CHAPTER 214

Fate of dredged material dumped off the Dutch shore

R. Spanhoff, Tj. van Heuvel, and J.M. de Kok [1]

Abstract

In the North Sea off the Dutch shore annually tens of millions cubic meters dredged material are dumped. Recent progress in assessing and predicting the fate thereof is described. Field studies and modelling activities are both required in the considered relatively complex situations.

Introduction

At several places along the Dutch shore harbours and their entrance channels have to be regularly dredged. Tens of millions cubic meters of dredged material are involved per annum. Notably the silt fraction therein attracts more and more attention in recent years because of its potential to transport and accumulate adsorbed contaminants. Therefore, the fate in the marine environment of dumped cohesive sediments is studied. Two locations are considered here, namely the dump site for the Scheveningen harbour near The Hague, respectively the site for the Rotterdam harbour region.
The latter dump site, called Loswal Noord, is of special interest because of the relatively large quantities of material dumped there, at present circa 15 million m^3 per annum. In the last ten years or so this site has been the subject of field studies, on the one hand to monitor the impact of the dumping on the development of the region, and on the other hand since the dumped amount should provide a noticeable signal in the sediment transport along the Dutch shore. In studying this signal tools can be developed to predict the transport and fate of fine sediments entering the marine environment at specific places. The strongest tool would be a sediment-transport model with a prognostic capacity. We are working towards

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[1] Project engineers, Tidal Waters Division, Rijkswaterstaat
P.O. Box 20907, 2500 EX The Hague, The Netherlands

such a model for the considered region. A proper dumping management would greatly benefit from such a tool which helps in deciding where to dump how much of a specific material.

History

The western part of Holland, which lies below sea level in the Rhine-Meuse-Scheldt delta, has been created over centuries in a continuous struggle of man with water. One has not only changed the shore line, but also the outflow routes of the mentioned rivers. For instance, the Nieuwe Waterweg, the canal to the original Rotterdam harbours, was constructed in the previous century in traversing the dunes, a natural protection against the sea. With the more recent completion of the so-called Delta Works, in which among others several river arms in this delta were closed in order to prevent a repetition of the 1953 inundation of the area, the Nieuwe Waterweg became the most important outlet of the river Rhine. The run-off through the Waterweg is regulated to a large extent, with a (tidally averaged) value in the order of 1500 m^3/s during most of the year.

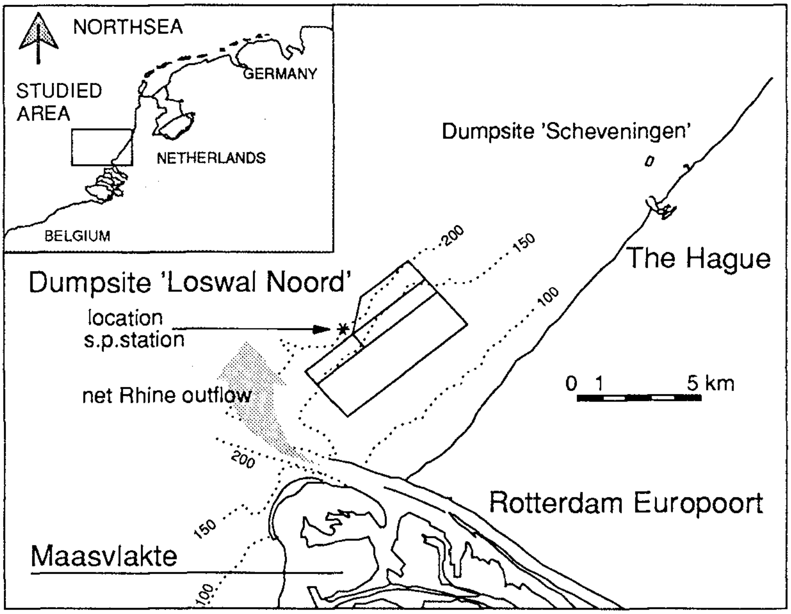


Figure 1. Studied area off the Dutch shore with two dump sites. The man-made Maasvlakte, the residual Rhine outflow and some depth contours (cm) are indicated

Another major man-made change in the present study area depicted in figure 1 was the construction in the beginning of the sixties of the extensive Europoort Harbour region and of the land acclamation Maasvlakte. Since then the need for dredging has increased significantly. The initial capital dredging concerned mainly sand. The later maintenance dredging, that turned out to be required permanently, involves mostly mud and fine sand (ratio circa 1:2 by weight). These materials are dumped on the Loswal Noord (see fig. 1) since 1961, annually on the average circa 20 million m^3. Polluted muds from the Rotterdam harbours are stored on land since 1982 (order 1 million m^3 per year).
The actual spots of the Loswal Noord to be used have gradually shifted towards its more northern sections, because of the induced rise of the sea bottom and of the larger draughts of more modern hopper dredgers.
The area was selected according to the best available knowledge of that time, among others balancing the extra costs of a larger distance from the harbour with the possible risk of a return of the dumped material to the sites to be dredged. For instance, the long-term residual currents are known to be directed to the North along the Dutch shore, so it is likely that sediments are transported in the same direction.

Area description

The sea bottom in the present study area is relatively flat outside the dump site, as can be seen in figure 2, with typical values in the range 10 - 20 m below mean sea level. A circa 25 m deep gully into Europoort harbour leads far to the open sea. Horizontal maximum tidal velocities are of the order of 1 m/s, and the tidal range is circa 1.8 m. Prevailing winds come from the Southwest thus lining up with the local shore line.
The fresh-water discharge of the Rhine through the Nieuwe Waterweg (the northern branch of the canal shown in fig. 1) is relatively large with a typical value of 1500 m^3/s. Fourfold values may occur during large river run-offs. Mixing of fresh and salt water in the tidally influenced region of the Waterweg is limited leading to stratified water masses entering the North Sea. Within a radius of 10 km around the mouth of the Nieuwe Waterweg mostly a strong and stable density stratification exists, leading to totally different residual current patterns in upper and lower layers.
The outflowing river water in the upper layer, influenced by Coriolis forces takes its way to the Northeast (fig. 1) together with the fluviatile sediments suspended in it. The sediments originating from the dump site Loswal Noord are confined to the lower layers, where residual currents are determined by the large density gradients of

the outflow plume, ranging untill 30 km off coast.
Up to ten km around the entrance of the Nieuwe Waterweg residual bottom currents are directed towards the outflow point and have magnitudes of 10-20 cm/s or more. More to the North, where the influence of the upper layer is larger, there is a tendency to follow the large-scale residual current pattern, that is directed to the North-east but cross-shore, southeastward components still amount 2-3 cm/s.
The resulting horizontal and vertical density gradients strongly influence the water and sediment transports along the Dutch shore, up to the Wadden Sea (Van Alphen et al. 1988). For instance, relatively high suspended-sediment concentrations result (see fig. 4) because of the rather permanent landward residual current near the bottom, where the sediments prefer to reside.

Investigations

Several activities have accompanied the use of the dump site Loswal Noord. They ranged from routine measurements with an operational purpose, such as echo soundings to check navigational depths, till scientific attempts to give a firmer basis for the chosen dump location. Emphasis was on field studies with an occasional laboratory experiment. Since a few years we have incorporated numerical modelling in our program as well, since we think that an integration of experimental and theoretical approaches is required to make progress. In the following some of the activities and their results are discussed.

Mass balance

The changes in the bottom topography at the Loswal Noord as a consequence of the dumpings there, were regularly monitored.
Every two years a finely-spaced depth sounding program was performed, with cross-shore sections 250 m apart. An example of the results is shown in fig. 2 in a three-dimensional presentation.
In addition, every two or three years bottom-sampling campaigns were held, often with a relatively narrow grid size of 1x1 km^2. Thus, the mud content in the upper bottom layer could be determined.
From an analysis of the various depth-sounding charts of the region the amounts of material stored there can be determined. They were compared with the amounts dumped, for which a book keeping is available (see figure 3). For instance, for the period 1968-1986 in total 119 million m^3 was stored, from the 291 million m^3 dumped. Accounting for the estimated fractions of mud, sand and water in the hopper and at the site, respectively, a net loss of mud from the site is calculated. We have calculated the values

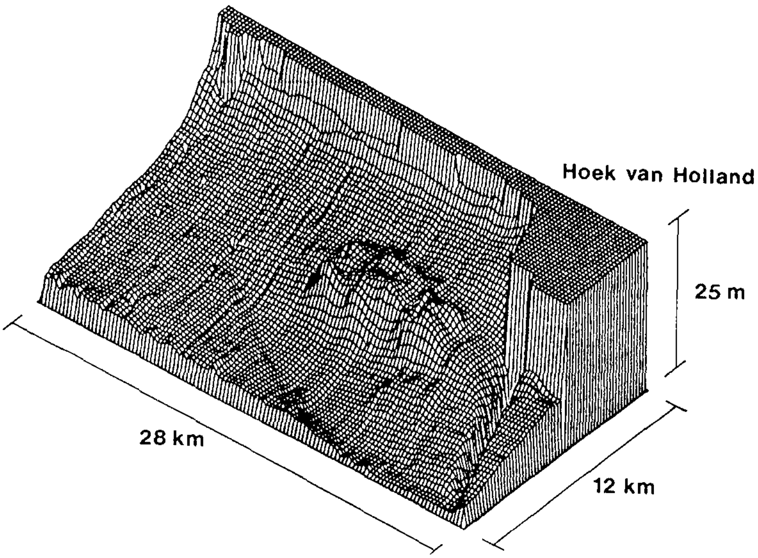
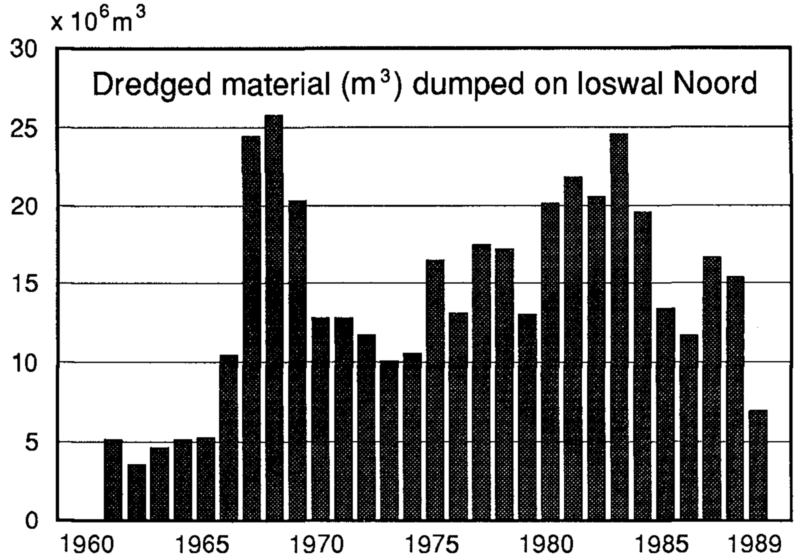


Figure 2. Three-dimensional presentation of the sea bottom echo-sounded in 1979, seen from the West

for the various considered time frames assuming constant loss rates therein. These are plotted in fig. 3 as well; the average value amounts circa 80 kg/s. Some 80 per cent of the dumped mud leaves the site. Since the beginning of the eighties this value tends to decrease to about 50 per cent; by dumping into deeper waters the mud probably has a better chance to settle permanently there.
The sand fraction of the dumped material turns out to be stored rather permanently at the site, albeit that some 30 per cent migrates to its surroundings.

Hydrodynamics and sediment transport

Salinity and current profiles were regularly measured during 13 hours (covering a full tidal cycle) with ships at specific positions. Various stations in the area have been visited over the years. Clear vertical and horizontal gradients were observed, see e.g. figure 4. The relatively small survey vessels could operate at moderate wind conditions only. In a few cases moored self-recording current meters have been deployed that could measure during storm periods as well.
From these survey vessels in many cases sediment-concentration profiles were measured also, with in-situ optical turbididy sensors as well as by water sampling and subsequent filtering and determining the sediment's weight.



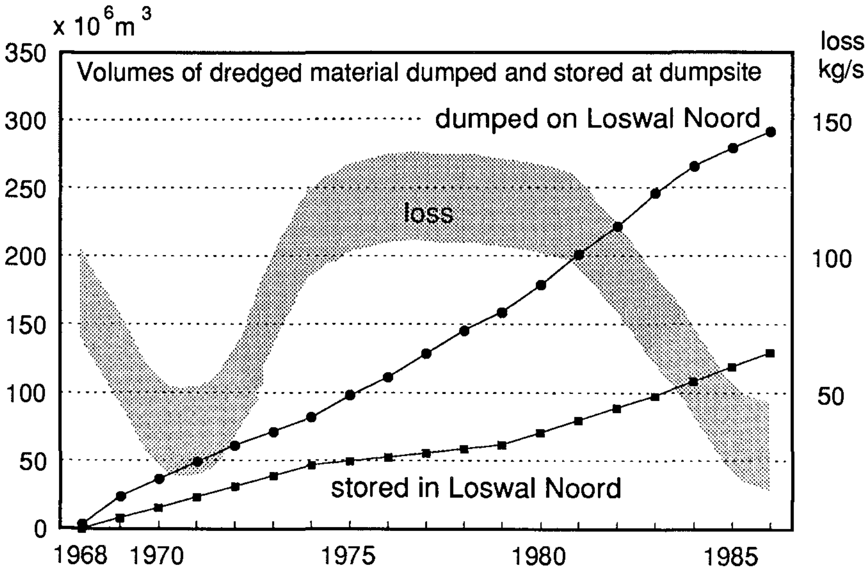


Figure 3. Top : Amounts of material dumped annually at the Loswal Noord
Bottom: Cummulative amounts dumped and stored materials and the calculated loss per second

Combining the current and concentration profiles as measured over a tidal cycle provides indications of the rates of suspended-sediment transport in the area. These rates were much lower than expected when assuming a constant emission from the dump site, suggesting that special conditions such as storms or phenomena that escape detection play a dominant role. Current data under storm conditions were scarce while sediment-concentration information was lacking completely. Therefore, instruments were developed under contract for Rijkswaterstaat to fill these gaps, the so-called semi-permanent stations.
The chosen set-up consists of a complete package of sensors, batteries and electronics to be installed at the sea bottom in up to 25-m deep water that can measure and registrate the data autonomously for one or two months, thus also under storms, according to a preset program. The measuring intervals are chosen in a compromise between total operation time (data-storage capacity, power) and the frequencies of the phenomena of interest. At present, recordings are made every one to five minutes.
The sensors are mounted on one or two poles and are situated between 15 and 100 cm above the sea bottom, in

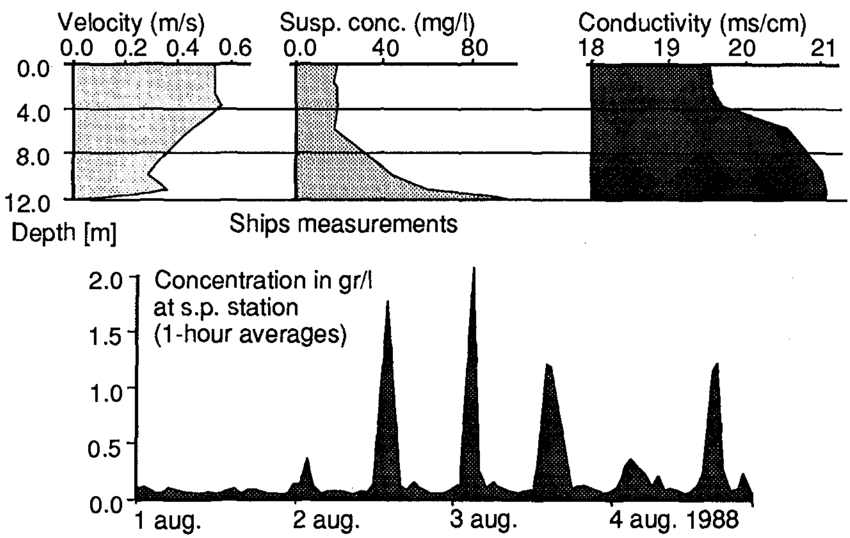


Figure 4. Current, sediment-concentration and conductivity profiles measured from ships (top)
Near-bottom sediment concentrations measured at the semi-permanent station (bottom)

practice. In general two optical (infrared) concentration probes are combined with one electromagnetic current sensor, but other configurations including more types of probes are possible. The equipment is brought into position by a diver at relatively calm weather conditions at the turn of the tide. The electronics and batteries are placed in a hole in a concrete foundation stone in the sea bottom to protect them against possible damage from the rather intense fishery in the area. Sometimes a sensor pole is overturned or even lost.
The equipment now has reached an operational stage, and it will be used almost continuously. Several weeks of data have been obtained in 1988 and 1989 with prototype versions. A result of a measured (time-filtered) sediment-concentration recording is presented in figure 4.

Description of the paths and fate of dumped materials

As a preriquisite for the best judgement of the costs and possible effects on the coastal-water system of the dumping of dredged materials, a description of the paths and fate of the latter is needed. A general insight in the existing situation has been required with the above field investigations, but predictions of the consequences of changes in the dumping scenario's, such as the use of alternative dump sites, have a qualitative nature only. For more stringent predictions more powerful tools such as models with some prognostic capability are required. The degree of sophistication of the tools to be used, and thus in practice among others the amount of physics incorporated in the model, depends on the acceptable uncertainty margins in the required predictions.
Important processes with respect to cohesive-sediment transport take place near the bottom. This follows not only from the increased values there of the measured concentration profiles but also from the observation of (temporary) sedimentation areas. Thus processes as settling, sedimentation and erosion may be important. Furthermore, the salinity and current profiles in the study area of fig. 1 display strong vertical gradients, with different residual currents for the top and bottom layers of the water, respectively. Therefore a full 3D description of water and sediment transport is appropriate in this case, including some of the mentioned processes of the latter.
As an example figure 5 is discussed. It was prepared as a 'first-order (3D) sediment transport model' at a time (1986) we did not have a hydrodynamic 3D model of the region. In this approach emphasis on the near-bottom suspended-sediment transports was put by considering current measurements made at circa 1 m above the bottom: a large collection of ships measurements in the area was normalized to mean-tide conditions and arranged according

to a standard time (high tide in Hook of Holland) with respect to the tidal phase. Thus it was possible to calculate at every time step for every place in the field the current vector by linearly interpolating between values observed at neighbouring stations. The sediment transport at 1 m above the bottom was simulated by considering the net displacements (in a large number of time steps) over a full tidal cycle of a large number of particles in the varying current field. The particles were moving with the water when the local current exceeded some critical value, and they returned (instantaneously) to the bottom as soon as the current was less than another fixed value, thus accounting for sedimentation and erosion.
A fair picture emerged of the transport directions from the Loswal Noord and Scheveningen dump sites. It should

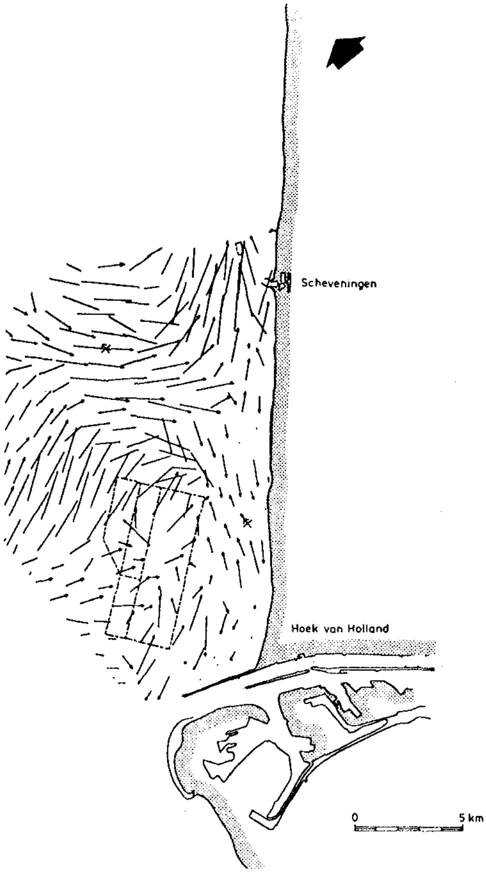


Figure 5. Residual near-bottom displacements of sediment particles calculated with measured current data

be noted that this picture applies to fair-weather conditions only because of the used current data (see above). Still, the picture is probably valid more generally, since it agrees quite well with the mud-content pattern in the bottom as deduced from the bottom samplings, see figure 6. The latter for instance also suggests a return flow along the shore to the South of mud dumped at the Loswal Noord.

<u>3D sediment-transport model</u>

As a further step towards a prognostic capacity a numerical 3D sediment-transport model was developed. It combines a hydrodynamic model with a sediment-transport part. The hydrodynamic-model equations are the momentum and mass balance equations, with hydrostatic and Boussinesq

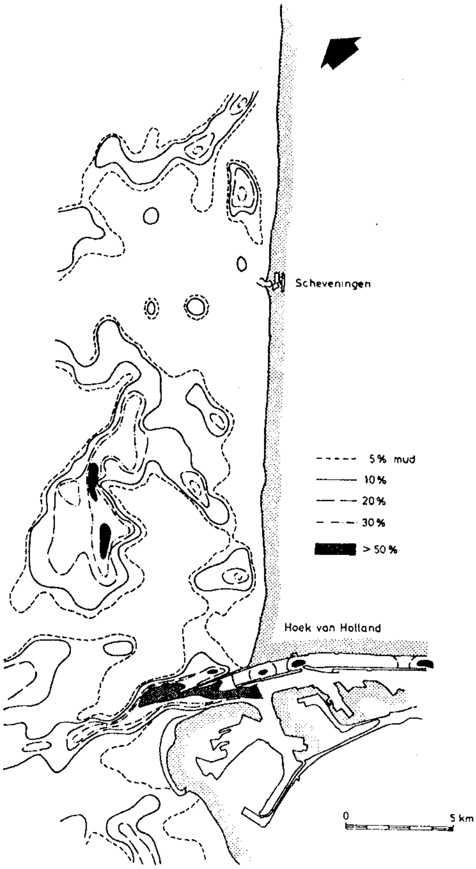


Figure 6. Mud contents (5%,10%,20%,30%,>50% contours) in samples of the upper bottom layer

assumptions, integrated over the layer depth in order to assure mass conservation. An explicit leapfrog difference scheme is used on a space staggered grid (Leendertse 1973).
The lower layers have a uniform, small depth for good near bottom resolution of the model with a horizontally uniform numerical error. Since layers are not horizontal anymore, both vertical and horizontal density gradients are represented in the momentum equations.
For salinity a seperate advection-diffusion equation is solved and coupled to the momentum equations via the density gradients. Also the vertical turbulent exchange of momentum and mass is influenced by the vertical density gradients via the turbulent diffusion coefficients.
Sediment concentrations are computed with an advection-diffusion equation, with a fall velocity superimposed on the vertical velocity field, and an extra bottom layer for sedimentation and resuspension, depending on bottom shear stresses. No consolidation is taken into account yet.
In order to obtain a good reproduction of point releases a highly accurate finite difference method has been developed, with the possibility of representation of subgrid-scale details like first and second mass moments and cross moments. In de Kok (1989,1991) more details are given.
The modelled area was a coastal strip of 15 x 56 km, on a grid with a horizontal mesh width of 1 km, and a vertical mesh width of 1 m at the bottom until 10 m for the surface layer, depending on the depth. There were everywhere 5 layers. Time step size was 60 s for the hydrodynamic part and 500 s for the sediment transport part.
Boundary conditions were obtained via a series of coarser nested 2-DH models, beginning with a Continental Shelf model, then a North Sea model, then a Southern Bight model and finally a two layer coastal model.
Values for bottom roughness, eddy viscosity and eddy diffusivity where calibrated with observational data of velocity and salinity. Special attention had the maximum flood velocities, and the annual means of salinity and velocity in certain cross sections.
Computations were done for several wind and salinity conditions, and for several sediment grain sizes.
The transport of fine sediments from various sources, such as an individual dump release at a specific place, can be calculated for chosen environmental conditions. Various scenario's including the present situation can thus be simulated.
In the calculated (Lagrangian) velocity field for particles near the bottom an anticyclonic gyre in the residual currents around the present dumping site is emanent (see figure 7). It corresponds nicely with the transport

directions suggested independently by the mud contents in the bottom (see above), thus an appreciable return flow to the harbour mouth is likely. Furthermore a direct residual current to the mouth from the western part of the dump site is predicted, also in accordance with the mud chart. The latter current is induced by density differences. The former gyre is located in the lee of the relatively strong flood current of the land acclamation Maasvlakte extending into sea, and it is probably largely caused by it, as well as by the bottom topography around the dump site. Sediment concentrations calculated near the bottom with the 3D model confirm the above trends of a return flow (see figure 8).

Discussion

A large number of variables determines the hydrodynamics in the area of fig. 1, such as the tide, the wind which induces among others strong circulation currents and waves, swell, the only partially mixed variable Rhine outflow with its strong density gradients and induced residual currents, etcetera. Thus the hydrodynamics are hard to measure and to model. This holds even stronger for the sediment transport, being not only determined to a large extent by the hydrodynamics but also being subject to often poorly understood processes in flocculation, settling, sedimentation, consolidation and erosion. Thus at present, and in the near future, any sediment-transport model in the considered region has to be a mix of deterministic physics, parameterized formulations and empirical phenomenolgy.

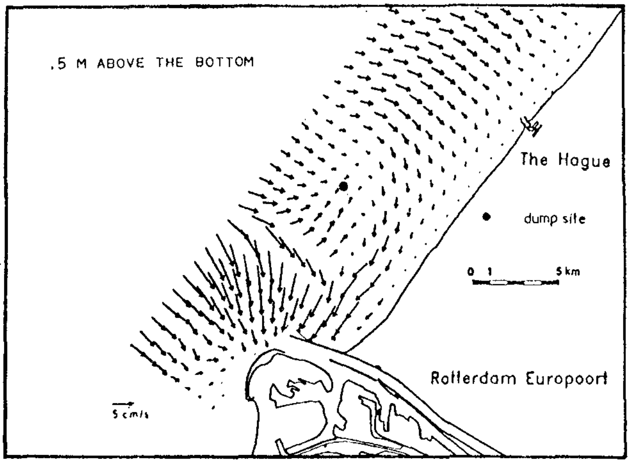


Figure 7. Near-bottom Lagrangian residual currents calculated with the 3D model

This is reflected in our program in which we combine field studies and numerical modelling. Proces-related field studies give clues of what proces should be included in the model and how. In turn, various processes, e.g. taken from the literature, can relatively easily be incorporated in the model that can predict in a kind of sensitivity analysis what the consequences in the field would be and where they should be clearly detectable. Thus the (expensive) field program can be directed.
For instance, at present we assume that the dumped material is spreading below the hopper dredger over the bottom and that the transport of the major part of the finer fractions is governed quickly by the water movement there. This hypothesis is hard to verify directly in the field but it can be tested indirectly with the registrations of our sediment platforms at the bottom when combined with model calculations. Other points thus to be addressed are the hypotheses that spring tides have a dominant effect because the stronger currents only then exceed the critical erosion velocities at many places, respectively that storms influence the sediment transports not only by induced currents but also by their waves that help in faster eroding the bottom. If so, the present relatively simple parametric formulation of the latter effect in our model then will be verified.
With the approach sketched we anticipate a constant improvement of the quality of our model predictions. In the mean time the model is used as a tool to analyse the present situation, with respect to return flow etecetera,

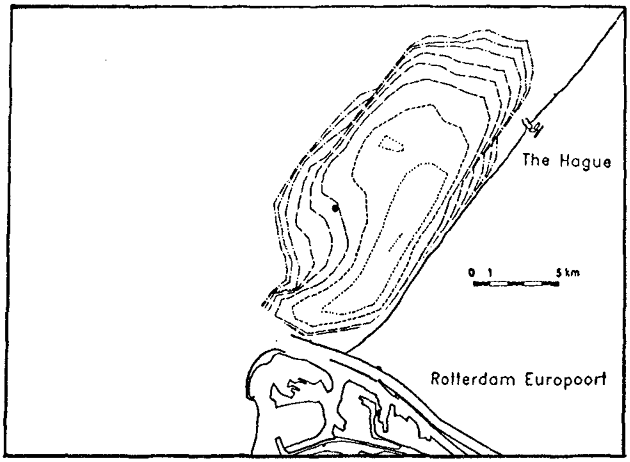


Figure 8. Calculated near-bottom sediment concentrations (arb. units) five days after a release at the indicated dump site. Note the high near-shore concentrations extending southwards

and to develop alternatives in terms of dump sites, for istance.
One of the questions to be addressed is how much the sediment concentrations in the Dutch coastal zone, and thus e.g. in the Wadden Sea, are affected by the dumping. This problem is relevant, since the amounts of mud disposed of are comparable with those transported in a 20-km wide zone along the Dutch shore (Van Alphen 1990). To answer this question, the present detailed analysis of the area of fig. 1 is required. Namely, the amounts of fine sediment returning to the harbour region that are dredged several times do not contribute to those concentrations. Furthermore, the presently dumped sediments originate from the sea and thus are artificially trapped by the man-made constructions in the area. Viewed on a large scale the dumping in first order simply compensates for this effect, but by injecting the material at one specific site local changes in the coastal zone may be induced, with some bearing on the large-scale sediment distributions. The problem can be tackled by nesting the present model, once validated, in a larger model for the whole of the Dutch coastal zone.

Conclusion

Field studies and model results suggest a relatively strong return flow of mud dumped at the present dump site Loswal Noord, largely due to an observed gyre in the residual currents and to density differences. In combining field studies, with innovative equipment, and modelling activities a promising program towards a more quantitative assessment is performed.

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