Modelling of cohesive sediment transport.
A case study: the Western Scheldt Estuary

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Abstract

A depth-averaged numerical model for the erosion, sedimentation and transport of cohesive sediment is applied to a mesotidal estuary. The transport model is coupled to a hydrodynamic and a wave model. First results are presented as part of the aim to predict year-averaged quantities. Comparisons with measured data of net sedimentation and suspended concentration are made. As the bed of the estuary consists mainly of non-cohesive sediments, the erosion formula is adapted to account for the local (non-)cohesive fraction in the bed. The effect of the spatial variation in this property of the bed is significant. Furthermore the influence of surface waves is investigated and showed to be of great importance in a qualitative and quantitative sense. The model can take into account the dumping of dredged material and gives reasonable results in case of the spreading and sedimentation of mud from one source, as shown by a simulation of the transport of fluvial mud.

Introduction

In the Western Scheldt Estuary (figure 1) in the south-western part of the Netherlands the input of severely contaminated fine sediments from the river Scheldt causes a considerable environmental problem. Especially in sedimentation dominated areas, like the great marsh land in the eastern part of the estuary, these sediments with cohesive properties accumulate in the bottom influencing the environment for many years to come. There is a need for models capable of simulating these processes and predicting the consequences of measures to reduce the pollution. Such models must

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undoubtedly include the transport of cohesive sediments.

In the estuary the main channels are dredged frequently because of the shipping to the harbour of Antwerp up the river in Belgium. Also harbours along the estuary are regularly dredged. These activities involve not only high costs but also environmental problems in case the dredged material contains polluted sediments. A model for predicting the fate of dumped sediments is a powerful tool for decisions about the assessment of dump sites.

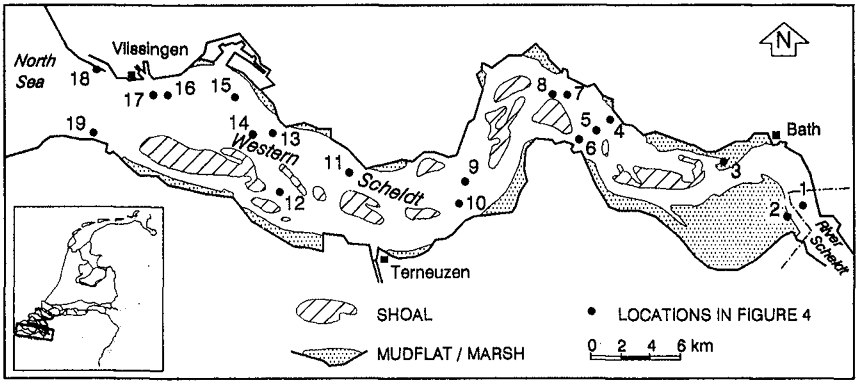

Figure 1. The Western Scheldt Estuary.

This paper presents some results of the numerical modelling of the transport of cohesive sediment or mud-here defined as the anorganic fraction finer than 63 micron - related to the problems in the Western Scheldt Estuary. The model involves hydrodynamics, surface waves and sediment transport. Descriptions of and experiences with models for estuaries (e.g. Hayter (1983), Sheng (1986), O'Connor and Nicholson (1988), Fritsch et al (1989)) showed that strongly empirical relations have to be used and that the incorporation of all relevant processes as well as the schematization of hydraulic and meteorological conditions form an enormous task. Therefore some processes are neglected in the present model while others are investigated, viz. the importance of the local mud fraction and the role of surface waves. Our final aim is a predictive model for long term behaviour of the cohesive sediment. Especially the spreading of fluvial mud is of interest and a simulation is presented.

Model description

Because of the considerable morphological variety in the lateral direction of the estuary (see figure 1) and the fact that the estuary is well mixed, two-dimensional horizontal (depth-averaged) models are used: a hydrodynamic model, a surface wave model and a sediment transport model.

The hydrodynamic model (WAQUA) calculates the water flows, water levels and densities on a time scale much smaller than the tidal period (Stelling, 1983). Calibration of the model was carried out by others (Dekker, 1985). Wind induced currents appeared to be very small and are not taken into account in the calculations. Also the wind generated water level rise is neglected. The tidal range in the estuary varies between 3 and 4 m, while the average depth is 10 m. The simulation was carried out for a tidal cycle of 24.5 hrs of a semi-diurnal tide with a tidal range 5 % higher than the long term mean value. The grid is rectilinear and the element size is 400*400 m. The bottom schematization of the hydrodynamic model was used as input for both the wave model and the transport model, via different interface programs.

The wave model (HISWA) is suitable for shallow water waves and produces stationary wave fields. It solves a spectral action balance and takes into account the generation, dissipation, refraction and diffraction of waves (Booij et al, 1985). To restrict the computational costs a limited number of boundary conditions is used. As input for the wave calculation the mean values of wind speed (1983-1987) are used in four dominating wind directions: 220° (wind speed 10.3 m/s), 250° (9.7 m/s), 280° (9.3 m/s) and 310° (9.6 m/s; North=0°=360°), respectively representing 16%, 12%, 9% and 7% of time within a sector of 30°. The remaining 56% of time fair weather conditions are assumed. Because the model is stationary, an interpolation is performed between the calculated wave heights and wave periods at four different tidal stages: LW slack, maximum flood current, HW slack and maximum ebb current. The interpolated values are used to determine the orbital velocity and consequently the bottom shear stress component due to waves. Verification of the model at 6 locations throughout the estuary showed a systematic overestimation of the long term mean wave height of about 30% by the model. However, the available observations were made visually and exclude rough weather conditions. Therefore the wave model results are satisfying.

The dynamic model for the cohesive sediment transport, based on the program package DELWAQ (Delft Hydraulics, 1990), incorporates advection, diffusion and bottom exchange by sedimentation and erosion. The model solves the finite volume advection-diffusion equation with sink and source terms on the same grid as WAQUA. The tidal cycle can be repeated until a dynamic equilibrium is reached. The dispersion coefficients were chosen constant and equal in both horizontal directions. Although the bottom exchange processes are extremely complex and influenced by physical, chemical and biological factors for practical reasons we adopted well-known empirical expressions for sedimentation (Krone, 1962) and erosion (Partheniades, 1962), in which the bottom exchange rates both linearly depend on the bottom shear stress with critical shear stresses of 0.2 and 0.4 Pa respectively. A constant settling velocity of 2 mm/s was used, based on indications from field measurements. The bottom shear stress can have three components: (i) the depth-averaged current velocity, assuming a logarithmic profile, (ii) the orbital velocity and (iii) the horizontal density gradient. The influence of the waves is restricted to the shear stress in the bottom exchange terms. The third component is omitted in this paper because of the relatively small effect on the presented results. The wave and current bottom shear stresses, τ_{bw} and τ_{bc} respectively are combined according $\tau_{bw}+\alpha_w\tau_{bc}$, in which α_w is a reduction factor related to the wave-current interaction (van Rijn and Meijer, 1986). The model takes into account one homogeneous bottom layer with a space and time dependent thickness although consolidation is neglected. In order to use the model to determine optimal dump sites for dredged material a special subgrid scale dumping routine is incorporated (van Heuvel, 1988). At first the dumped mud undergoes the process of transport on a detailed scale governed by the flow velocity and the slope of the bottom at the dump location. Than the location and the thickness of the layer after complete sedimentation in the neighbouring grid elements is determined by the dumping routine. Subsequently resuspension and transport can proceed under the proper hydrodynamic circumstances. Although simulations of the dumping and spreading of dredged material have been made the results could not be verified and are subject of further study.

Results

The results presented here concern the cohesive sediment transport only. A study of two influencing factors, the local mud fraction and the waves respectively, is performed. These factors are presumed to be very important for a reliable model result. Furthermore an application to the spreading of polluted mud from the river is made. Some verification of the model is made by comparison with measurements of net sedimentation and (suspended) concentrations. It is assumed that morphological changes in the estuary can be neglected.

The influence of a local mud fraction

The mud fraction in the bottom of the estuary shows a strong spatial variation (figure 2). In the channels the mud fraction is very low (<0.02) while the average fraction is about 0.15. This is partly the result of a morphodynamic process and it questions the applicability of a sediment transport model without the influence of the non-cohesive material. Because of the supposed effect on the availability of mud during erosion or resuspension, this influence is taken into account by putting the mud fraction $f_e(x,y)$ in the formula for the erosion rate E [kg/m²/s]:

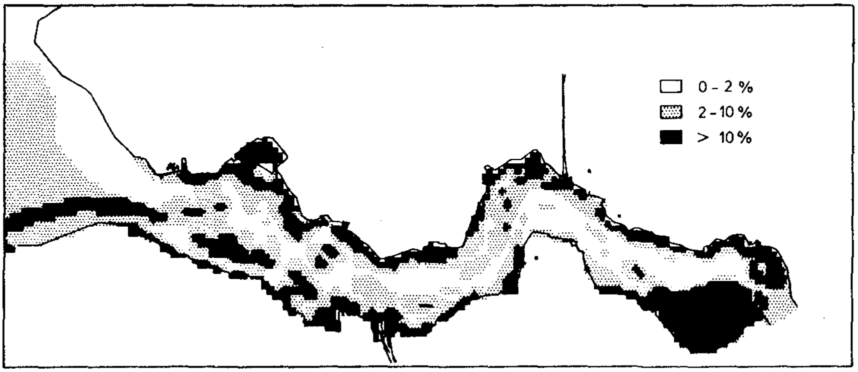

Figure 2. Silt content in the top layer (0 - 10 cm) of the bed (1980-1985).

$$E(x,y,t) = f_e(x,y)\ M\ (\tau_b(x,y,t)/\tau_{ce} - 1) \qquad \text{if } \tau_b > \tau_{ce}$$

$$E(x,y,t) = 0 \qquad \text{if } \tau_b \leq \tau_{ce}$$

in which M [kg/m²/s] is the erosion constant, τ_b the bottom shear stress and τ_{ce} the critical shear stress for erosion. Two calculations are made representing two extreme cases: (i) assuming a bed of pure mud, i.e. $f_e(x,y) = 1$ (with $M = 5.10^{-5}$) and (ii) using values of $f_e(x,y)$ for each grid cell obtained from the measurements (with $M = 7.10^{-4}$). For each case the value of M is found by calibration to obtain suspension concentrations of the same order of magnitude as the measured values in order to make a meaningful qualitative comparison. In both cases the bottom layer thickness is not a limiting factor and only fair weather conditions are applied. It appears that the tide-averaged sedimentation, see figure 3, and concentration, did not show important differences on a large scale. However in the channels with very low mud

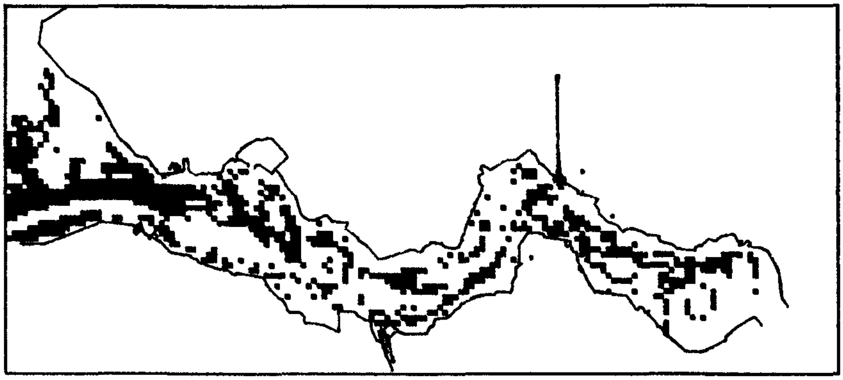

Figure 3. Non-corresponding areas (black) of erosion or sedimentation for case 1 and 2.

fraction the sedimentation pattern can differ importantly, while the tide-averaged concentration in some areas can differ more than 30% (after correction for systematic difference). Comparison of the calculated and measured concentrations, corrected with respect to tidal and seasonal effects, at 19 locations, mainly located in the channels, shows reasonable agreement in both cases (see figure 4). Case 2 seems to be better than case 1 at locations 1-8. For one particular location with a water depth of 10 m and a low mud fraction the comparison of the time series is displayed in figure 5. Apart from a systematic deviation between the three time series, there are the following differences: a quick increase of concentration in case 1 directly after LW slack, which is absent in case 2. So the availability of mud in the bed influences the time series strongly. From the measured values it seems that in reality the availability of mud is high directly after slack tide, while afterwards it is low (other measurements show a similar pattern). This qualitative disagreement with the model is likely to be caused by the spatial variation in the presence of mud in both horizontal and vertical direction. Hence a more sophisticated model, including a sand transport model to account for fractional sorting in the bed, could be more appropriate. Due to tidal dynamics and the very small thickness of the active mud layer (in the order of 1 mm) consolidation may be excluded in case of sandy channels.

A consequence of the results above is that a spatial variation in other erosive bed properties, like biological activity or the composition of the mud, could have a similar impact.

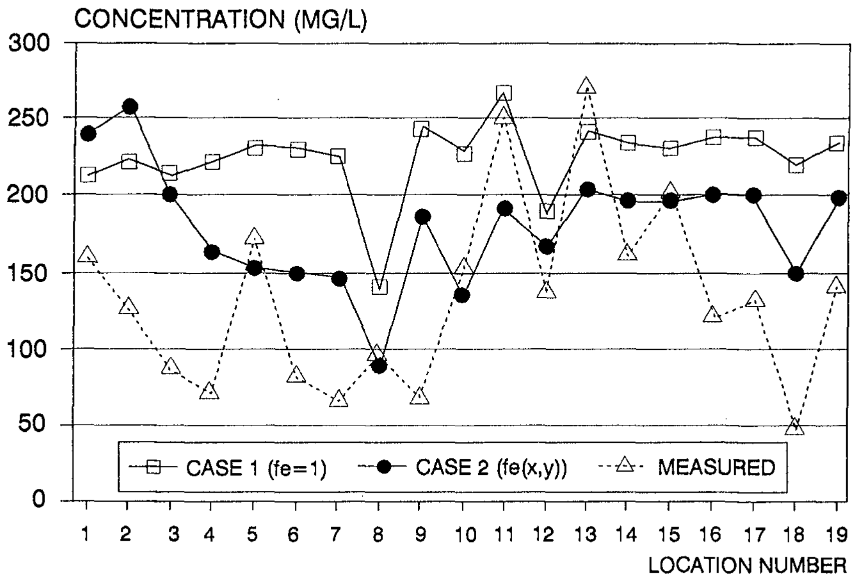

Figure 4. Measured and calculated (case 1 and 2) tide-averaged concentration at 19 locations (see figure 1).

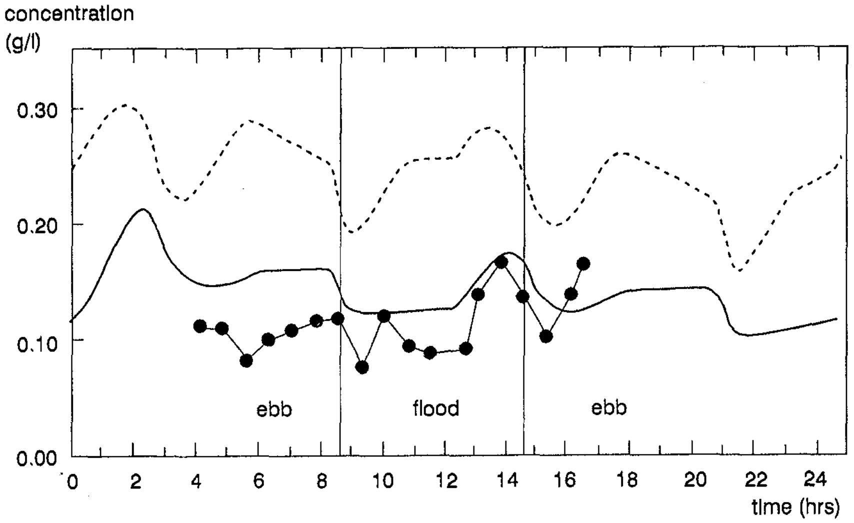

Figure 5. Calculated concentrations for case 1 (dashed) and case 2 (solid) and measured values (dots).

The influence of waves

From observations in several estuaries, the Eastern Scheldt e.g., it is clear that rough weather conditions lead to a resuspension of material in the intertidal zone of shoals and marshes and consequently to a transverse transport to the channels. During fair weather conditions this process is reversed resulting in a dynamic equilibrium on a time-scale of years. To verify this process and to examine the importance of it, some calculations are made assuming that the imposed tidal and wave conditions are representative for a yearly averaged situation. Figure 6 shows the tide-average sedimentation for the 4 different wind directions and the fair weather condition (current only). The area of the estuary between Vlissingen and the Belgian border is divided into five morphological units: tidal channels, shoals, i.e. the ones surrounded by channels, flats, i.e. muddy or sandy flats near the embankment, marshes and harbours. The differences between the wind directions is significant as well as the difference with currents only. In the simulation the superimposed waves cause extra transport from the shoals (more eroded with respect to currents only) and the marshes (more eroded) to the channels (less eroded). Whereas one part of the flats is more eroded, the other part, partly because of the sheltered position, shows more sedimentation leading to an overall increase of sedimentation on the flats. Because the channels form the interface between the other four units the increase in sedimentation of the flats and the harbours can be explained by the increase in concentration in the channels caused by extra erosion of shoals, marshes and some flats. Qualitatively this is in good agreement with observations. However, this result can be affected by some important limitations of the model, namely (i) the absence of water level set-up during storm events, by which more sedimentation can take place on marshes and flats, and (ii) the rough schematization of the marshes and harbours.

In a qualitative sense the yearly averaged sedimentation of the five morphological units (current+waves in figure 6), which is assumed equal to the tide-averaged value of the five schematized meteorological conditions combined by means of the percentage of occurrence, is in agreement with measured data. However, in a quantitative sense there is a disagreement of one order of magnitude, or even more in areas with a low mud fraction (channels 6%, shoals 7%). In areas with a high mud fraction (marshes and harbours up to 80%) the agreement is better. It should be noticed that the model was not calibrated again in the case of waves, which led to an important overestimation, and that the reliability of the measurement is not known. Nevertheless the result indicates that the bottom exchange of mud is more easily simulated for sedimentation dominated regions than for erosion dominated ones, where bottom properties are more important.

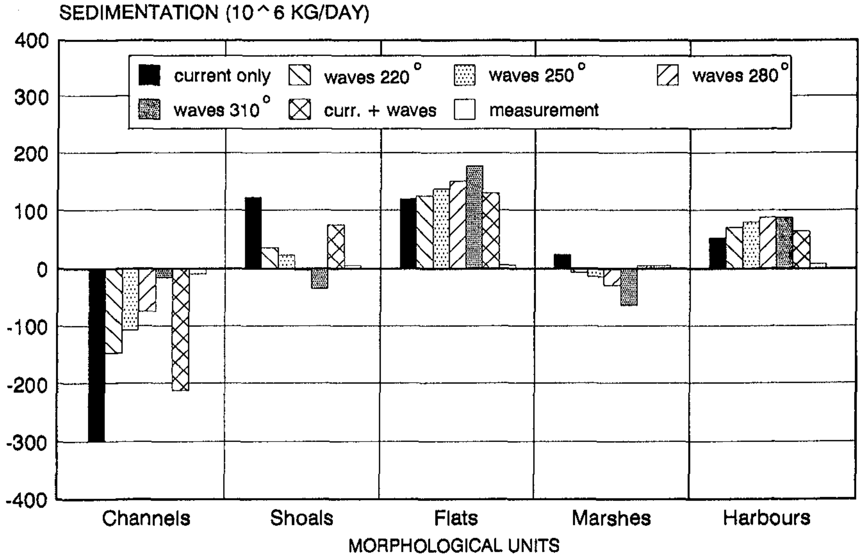

Figure 6. Tide-averaged sedimentation/erosion for each morphological unit calculated with and without wave influence (for 4 different wind directions and in total) and according to measurements.

The spreading of fluvial mud

One of our main purposes is the application of the model to the transport of the polluted fluvial mud. The fluvial and marine mud fraction can be distinguished by means of an analysis of carbon isotopes. Measurements of bottom level change (1980-1985) in combination with the observed mud fraction and correction for dredging and dumping quantities are used to estimate the year-averaged sedimentation or erosion. Verifying this with estimations of the river input has led to the fluvial mud sedimentation given in figure 7a, where the sedimentation of each grid element is related to the total input.

In the simulation only mud input from the river was allowed and the bottom layer started with zero-thickness. The result, see figure 7b, applies only to fair weather conditions and is presented in the same way as the measurements because of different the river inputs (15.10^5 against 23.10^5 kg/day).

In both the simulation and the measurement the main part of the river mud is deposited in the eastern part of the estuary. Areas with pronounced sedimentation are reproduced satisfactorily, although the agreement on a detailed scale can be poor.

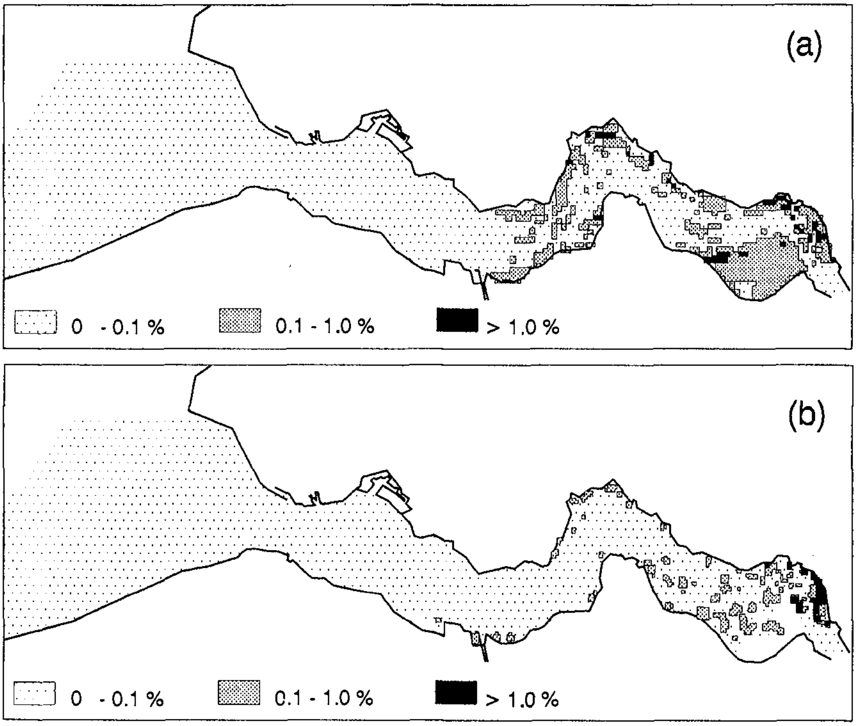

Figure 7. Measured (a) and calculated (b) fluvial mud sedimentation (relative to total river input).

Conclusions

First results of a numerical model, existing of a hydrodynamic, wave and sediment transport model, applied to the Western Scheldt Estuary are presented. Boundary conditions are roughly schematized in aiming at simulations of year-averaged quantities. Dumping of dredged material is modelled but needs verification. With the model the influence of the non-cohesive material in the bottom and the influence of surface waves is investigated. The results show that the spatial variation in erosive properties of the bed and the availability of mud have an important influence on the space and time dependent distribution of concentration and sedimentation. The influence of waves according to the model is significant and qualitatively in reasonable agreement with reality. Waves redistribute the sediment from the wave-attacked shallow areas of shoals, flats and marshes to the deeper parts of channels and harbours and to the sheltered parts of flats. Spreading and sedimentation of the polluted fluvial mud can be simulated satisfactorily. It is believed that sedimentation can be modelled more easily than erosion, due to the strong influence on erosion of the usually poorly-known bed properties. For the present this justifies the use of the erosion constant as a tuning parameter.

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