 0.75. The velocity of the density current is then a function of the density difference and the height of the density current. The density difference is determined by the quantity of sediments brought into suspension following the impact of sediments on the sea floor. This quantity is known from equation 3.

2.3.2 Height of the density current

Equation 10 shows that V_t is a function of H_t and it is then possible to determine the initial height (H_{ti}) of the density current. Equation 10 is introduced in equation 8 and H_{ti} is defined explicitly as:

$$H_{ti} = [(R_{ti}W_{fi})^2/(4Fr^2gD_{ti})]^{1/3} \tag{11}$$

This algorithm effectively sets the initial height (H_{ti}) of the density current in such a way that the conservation of flux is respected, as defined by equations 4 and 5.

2.3.3 Evolution of the density current

The following initial conditions are assumed to define the evolution of the density current: 1) the density current forms a tore that expands radially (Bokuniewicz et al., 1978), 2) the volume of the tore is constant, and 3) the width (L) of the tore is constant. Consequently, in order to maintain the volume constant, the height of the tore (H_t) diminishes as the tore spreads radially. It implies that H_t is a time dependent variable.

Sediments suspended in the density current are settling on the sea floor according to their nominal settling velocity (W_s) and, consequently, the density of the density current diminishes as the settling of sediments on the sea floor progresses. The concentration of sediments in the density current can be defined by the following differential equation:

$$dP_t/dt = -(P_t/M_t)W_sA_t \tag{12}$$

where P_t is the quantity of sediments in the density current, M_t is the volume of the density current, W_s is the settling velocity of sediment particles and A_t is the surface area of the density current. As:

$$M_t/A_t = H_t \tag{13}$$

where H_t is the height of the density current. Equation 13 can be rewritten as follows:

$$dP_t/dt = -P_tW_s/H_t \tag{14}$$

As mentioned above, H_t is itself time dependent. This equation is solved numerically; initially using a Runge- Kutta algorithm, but it is handled more efficiently by linear iteration.

The rate of deposition on the sea floor of sediments contained in the density current is proportional to the sediment concentration in the density current. That rate of deposition is also inversely proportional to the velocity at which the density current is moving on the the sea floor; for example, when the density current is moving faster, the sediments settling on the sea floor are spread over a larger area.

2.4 Advection by tidal currents

Tidal currents play an important role in estuarine environments. At the present stage of development of the model, tidal currents are simply advecting the density current (Fig. 2). In theory, advection should have an influence on the densimetric Froude number but, in practice, it is not significant within the context of the present model.

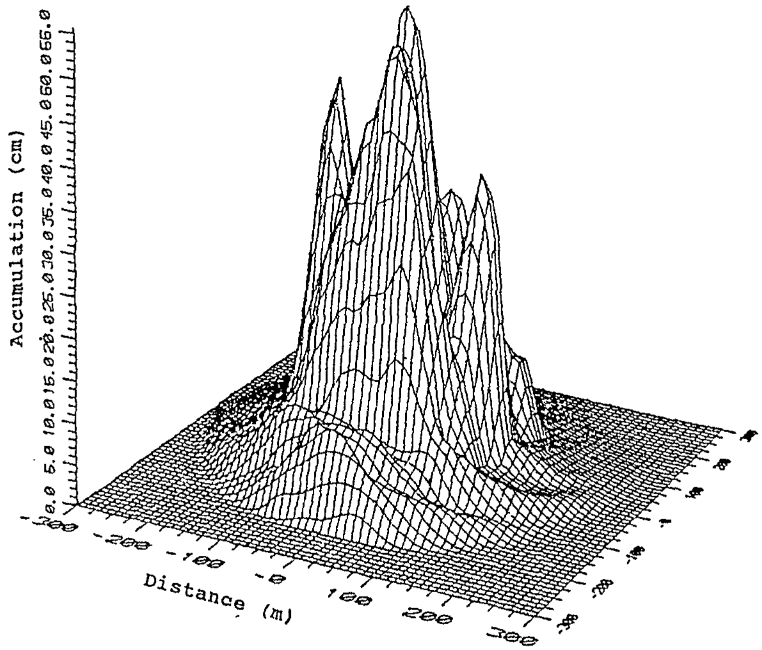

Figure 2. Three-dimensional mesh of sediment accumulation on the sea floor resulting from the simulation of 125 dumps totaling 50,000 m^3 of dredged sediments at a water depth of 20 m. and tidal currents reaching .4 ms^{-1}. The bulk of sediments is deposited within a 150 m. radius and the remainder is transported by density currents advected in different directions depending on the phase of the tide.

2.5 Sedimentation grid

The present model is designed to describe the cumulative effect of dredging operations resulting from many dumps at a given site. The cumulative sedimentation resulting from successive dumps is handled by implementing a grid system that works as follows. The spatial and temporal scales to calculate the amount of sedimentation on the sea floor are set to obtain sedimentation measurements spaced approximately 10 m. apart. A 2x2 kilometer grid, using a 10 m. mesh size, is established and each sedimentation calculation is attributed to the corresponding mesh. This procedure permits to record sedimentation from successive dumps even if they do not originate from the same location on the dumpsite (Fig. 2). This feature is important to allow for the possibility to simulate inherent navigation errors and also to take into account that scows are not necessarily completely stopped during dumping operations.

2.6 Drifting during dumping

Most operators prefer not to stop completely during dumping operations. This situation is simulated by spreading sediments settling at the point of impact over a 50x50 m. area instead of a single point. Other dimensions can be chosen at will, depending on the speed of the scow and the time taken to unload.

2.7 Positioning error

The positioning of a scow over a dump site is more or less precise depending on the navigation system used. This inherent error is dealt with by choosing at random a position within a circle corresponding to the positioning uncertainty, typically 150 m. in the St. Lawrence Estuary.

3. INPUT / OUTPUT

3.1 Input

The following parameters are used as input: 1) volume of sediments dumped, 2) number of dumps, 3) water depth, 4) sediment grain size, 5) radius of navigation error, 6) currents (current-meter records or tidal- current ellipses).

Three sediment grain sizes with corresponding percentages are used to describe the texture of dredged sediments. Two options are offered to input current data: current-meter data files or keyboard input of tidal current ellipses. When a current-meter data file is used as input, the data sampling from the file is organized to correspond as closely as possible to the dredging operations. For example, data sampling from the file starts to coincide with the beginning of the dredging operations and sampled data are averaged to correspond to the dumping routine (e.g one dump every hour). Furthermore, if dumping operations are not continuous, the idle periods (night time) are not sampled. When current meter data are not available, tidal currents are simulated by the model on the basis of tidal current ellipses. Speeds and directions of tidal current ellipses are input from the keyboard to simulate estuarine conditions prevailing at the studied dump site.

3.2 Output

Data produced as output are: a) three files: 1) sedimentation matrix file, 2) N-S cross-section file, 3) W-E cross-section file and b) four graphics: 1) Contours of dredged sediment deposit (Fig. 2 and 5), 2) 3-D mesh of sediment deposit (Fig. 2), 3) N-S sediment deposit cross-sections, and 4) W-E sediment deposit cross- section. Graphics displays are produced by the software package "Surfer" (Golden Software, Boulder, U.S.A.).

4. FIELD MEASUREMENTS

4.1 Location and dredging equipment

Field experiments were carried out at two locations in the St. Lawrence Estuary to verify the present model. At Rivière-du-Loup the dump site was located in 10 m. water depth and tidal currents reached 1.5 ms^{-1}. At Rimouski, the water depth was 20 m. at the dump site and tidal currents reached 1.0 ms^{-1}. The dredging equipment operating at both locations was a clamshell dredge loading 400 m^3 scows.

4.2 Sediment types

The operations monitored were maintenance dredging at both sites. The sediments dredged were poorly sorted very fine sands mixed with silty muds, the grain size ranging between 0.015 and 0.250 mm.

4.3 Field measurement equipment

Echosounder: A 200 kHz echosounder was used to track the dispersal of dredged sediments. That frequency is very effective to trace sediment clouds in the water column (Fig. 3).

Transmissometer: Transmissometer measurements could confirm the presence of density currents but more in a qualitative than a quantitative way.

Water samples: Water samples were taken to calibrate transmissometer data.

Sediment traps: Sediment traps were very useful to calibrate the model, because they provide factual measurements of sedimentation rates. The traps were made of 30 cm. high by 10 cm. wide plastic cylinders. The cylinders were mounted in lead containers, that were heavy enough to be placed directly on the sea floor.

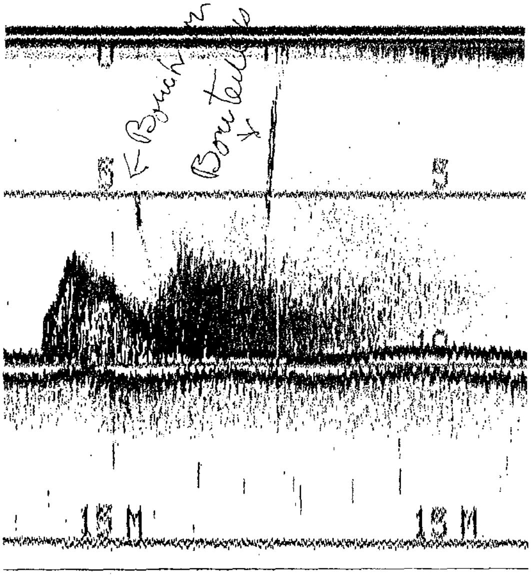

Figure 3. Example of density current observed using a 200 kHz echosounder from a boat anchored in 10 m. water depth. The sharp front of the density current appears on the left side of the recording and the more diffuse tail is recorded in the right portion of the echogram.

5. RESULTS

Model estimates of dredged material accumulation on the sea floor are compared with field measurements obtained from sediment trap deployments. The model is run to simulate the dumps that were monitored with sediment traps and results from the model are compared with sediment trap measurements in figures 4 and 5. The dots on the six diagrams shown in figure 4 are the sediment trap measurements and the full lines show the results of model estimates of sedimentation corresponding to specific dumps monitored at Rivière-du-Loup. The sharp breaks in model estimates result from the fact that sediment accumulation is much higher near the point of impact, where a large proportion of the dumped sediments are settling.

Figure 5 shows the monitoring settings for dumps #4 and #11. Contours of sediment accumulation on the sea floor predicted by the model are plotted on a grid. The location of sediment traps is indicated by dots. Model estimates corresponding to sediment trap measurements are outlined in the upper right corner of each diagram.

6. DISCUSSION AND CONCLUSIONS

The dumping of dredged sediments from a scow is an operation which is difficult to monitor, particularly when tidal currents are strong. Sediment traps have to be deployed ahead of time before dumping takes place. The success of the operation depends on the ability to foresee the direction and intensity of tidal currents at the very moment the dumping of dredged sediments will take place. Because of tidal currents and winds, dumps do not always take place at the exact location where they had been planned, with the consequence that the alignment of sediment traps is not always optimal. In addition, sediments dredged with a clamshell remain clumsy and scows are equipped with doors that do not open instantly. The result is that dumped sediment loads are not always as uniform as one would like from an experimental point of view.

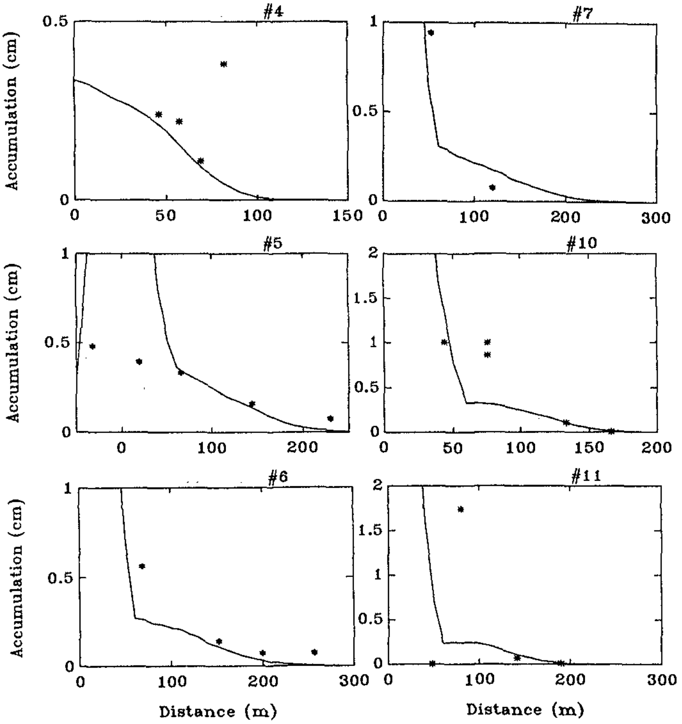

Figure 4. Comparison of model estimates and sediment trap measurements. The full lines on these six diagrams show the model estimates and the dots are the sediment trap measurements. The sharp breaks in model estimates result from the fact that sediment accumulation is much higher near the point of impact, where a large proportion of the dumped sediments settle out.

Despite the problems inherent with the monitoring of dispersal of dredged sediments, the monitoring carried out at Rivière-du-Loup and Rimouski was successful enough to warrant that the concepts used to develop the present model are realistic. As it can be seen in figure 4, dump #4 shows a good agreement between measurements and model except for the fourth sediment trap for which there is no explanation. Dump #5 is one of the most interesting, because it shows that the sedimentation rate as a function of distance from the point of impact is well predicted by the model, although the point of impact of the model (coordinates 0,0) does not coincide with the location where the dump effectively took place. The other diagrams show a relatively good agreement between measurements and estimates. An exact fit between model and field measurements is beyond expectations. However, the overall trends and rates of sedimentation as a function of distance from the point of impact estimated by the model are realistic.

The correlation between model estimates and sediment trap measurements is outlined more explicitly in figure 5. Dump #4 took place when tidal currents were weak, .1 ms^{-1}, and dump #11 was carried out when tidal currents reached .7 ms^{-1}.

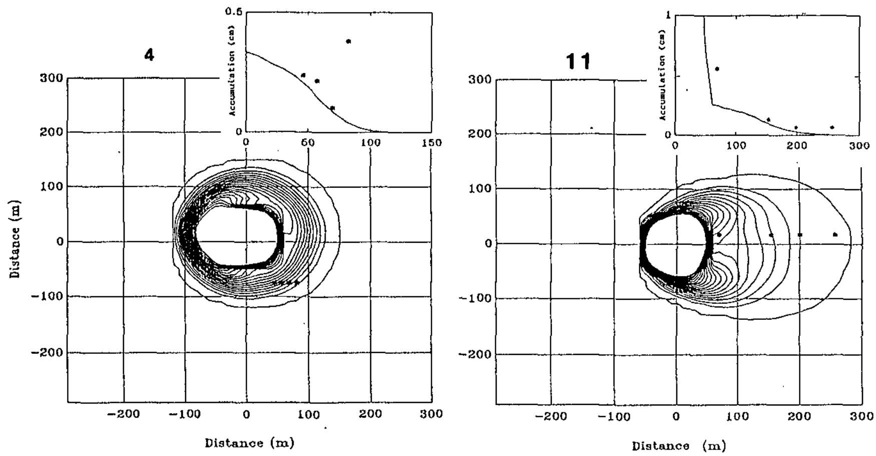

Figure 5. Examples of sediment distribution for different tidal conditions. Results obtained from the model are compared with accumulation in sediment traps. The quantity of sediments dumped is 400 cubic meters and the water depth is 10 m. Tidal currents are .1 ms^{-1} for the plot on the left and .7 ms^{-1} for the plot on the right. Dots on the plot show the location of the sediment traps. The diagrams on the upper right corner of each plot compare the simulation from the model (the full line) with the measurements from the sediment traps.

In both cases the agreement is good between the model estimates and field measurements. Comparison of these two experiments outlines the importance of tidal currents as well as the capacity of the model to cope with it. The principal effect of tidal currents is to advect dumped sediments. The distance reached by sediments when tidal currents are strong (.7 ms^{-1}, dump #11) is 200 m., which is twice the distance reached under weak tidal currents (.1 ms^{-1}, dump #4).

At the present stage of development, the quantity of sediments settling at the point of impact versus the quantity entrained in a density current is based on approximate qualitative observations. We can only say that the formulation used in the present model seems acceptable because the sediment trap measurements obtained for specific dumps are adequately estimated by the present model configuration. The evaluation of settling of sediments at the point of impact would need to be investigated further. One difficulty is that it is not possible to place sampling instruments directly under the scow, because they would be buried by the sediment load settling at the point of impact. One avenue is to experiment in flume tanks to gain a better understanding of the physics of this phenomenon. An other approach would be to survey the dumping operations with a multi-beam echosounding system. The present experiments were carried out using a single echo-sounder aboard a ship at anchor, which is equivalent to carrying out eulerian measurements at a single point of observation. A stationary multi-beam system would provide a two- dimensional perspective of the phenomenon. Furthermore, if positioning were precise enough and the ship could move rapidly by comparison with the cloud of dumped sediments, a three-dimensional perspective of dumped sediment dispersal could be obtained.

ACKNOWLEDGMENTS

This publication is a contribution of the Oceanographic Centre of Rimouski - a partnership of INRS (Institut National de la Recherche Scientifique) and UQAR (Université du Québec à Rimouski) operating under the auspices of University of Quebec. The research presented in this paper was sponsored by Fisheries and Oceans Canada, contract No FP707-9-4296/01-XSK. The authors are grateful to Dr. A. Walton for reading the manuscript and they also acknowledge the collaboration of Captain P. Tremblay.

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