The influence of fresh water distribution on SPM transport in the Dutch coastal zone

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Abstract

The rivers Rhine and Meuse - interconnected in the Dutch delta - flow into the North Sea through two outlets: the Rotterdam Waterway and the Haringvliet. The distribution of fresh water between the Rotterdam Waterway and the Haringvliet can be controlled by the management of sluices in the Haringvliet. A change in the management of the Haringvliet sluices can cause a different distribution of river run off over the two outlets and consequently a different salinity pattern around the mouths of Haringvliet and Rotterdam Waterway. This results also in a different transport pattern of cohesive sediment in the area, as it is strongly influenced by the salinity distribution.

A case study with a high resolution 3D baroclinic tidal model combined with a cohesive sediment transport model was conducted to assess the intrusion of cohesive sediment in the Rotterdam Waterway. The model results indicate a reduction of 30 - 60 % of the deposition of cohesive sediment in harbours and shipping channels as a result of a different distribution of fresh water over the two outlets.

1 Introduction

The rivers Rhine and Meuse, with a total year average run off of about 2200 m³/s, meet in the Dutch delta. Their waters flow into the North Sea through two outlets: the Rotterdam Waterway and the Haringvliet (fig. 1).

The Haringvliet is a former estuary, but nowadays it is divided into two parts, separated by sluices. At present these sluices are opened only to discharge fresh water into the western part, but no sea water can enter the eastern part. The
western part is referred to as the “mouth of the Haringvliet”. It is connected to
the North Sea by a number of tidal gullies and has an estuarine character. The
eastern part is referred to as “the Haringvliet”. It contains only fresh river water
and tidal motion is virtually absent.

The most seaward part of the Rotterdam Waterway, together with the adjacent
fairways is called the Maasmond (see fig. 2). The Maasmond is the entrance to a
vast harbour area with intensive shipping traffic, including the largest bulk
carriers. The Maasmond is a completely artificial water way with a width of
1000 m and a maintenance depth of 25 m below mean sea level. Deposition
rates of sands and cohesive sediments, both coming from the sea, are very high.
Yearly an amount of more than 6 million tonnes dry weight of sediment has to
be dredged away from fairways and harbour basins. Deposition of sand takes
place mainly in the most western part of the Maasmond. The dredged amounts of
sand and cohesive sediment are roughly equal to each other.

Cohesive sediments are intruding farther into the Maasmond than sands
(Spanhoff & de Kok, 1991). Marine cohesive sediments can still be found in the
nose of the salt wedge in the Rotterdam Waterway, some 25 km from the sea. It
is estimated that near the turbidity maximum half of the deposited sediment is of
marine origin, the other half being supplied by the river.

During the winter and spring seasons the bottom of the Maasmond is covered
with a fluid mud layer with a thickness between 2 and 4 m. Its density varies
from 1030 kg/m³ at the top until 1300 kg/m³ near the sand bed. The upper part
of the layer is very mobile with flow velocities above 0.2 m/s.

![Schematic map of the Dutch Delta.](image)
Figure 2: Schematic view of computed residual near bed currents near the Maasmond and the Mouth of the Haringvliet. North-west of the Slufter the circulation is directed towards the Maasmond. To scenario, year averaged river outflow and wind and tidal conditions.

The Maasmond is sheltered from incoming waves and alongshore tidal currents by breakwaters with a length of more than 4 km. Incoming tidal currents can reach velocities of more than 0.7 m/s near the lutocline, where internal friction is minimal as a result of the damping of turbulence (Winterwerp e.a., 1998).

Outside the breakwaters tidal current velocities near the bottom are much higher. Together with wave activity they prevent the formation of a mud layer. However, around the turn of the tide benthic suspensions with concentrations of
up to 10 g/l are often observed. Wave activity and hindered settling effects keep the sediment flocs in suspension. At mid depth suspended matter (SPM) concentrations vary between 10 and 500 mg/l, depending on wave activity and current velocity.

However, simultaneously observed SPM concentrations showed large differences over distances of less than 2 km. Observed diameters of aggregates near the bed are between 100 and 200 $10^{-6}$m, depending on tidal phase. Observed primary grain diameters are between 6 and 10 $10^{-6}$m.

Figure 3: Computed salinity values in PSU during low water slack in the mouth of the Haringvliet and around the Maasmond. The gradients west of the Slufter are about 3 PSU/km. T0 scenario, year averaged river outflow and wind and tidal conditions.

2 Estuarine circulation and SPM fluxes

The general residual circulation along the Dutch coast is driven by wind, tides and the effects of river outflow. The main flow is directed towards the Nort-East (de Kok, 1996, 1997). This current supplies most of the cohesive sediment in the Dutch coastal area.
The net alongshore SPM flux is estimated at at least $10^7$ tonnes a year (van Alphen, 1990), but more recent estimates are several times higher (Mc.Manus and Prandle, 1997).

A substantial part of it is entering the Maasmond and the mouth of the Haringvliet as a result of the presence of horizontal and vertical salinity gradients and the associated density gradients in the coastal water (de Kok et al., 1999). These salinity gradients are caused by the outflow of fresh water of the rivers Seine, Scheldt, Meuse and Rhine into the sea.

Along the entire continental coast of the North Sea cross shore density gradients exist, which are maximal in the outflow area of Rhine and Meuse (fig. 3). The density gradients cause baroclinic pressure gradients, which are increasing in downward direction, leading to an estuarine cross shore circulation with a shoreward near bed residual current (De Ruijter e.a., 1992). Because there is always more cohesive sediment in the lower half of the water column than in the upper half, this near bed current causes a shoreward net flux of SPM and accumulation of fine sediment in a narrow coastal strip of several km (Visser et al., 1991).

Along the Belgian coast the cross shore salinity gradients have on average values around 0.1 PSU/km, but near the Maasmond and the mouth of the Haringvliet the averages can reach values of more than 1 PSU/km. Instantaneous surface salinity gradients can be as high as 10 PSU/km in the river plume front. As a result the near bed residual currents are very strong in this area and directed towards the outflow points of fresh water.

Strong salinity gradients and estuarine near bed currents occur also in the mouth of the Haringvliet, in the Maasmond and in the Rotterdam Waterway. Residual velocities are as high as 0.4 m/s and are generally eastward directed. In the direct outflow area of Rhine and Meuse a strong salinity stratification exists most of the time, causing the damping of turbulence and leading to very slow vertical mixing of SPM. This results in SPM concentrations in the lower water layers that are several times higher than in the upper layers. Therefore most of the SPM transport in this area takes place in the lower layers following the near bed residual current pattern.

This leads to a high import of marine cohesive sediment into the Maasmond. The average distance of the flocs to the bed is relatively small. Around the turn of the tide most flocs with fall velocities above $5 \times 10^{-4}$ m/s will merge with the fluid mud layer at the bed within an hour. From there practically no resuspension takes place.

3 River water and 3D density distribution

The sluices in the Haringvliet are opened (within a time frame around low water) only when the river discharge through the Rotterdam Water Way exceeds 1500 m$^3$/s. The remainder of the Rhine/Meuse run off is discharged then through the Haringvliet. The long term average of this discharge is less than 700 m$^3$/s, but
the outflow is very pulsed, with high peaks during ebb tides in the winter and spring seasons. Peak values can be as high as 10,000 m³/s.

River water that is running off through the Maasmond flows along the Dutch coast towards the North-East with an average speed of 10 km a day. River water that is running off through the Haringvliet remains more than a day in the mouth of the Haringvliet before it joins the Dutch coastal current north of the Maasmond.

This means that outflow of river water through the Haringvliet leads to a salinity structure that is different from that, caused by outflow of the same amount of fresh water through the Maasmond.

Outflow through the Haringvliet leads to less saline water in the mouth of the Haringvliet. Outflow through the Maasmond leads to stratification and less saline surface water north of the Maasmond.

A different salinity structure of the coastal water leads also to a different residual current structure and a different transport pattern of cohesive sediment. As we will see, numerical model results indicate, that a small shift of the SPM transport paths to the west can have a large impact on cohesive sediment intrusion into the Maasmond.

For ecological reasons the Dutch government is considering a management scenario for the Haringvliet sluices, in which several sluice gates are permanently opened, also at flood time. This will partly restore the estuarine character of the Haringvliet, bringing back salinity gradients and a modest tidal motion. It will also result in an increase of the year average discharge through the Haringvliet to 1100 m³/s. As a consequence the year average discharge through the Maasmond will decrease from more than 1500 to 1100 m³/s.

This will result in a different salinity structure of the coastal water around the both river mouths, and in different SPM transport patterns.

To assess the impact of these changes on siltation of harbours and fairways in the Maasmond area a three-dimensional numerical model for hydrodynamics and SPM transport is used to study the supply of cohesive sediment to the Maasmond.

4 Model description

The primitive equations for 3-D hydrostatic incompressible free surface flow with Boussinesq approximation for density gradients (see e.g. Csanady, 1984) can be integrated over non horizontal layers, using Leibniz rule.

After minor simplifications this yields:

\[
\frac{\partial u_k}{\partial t} + u_k \frac{\partial u_k}{\partial x} + v_k \frac{\partial u_k}{\partial y} + \frac{\omega_k u_k' - \omega_{rk} u_{rk}'}{h_k} f v_k + \frac{I}{\rho_k} \left( \frac{\partial P}{\partial x} \right)_k = v_h \Delta^2 u_k + \frac{\tau_{xrk} - \tau_{xdk}}{\rho_k h_k}
\]

(1)
The layer integrated transport equation for dissolved and suspended matter reads

\[
\frac{\partial v_k}{\partial t} + v_k \frac{\partial v_k}{\partial y} + u_k \frac{\partial v_k}{\partial x} + \frac{\partial v_k}{\partial x} - \frac{\partial v_k}{\partial y} = \frac{f u_k}{\rho_k} \left( \frac{\partial P}{\partial y} \right)_k + \tau_{y,k} - \tau_{y,d,k} = v_h \nabla^2 v_k + \frac{\tau_{y,k} - \tau_{y,d,k}}{\rho_k h_k}
\]

(2)

\[
\frac{\partial h_k}{\partial t} + \omega_{rk} - \omega_{dk} + \frac{\partial h_k}{\partial x} + \frac{\partial h_k}{\partial y} = 0
\]

(3)

The layer integrated transport equation for dissolved and suspended matter reads

\[
\frac{\partial h_k S_k}{\partial t} + \omega_{rk} S_k - \omega_{dk} S_{dk} + \frac{\partial h_k u_k S_k}{\partial x} + \frac{\partial h_k v_k S_k}{\partial y} = D_h \left( \frac{\partial h_k \partial S_k}{\partial x^2} + \frac{\partial h_k \partial S_k}{\partial y^2} \right) + D_z \left( \frac{\partial S_k}{\partial z} \right)_k - D_z \left( \frac{\partial S_k}{\partial z} \right)_b + S_0 - S_i
\]

(4)

\[ u = (u,v,w), \text{ velocity vector,} \]
\[ P = \text{ pressure,} \]
\[ \nu = \text{ turbulent viscosity coefficient tensor,} \]
\[ S = \text{ concentration of dissolved or suspended matter,} \]
\[ D = \text{ turbulence diffusion coefficient tensor,} \]
\[ \rho = \text{ water density,} \]
\[ g = \text{ acceleration of gravity,} \]
\[ h_k = \text{ depth of layer } k, k=1,\ldots,b \text{ from surface to bottom,} \]
\[ u_k, v_k, \rho_k, S_k : \text{ vertically averaged over } h_k \]
\[ u'_k = u-u_k, v'_k = v-v_k, \]
\[ \omega_{ik} = w_{ik} - \frac{\partial z_k}{\partial t} - u_{ik} \frac{\partial z_k}{\partial x} - v_{ik} \frac{\partial z_k}{\partial y} \text{ vertical transport velocity through layer interface,} \]
\[ z_k = \text{ position of top of layer } k, \]
\[ z_1 = \text{ position of watersurface.} \]
\[ ^t_{ik} = \text{ at top of layer } k, \]
\[ ^d_{ik} = \text{ at bottom of layer } k, \]
\[ ^d_{ik} = ^t_{ik+1} \]
\[ f = \text{ Coriolis parameter,} \]
\[ \nabla^2 = \text{ horizontal Laplace operator,} \]
\[ v_h, D_h = \text{ horizontal turbulence viscousity and diffusion coefficients (assumed uniform),} \]
\[ v_z, D_z = \text{ vertical turbulence viscousity and diffusion coefficients,} \]
\[ \tau_x = \rho v_z \frac{\partial u}{\partial z}, \tau_y = \rho v_z \frac{\partial v}{\partial z} \text{ 2 shear stress between layers,} \]
\( \tau_{x,y} = C_d \rho_w |w| w_{x,y} \): windstress, at the surface,
\( C_d = \) wind coefficient,
\( \rho_w = \) air density,
\( |w| = \) magnitude of wind speed,
\( w_{x,y} = \) wind velocity component in x or y direction,
\( \tau_{x,y} = \rho_b u_b |u_b| v_b k_b, \tau_{y,x} = \rho_b u_b |u_b| v_b k_b, \) bed stress, in the bottom layer b,
\( k_b = \) bottom friction coefficient,
\( S_o = \) source term, erosion or resuspension
\( S_i = \) sink term, deposition

The pressure gradient terms contain both barotropic and baroclinic contributions. Equations (1) and (2) apply to horizontal momentum only.

Density and salinity are coupled via an equation of state with constant temperature.

Equation (4) is solved every time step for salinity and for turbulence kinetic energy (k) and energy dissipation (\( \varepsilon \)) after which density fields and vertical mixing coefficients are computed.

The numerical model uses orthogonal curvilinear horizontal coordinates on a C-type grid and a \( \sigma \)-layer approach in the vertical. The difference scheme is alternating implicit/explicit in the horizontal, allowing for relatively large time step sizes (Stelling and Leendertse, 1994). The horizontal gradient terms are within the \( \sigma \)-plane. This means that \( \sigma \)-planes have to be approximately horizontal.

The SPM transport model is based on the advection-diffusion equation (4), using a fall velocity that is in principle fixed in time and space. The fall velocity \( w_f \) is subtracted from \( \omega_k \) at the layer interfaces.

The mass M of deposited sediment is stored in a separate bed layer for each horizontal grid point. Deposition takes place if the velocity magnitude in the lowest water layer \( |u_b| < u_{d,\text{crit}} \). The deposition rate is \( S_{ib} = w_f S_b \) with \( S_b \) the SPM concentration in the lowest water layer.

Resuspension takes place if \( |u_b| > u_{e,\text{crit}} \), and \( M > 0 \). The resuspension rate \( S_{ob} = E \), with values between \( 10^{-3} \) and \( 10^{-6} \) kg/m²s, independent of the flow velocity, but depending on local bed conditions.

\( u_{d,\text{crit}} \) may be different from \( u_{e,\text{crit}} \).

These formulations differ from those by Krone and Partheniades, because cohesive sediment layers are never observed on the sea bed in the studied area and settling of cohesive sediment for longer than several hours is only supposed to occur in the Maasmond and in a few former tidal channels in the mouth of the Haringvliet.

Vertical mixing of SPM is modeled via the vertical diffusion term in equation 4. The diffusion coefficient is obtained from the k-\( \varepsilon \) model in the hydrodynamic part.

The coupling with the hydrodynamic model goes only one way. Fields of velocities, water levels and vertical diffusion coefficients are transferred to the
SPM model. Density effects related to SPM concentration gradients are therefore not represented in the hydrodynamic model.

In the SPM model it is possible to define subareas where a domain dependent set of values of $w_f$, $u_{d,crit}$, $u_{e,crit}$ and $E$ can be imposed. The definition of the subareas can also be made dependent on local and instantaneous water depths. In this way the model can account for a specific local bed composition, wave conditions or sediment properties.

The numerical scheme of the SPM model is positive, non dispersive and it is able to reproduce very high gradients and higher derivatives without numerical diffusion or strong spurious oscillations (de Kok, 1992). This is especially needed, since SPM concentrations can have differences of an order of magnitude over a few grid cells.

Figure 4: Vertically averaged SPM concentrations in mg/l during low water slack from the T0 computation.
Figure 5: Computed net deposition of cohesive sediment during 1 tidal period. T0-scenario. Deposition in the mouth of the Haringvliet takes place in tidal channels and amounts to 4000 tonnes dry weight. This is higher than the computed net sedimentation in the Maasmond (3000 tonnes). During periods with high wave activity a part of the sediment in the mouth of the Haringvliet will be resuspended, which is not the case in the Maasmond.

5 Simulation of the present situation (T0)

With the model a simulation of the present situation with respect to the river discharges was run. As forcing for the hydrodynamic model year average conditions were chosen. Periodic water level elevations with an average tidal amplitude were imposed on the open sea boundaries (fig. 1). Observed river discharges of 1800 m$^3$/s in the Rotterdam Water Way and 400 m$^3$/s in the Haringvliet were imposed on the river boundaries. The Haringvliet sluices were closed as soon as the computed water level at the seaward side became higher than at the landward side, to be opened (partly) again in the reversed situation. A constant uniform long term averaged wind stress (5 m/s) was imposed on the surface. Also year averaged salinities were imposed on the open boundaries.
Critical current velocity values for deposition and resuspension were 0.15 m/s in the sea areas. In the Maasmond and in the harbour basins values of 0.3 m/s and higher were used, to account for the absence of wave activity. The latter parameters were used to calibrate the model to reproduce the observed siltation. The used global particle fall velocity was \(5 \times 10^{-4}\) m/s.

Figure 6: Computed salinity values in PSU during low water slack in the mouth of the Haringvliet and around the Maasmond. The gradients west of the Slufter are about 6 PSU/km. T1 scenario, year averaged total river outflow and wind and tidal conditions.

Eight \(\sigma\)-layers were used, with high resolution near the bed. Horizontal mesh widths ranged from 100 m in the Maasmond until 1000 m at the western open boundary.

The hydrodynamic computation resulted in a realistic reproduction of observed phenomena such as tidal elevations, tidal current profiles and amplitudes, direction and magnitude of residual currents, horizontal and vertical salinity distributions, length of the salt wedge and extent of the stratified area.

The direction of the residual near bed currents is schematically shown in fig. 2. The current pattern suggests a transport path from the South-West directly leading towards the Maasmond. The salinity gradients west of the Maasvlakte
are negative in the direction of the Maasmond, inducing a positive near bed current in the same direction (fig.3).

The initial condition for SPM concentrations was a zero field, both for bed and water column. A period of 20 days was simulated with long term averaged observed SPM concentrations on the boundaries. After 16 days the computed SPM concentration fields showed a periodic behaviour.

The computed SPM concentration fields show high gradients both in the vertical and in the horizontal (fig. 4). The computed concentration pattern is very patchy, which is in agreement with field observations. Concentration values above 800 mg/l are computed in the lowest model layer in a residual gyre west of the mouth of the Haringvliet. No deposition occurs here, as a result of the high tidal velocities.

Permanent sedimentation occurs in the former tidal channels in the mouth of the Haringvliet and in the Maasmond (fig. 5), which is in accordance with field observations. After tuning of the local parameters the computed deposited amount in the Maasmond was equal to the observed sedimentation of cohesive sediment in the different sectors of the area.

Almost 75 % of the net import of SPM took place in the two lowest model layers (2500 tonnes dry weight/ tidal period). The main supply route of SPM is near the bottom, west of the Slufter following the encircled current vectors in fig. 2.

6 Computation with “open sluice” scenario (T1)

The T0-computation was repeated with different discharge conditions on the river boundaries. The average discharge on the Rotterdam Waterway boundary was 1100 m³/s, equal to the average discharge on the Haringvliet boundary. Also one third of the sluice gates were opened now permanently. The remaining gates were operated in the same way as in the T0-situation.

This caused a considerable increase of the fresh water content of the mouth of the Haringvliet (fig. 6). West of the Slufter the computed salinity gradients are increasing to more than 6 PSU/km around low water slack. This increase causes a reversal of the residual current west and south-west of the Slufter (fig. 7). The SPM transport path is now directed towards the South-East, to the mouth of the Haringvliet, not to the Maasmond.

This causes a considerable decrease of the net import of SPM into the Maasmond. In the T1-scenario it dropped down to 1/3 of the import in the T0-situation. Scenario computations with stormy conditions and open sluices resulted in a decrease of 30 % of the computed net SPM import.

The increased SPM supply to the mouth of the Haringvliet in the T1-scenario does not lead to increased deposition there, because the tidal current velocities did increase as well, as a result of the occurrence of tidal motion in the Haringvliet. A tidal volume is now going again through the old tidal channels and critical velocities for deposition and resuspension are exceeded.
intermittently on most places in the mouth of the Haringvliet. Net settling occurs only at a few places now (fig. 8).

The mean SPM concentration values at some distance to the coast are higher. As a consequence the main north-eastward going transport of SPM now takes place at a greater distance to the coast and less SPM has the chance to enter the Maasmond.

![Diagram of computed residual near bed currents near the Maasmond and the Mouth of the Haringvliet.](image)

**Figure 7:** Schematic view of computed residual near bed currents near the Maasmond and the Mouth of the Haringvliet. West and north-west of the Slufter the circulation is now directed towards the mouth of the Haringvliet as a result of the strong salinity gradients in that area. T1 scenario, year averaged total river outflow and wind and tidal conditions.

### 7 Conclusions and discussion

A three-dimensional numerical model for hydrodynamics and transport of suspended matter was used to assess the impact of a change of the management of the Haringvliet sluices. This modeled change of management led to an increase of the fresh water run off through the Haringvliet by 700 m³/s and a decrease of the run off through the Maasmond by the same amount.
As a result the salinity gradients in the area between Haringvliet sluices and Maasmond decreased significantly and the residual near bed current near the Slufter will turn to the South-East. The numerical model results indicated a decrease by at least 30% of the net cohesive sediment import from the sea into the Maasmond as a result of this change.

Figure 8: Computed net deposition of cohesive sediment during 1 tidal period in the T1-scenario. Deposition in the Maasmond is now 1100 tonnes dry weight.

The model was calibrated to the known year averaged siltation rate. Vertical SPM concentration profiles were roughly tuned to averaged values, known from moorings and ship borne measurements.

Long term averaged surface SPM concentration values were used for boundary conditions. These were assumed to be vertically homogeneous. The total river run off was constant and fixed at the long term average.

The wind forcing was constant and uniform. However, separate runs were done for different wind speeds and directions. The computed cohesive sediment
import into the Maasmond during a SW-storm was comparable to the observed siltation during such periods.

Only the most elementary physical processes were modeled, using the most simple concepts. Wave effects, aggregation, hindered settling, strength development, fluid mud, bed forms and sediment properties were all parameterised in the most simple way by lack of information on sediment behaviour. This makes the prognostic capabilities of the model questionable.

However, more uncertainty results from the fact that the sediment import in the Maasmond depends strongly on wind, wave conditions and on river run off. The present model does not properly account for the time variability of these conditions.

This model study shows already, that a change in discharge distribution over the two outlets can have large effects on sediment import. Ongoing studies show, that the value of the total river run off has a comparable influence.

Significant wave heights (especially above 2 m, Roskam, 1995) have a very large effect on near bed suspended sediment concentrations (Jago & Jones, 1998) and on resuspension of cohesive sediments, deposited during quiet periods. Not enough information is available, however, to validate the model results with respect to these points.

As the computed siltation in the harbour area strongly depends on these processes, improvement of this specific model can only be obtained by frequent survey of the deposition and resuspension areas in the mouth of the Haringvliet and by including realistic time variation in the modelling of wave effects and river run off.

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References


