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Transport paths of suspended matter along the Dutch coast

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Abstract

A three-dimensional numerical baroclinic model for hydrodynamics and coupled fine sediment transport is used for the computation of dispersion of suspended fine sediment along the Dutch coast. Computational results are in agreement with observations that horizontal salinity gradients, due to the presence of river water, induce an estuarine-like cross shore circulation along the entire coast. Sediment transport paths are determined for various sub-areas. Computed residual eddies and shoreward near bottom currents have a major influence on transport paths. Long term transports of suspended fine sediment are computed with a fast PC-model for tidally integrated transport computations. Results show that suspended matter with fall velocities around 10^{-3} m/s tends to concentrate in a narrow strip along the coast.

1 Introduction

The Dutch coastal area is very shallow, the 20 m isobath lying between 15 km and 40 km off shore. Two large estuaries, the Western Scheldt and the Eastern Scheldt, are present in the southern part. In the middle part two outflow points of river water are associated with the fresh water plume of Rhine and Meuse, stretching along the coast in north-eastward direction until the German Bight. Fresh water is present until 50 km off shore, but the most important density gradients exist within 25 km from the coast. Density driven currents near the bottom are shoreward directed and have values between 0.02-0.04 m/s in the largest part of this area. Within a radius of 10 km from the river outflow points near Rotterdam these density driven bottom currents can reach values above 0.20 m/s, forming an important factor in the siltation of shipping channels and harbours.

In the northern part a large tidal basin, the Wadden Sea, is connected with the sea by seven separate tidal inlets. The Wadden Sea, Western Scheldt and Eastern Scheldt have an intensive tidal exchange with the coastal sea and contain important sedimentation areas for fine sediment.

Outside the sedimentation areas tidal currents are very strong, with along-shore amplitudes until 1.2 m/s at the surface and 0.5 m/s at 4 m above the sea bed (de Ruijter et al.[6]). The tidal signal is very asymmetric with flood velocities that are up to 30 % higher than ebb velocities. Flood velocities are north-eastward directed. This is also the direction of the M_2-tide, propagating as a Kelvin wave along the coast. Also the Rhine water, entering the sea through the Rotterdam harbour entrance, is deflected to the north-east by Coriolis. The long term averaged wind stress vector in the area is directed to the east-north-east. The main residual flow along the Dutch coast is north-eastward directed. This holds also for the transport of fine sediment, among others as a consequence of tidal asymmetry (Dronkers et al.[7]). As a result of particle aggregation under influence of salinity gradients average suspended sediment fall velocities increase in the coastal area, leading to high suspended sediment concentrations near the sea bed. In this water layer it is transported by the shoreward density driven current

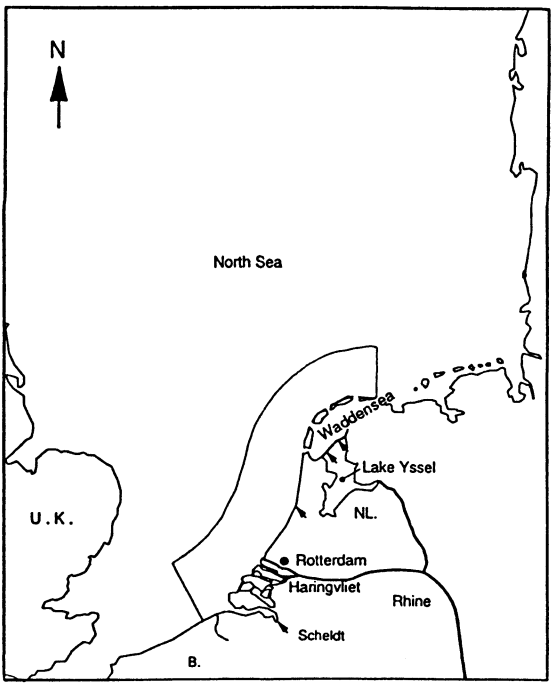

Figure 1 : Situation of the model area in the Southern Bight of the North Sea. Main fresh water outlets are the Rotterdam Waterway and the Haringvliet. Other outlets are indicated by arrows.

and concentrated along the coast. Especially in the outflow area of Rhine and Meuse vertical dispersion of sediment is suppressed by salinity stratification, resulting in highly concentrated benthic suspensions of up to several kg/m^3 and a strong shoreward transport.

Fine sediment is entering the Dutch coastal system via the Straight of Dover, flowing at some distance from the Belgian coast. It is assumed that a yearly 10^7 tons dry weight of fine sediment are transported through the Dutch coastal strip (van Alphen [10]). Under average conditions the residual circulation in the near-shore Belgian coastal area (within 15 km) causes exchange mainly with the Western Scheldt (see fig. 2,3).

Orbital velocities associated with wind waves are important in areas with depths below 20 m. Together with strong tidal currents they cause resuspension during more than 20 % of the time, except in the sedimentation areas of the estuaries and the Wadden Sea.

Sedimentation of marine sediments takes also place in the harbour entrances of Rotterdam and IJmuiden, but this does not influence the sediment balance, since most of the deposits are dredged up and released at sites from where it is resuspended very quickly. Dredged silt from contaminated harbours is deposited on land-based locations, but these sediments are mainly of riverine origin. The sediments from Rhine and Meuse entering the sea contribute only for a small percentage to the average suspended sediment concentration in the coastal area (de Kok [5]).

2 Hydrodynamic model

The hydrodynamic model, coupled to the fine sediment transport model, is a three-dimensional hydrostatic and baroclinic shallow water equation model including a prognostic salinity computation, but with fixed temperatures. Water levels and salinities are imposed at sea boundaries. At river outflow points discharges and salinities are imposed. Vertical eddy viscosity and diffusion coefficients are constant 0.02 m^2/s in homogeneous water and multiplied by damping functions to account for the suppression of turbulence in case of density stratification. Details can be found in de Kok [5]. The functions are of the Munk-Anderson type, but with a stronger damping than the latter. Around the mouth of the Rhine Richardson numbers are very often higher than 3, resulting in a drop in viscosity and diffusion coefficients down to 10^{-4} m^2/s, far below the numerical error level.

The number of layers is everywhere the same, so layers are not horizontal. Special attention is therefore paid to the discretisation of baroclinic pressure gradients and horizontal diffusion terms. It is possible to define layers with uniform constant thickness. The remaining vertical space is discretised according to the σ-transformation. We fixed the bottom and top layer thickness both at 3 m. The constant bottom layer thickness has the advantage of a uniform formulation of the bottom stress, which depends on the average bottom layer velocity. Also in the suspended sediment transport computation a uniform formulation for deposition and resuspension can be used. The surface layer depth of 3 m is a frequently occurring mixed surface layer

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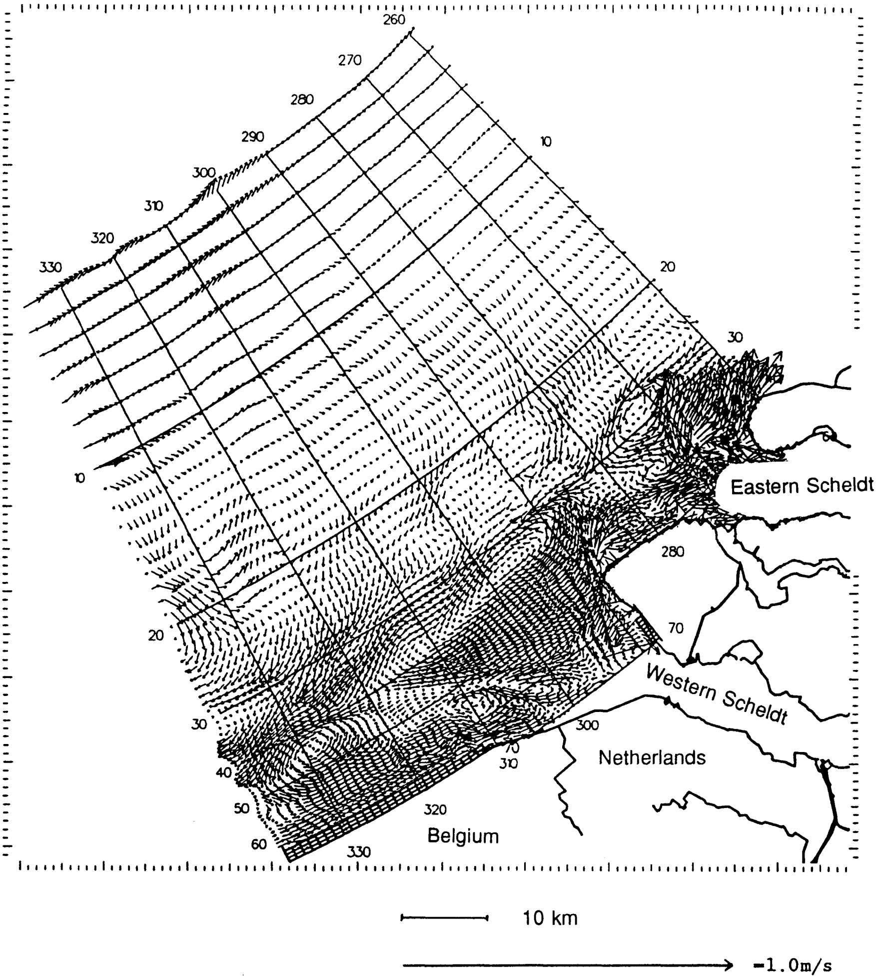

Figure 2 : Computed residual velocity vectors for the lowest layer of the model (until 3 m above sea bed) near the Belgian-Dutch border.
Only vectors between grid lines 260-338 and grid lines 1-70 are visible.
The entire Western Scheldt and Eastern Scheldt are part of the model.
Average tidal amplitude, average meteorology, average rive run off.

depth in the stratified part of the Rhine plume. In areas with total water depths below 12 m the σ-transformation is used for all layers. In our computations a total number of four layers was sufficient for the representation of yearly averaged vertical density and velocity gradients.
As the model is hydrostatic, vertical velocity components follow from the continuity equation. Down-welling at density fronts and up- and down-welling at coasts by wind effects is very well reproduced. The equations are horizontally solved with an alternating direction type semi-implicit higher order finite difference scheme (Stelling et al.[9], Leendertse[8]) on an orthogonal curvilinear grid. In the vertical a Crank-Nicholson-type implicit scheme is used. The modeled area stretches from the Belgian coast until the Wadden Sea (fig. 1) with a seaward width of 70 km. The mesh width ranges from 2 km at sea boundaries until 200 m near the coast. The mesh width in the estuaries is less than 1 km. The total horizontal number of active grid points is 20,000. Time step size is 120 s.

3 Results of the hydrodynamic computation

As a basis for the suspended sediment computation semi-periodic 3-D velocity fields were computed, representing a period of 25 hours, with time intervals of half an hour. The chosen period was a day between spring and neap tide when the tidal amplitude was equal to the year average. The initial salinity field was estimated and then computed during two months with realistic wind forcing and river run off. Then wind stress and river run off were fixed on the year average and a period of a week was simulated. The last 25 hours were used for model output. Uniform calibration coefficients for vertical eddy viscosity and diffusion were tuned for an optimal fit of computed velocities with measured data in the Noordwijk transect (see de Ruijter et al.[6]). Year-averaged residuals and amplitudes of tidal velocities showed errors of up to 35% with an average of 10 %. The model output was consistent with the characteristics described in the introduction. The computed residual current pattern shows a strong cross shore estuarine-like circulation. In the south-western part of the model strong topographic eddies exist. Especially the residuals in the lowest layer show the strong influence of bottom and coast topography (fig. 2). Residuals in the lowest layer in front of the Belgian coast are only far off shore clearly north-eastward directed. When stronger south-westerly winds are imposed on the model, also near-shore residuals are following this pattern.

4 Fine sediment transport model

The sediment transport model is based on the 3D advection-diffusion equation with extra fall velocity. A separate bottom layer has been added for which a mass balance is kept. From there vertical exchange with the lowest water layer is possible following a Krone-Partheniades-type formulation for deposition and resuspension. Details can be

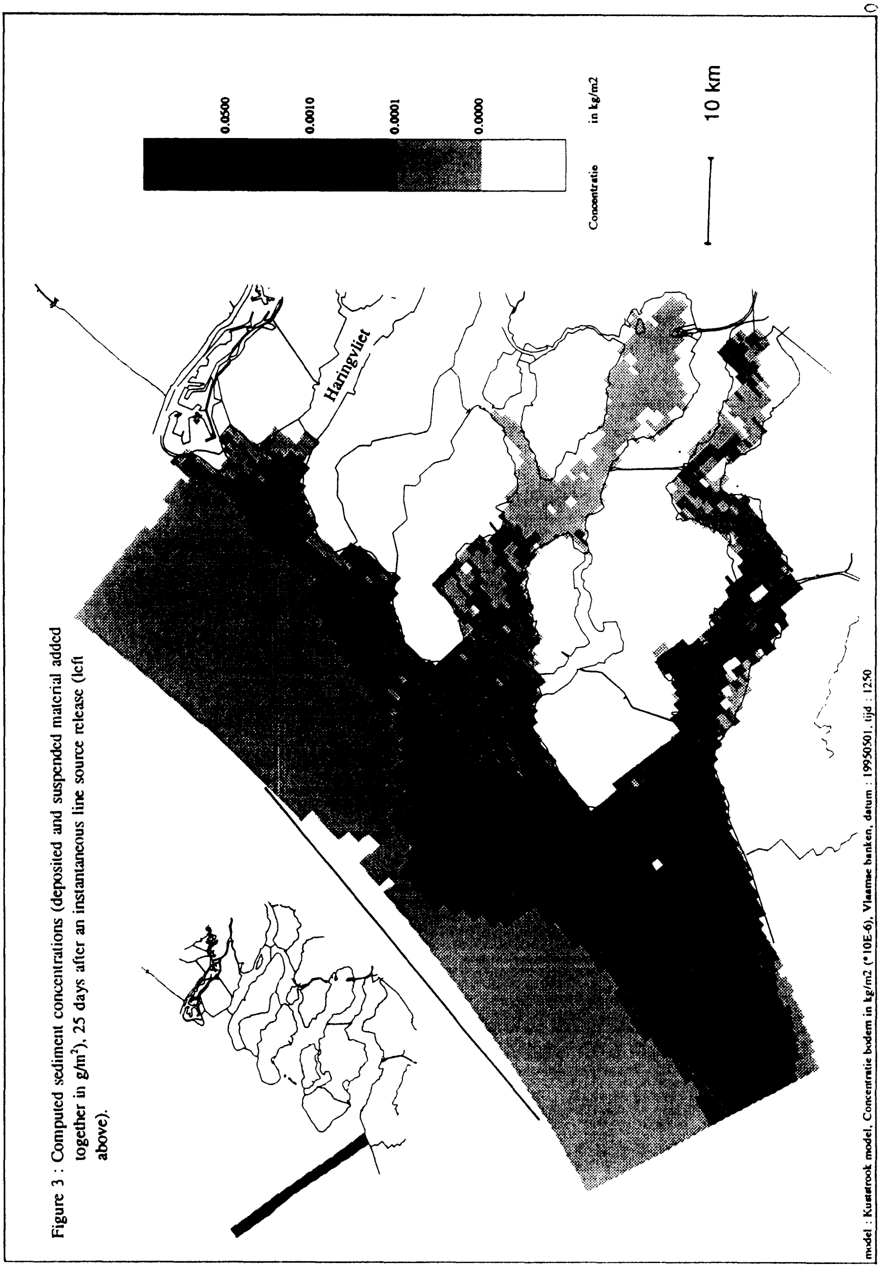

Figure 3 : Computed sediment concentrations (deposited and suspended material added together in g/m^2), 25 days after an instantaneous line source release (left above).

found in de Kok [2]. The influence of wind waves is simulated by wave and depth dependent critical stream velocities for deposition and resuspension. Without waves the latter are 0.25 m/s.

The finite difference scheme used is semi-Lagrangian and performs very well in the reproduction of fronts, discontinuities, higher spatial derivatives, thin oblong patches and concentration patterns related to point sources. It conserves mass as well as first and second mass moments. Therefore isolated patches do not spread out by numerical errors, but have generally limited volumes. Details can be found in de Kok [3]. The mentioned properties are needed in the simulation of suspended sediment concentration patterns on a relatively coarse grid. Both vertically and horizontally almost discontinuous distributions occur frequently by instantaneous resuspension of bottom material that has been deposited around the turn of the tide.

As the numerical scheme is semi-Lagrangian, the model does not use Eulerian velocities, but displacement vectors, computed with second order in time accuracy (Chapman& Dortch [1]) with a time step of 120 s. The output time interval of the displacement vectors and also the time step size of the sediment transport computation is 1800 s. This large time step size reduces the computational effort, but it does not affect the accuracy (de Kok [5]). The displacement vector file represents a period of 25 hours and is cyclicly used.

Figure 3 shows the result of a 20 days simulation after an instantaneous release of a line source perpendicular to the coast. As a result of the asymmetry of the tide a lot of mass is transported via deposition and resuspension into the Western Scheldt, opposite to the main residual flow. It is also clear that the gyres, visible in the residual Eulerian current pattern, are retaining a lot of mass.

Another important transport mechanism is vertical shear dispersion. This can cause a quick, anisotropic transport by oscillating flows, even in non stratified water with high vertical eddy diffusivities. The vertical diffusion coefficients used by the sediment transport model are the same as those used by the hydrodynamic model for the computation of salinity and are part of the model output. The sediment fall velocity is 1 mm/s.

5 Tidally integrated fine sediment transport computation

As three-dimensional hydrodynamic and sediment transport computations are time consuming, a long term simulation is not possible on a PC. Operational tools for water management have to run however often on PC's. Therefore a fast PC-programme for long term fine sediment transport has been developed on a tidally integrated and vertically-averaged basis. The programme uses tidal sediment dispersion patterns, computed with the full 3D tide resolving hydrodynamic and sediment transport model.

The dispersion patterns are computed as follows: A coarse horizontal grid is constructed (fig. 4), that covers the model area. Each coarse grid cell is the union of several adjacent cells of the original fine grid. Generally squares of 4 to 9 fine grid cells are merged to form one coarse grid cell. In each coarse grid cell an initial mass of suspended sediment is placed, equivalent with a concentration of 10 mg/l vertically

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averaged. This initial mass is vertically distributed according to an equilibrium profile with a fall velocity of 1 mm/s and a vertical diffusion coefficient of 0.02 m^2/s. Also on the bottom of each coarse grid cell an initial mass of 50 g/m^2 is placed. The erosion constant used in the resuspension formula is 5 10^{-5} kg/m^2s.
For each initial mass a separate transport computation is conducted for one tidal period. The result is a dispersion pattern per initial mass, of which the following characteristic numbers are stored : the index of the cell of origin, a binary flag indicating the compartment of origin - water column (suspended) or bottom (deposited) - , the amount of initial mass, the number of coarse grid cells, where mass is present after one tidal period, and for each of these cells : the amount of mass, the cell index and a binary flag for suspended or deposited mass. No distinction is made between separate layers in the water column. It is assumed that the mass is vertically distributed according to the standard equilibrium profile. The number of occupied cells generally does not exceed 20, as a result of the fact that the used numerical method tends to compress the tails of Gaussian distributions.
Once these dispersion patterns are computed for each cell of the coarse grid (about 2500 in this case) for a standard tidal period, they can be used for a long term computation with time steps of one tidal period, using the superposition principle. A rather simple PC programme performs the following three substeps per tidal period :
substep one : boundary conditions and source inputs are imposed on the concentration fields for bottom and water column, resulting from the previous time step or given as initial condition,

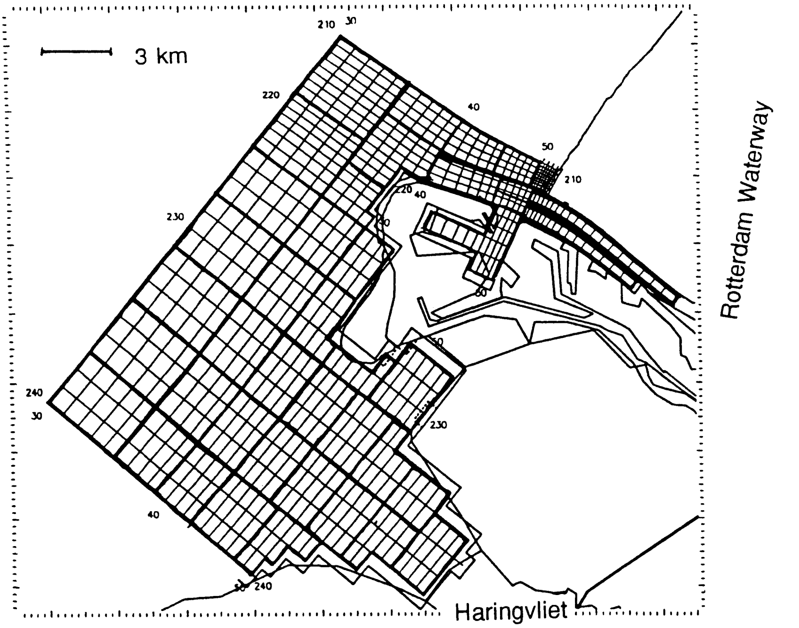


Figure 4 : Part of the fine resolution grid in the area of Haringvliet and Rotterdam Waterway. The coarse grid used for the tidally integrated model is indicated by thick lines.

substep two, redistribution : for each grid cell the mass present is distributed according to the precomputed dispersion patterns,
substep three, superposition : for each grid cell all the mass that has entered that cell as a result of the redistribution substep is added together. Bottom and water column are kept separately (fig. 5).
The algorithm is very simple and straight forward. Mathematical details and an analysis can be found in de Kok [4]. We call the method tidally integrated rather than tidally averaged, as no time averaged quantities are involved: the computed concentration values are instantaneous.
At the start of every time step several limiting assumptions are made : the mass is horizontally homogeneously distributed over the grid cell, and vertically distributed according to the preset standard equilibrium distribution of which the shape does not depend on the amount of mass. Also the time needed for resuspenion of the bottom material is independent of the amount of mass. These limitations do not seem to be very restrictive. Comparison of results of tidally integrated computations with direct 3D tide resolving computations do not show important qualitative differences on spatial scales associated with middle and long term transport (compare fig. 3 and 6). This is among others a consequence of the fact that the very anisotropic dispersion patterns, present along the coast and in tidal inlets, are computed explicitly with the tide resolving fine resolution model and then transferred to the tidally integrated model without loss of their anisotropy.
If one whishes to do a computation with different sediment properties, such as fall velocities, critical current velocities for deposition or resuspension, or erosion parameters, a new dataset with precomputed dispersion patterns has to be generated. This is also the case, when other hydrodynamic or meteorological conditions are to be simulated. For a realistic long term hindcast it is therefore necessary to dispose of a set of data files containing dispersion patterns for various characteristic conditions.
Figure 7 shows the result of a tidally integrated computation with an initial line source (with increasing concentrations towards the coast). The effect of the cross shore estuarine circulation is clearly visible in the shoreward movement of the centre of mass. Seaward of the first tidal inlet of the Wadden Sea a residual gyre is retaining much mass. Sediment is slowly entering the Wadden Sea. The white spots are sand banks that have fallen dry during the tidal phase represented in the plot.

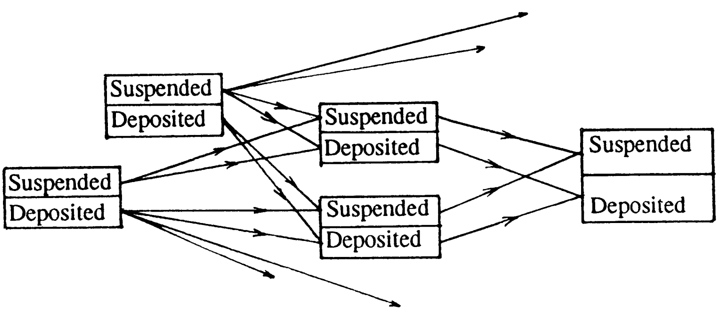
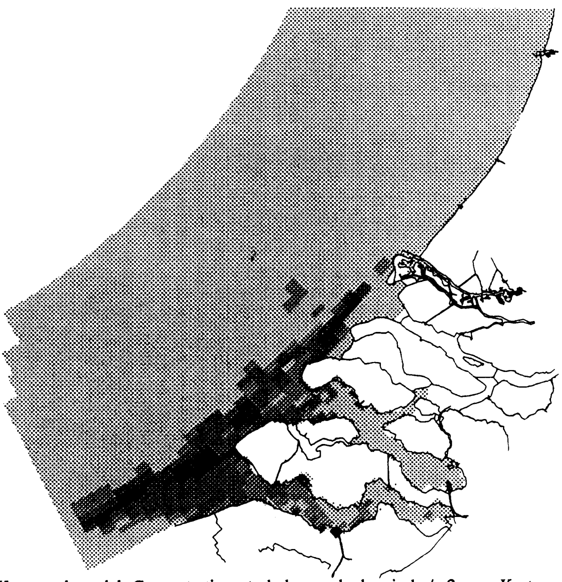


Figure 5 : Redistribution and superposition substeps in the tidal integrated computation

6 Conclusion

A three dimensional tide resolving fine resolution hydrodynamic and transport model for the Dutch coastal waters is used for the computation of transport paths of fine sediment under year averaged conditions. The model reproduces residual eddies with diameters of several kilometers. These eddies are stagnation points in the transport of fine sediment, that elsewhere is flowing to the north-east with a clear coastward component. This coastward flow is the result of cross-shore estuarine-like density driven circulation
Dispersive transport and transport by tidal asymmetry via deposition and resuspension brings marine sediment into the estuaries and in the Wadden Sea, opposite to the direction of Eulerian residual water flow.
With the model local dispersion patterns are determined for use in a fast PC model, working on a tidally and vertically integrated basis on a coarse grid. Results of this PC-model are qualitatively in agreement with results of the fine resolution tide resolving 3D model on scales associated with middle and long term transport.
The computed dispersion patterns are very anisotropic, stretching alongside the coast.



model : Kuststrook model, Concentratie waterkolom en bodem in kg/m2 Kust zone, datum : 19950403, tijd : 50

Figure 6 : Concentration pattern 25 days after an instantaneous line source release at the Belgian Dutch border. Computed with tidally integrated model.

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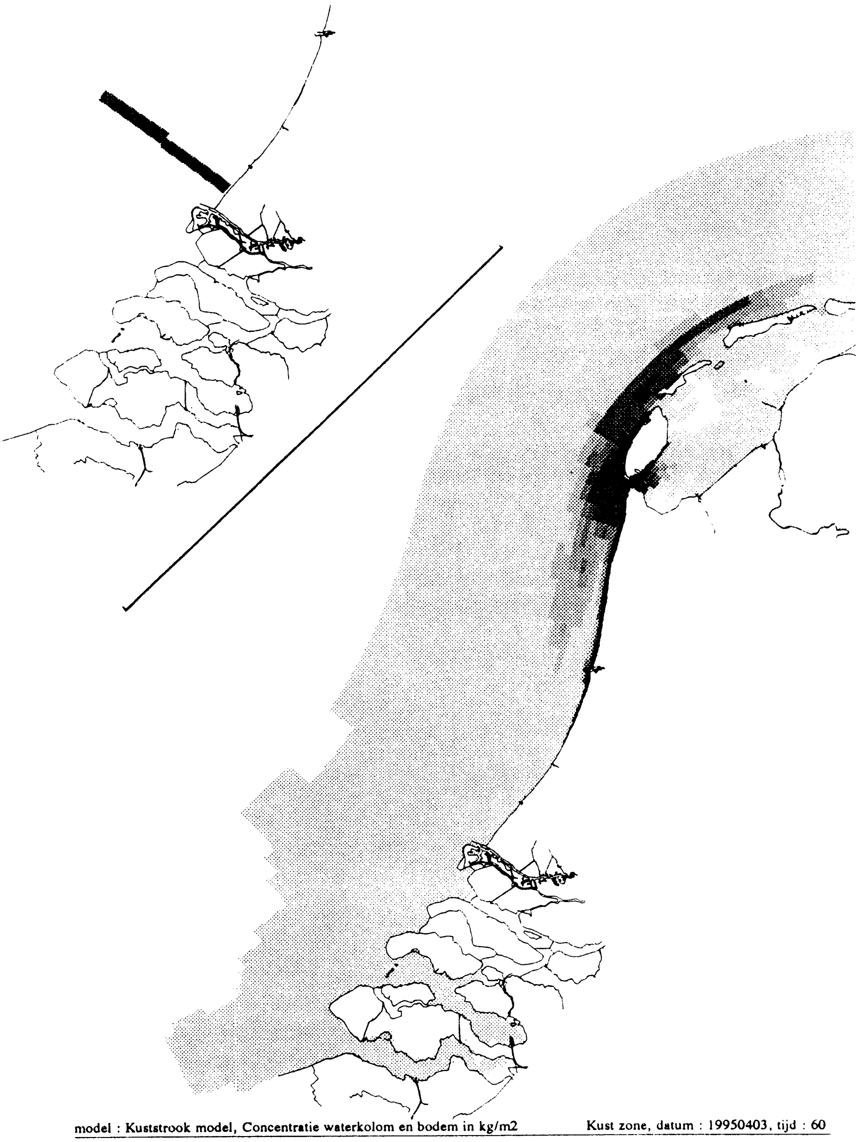

Figure 7 : Concentration pattern 30 days after an instantaneous line source release near the Rotterdam Waterway. Computed with tidally integrated model.

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