Modelling the Turbidity Maximum in the Seine Estuary (France): Identification of Formation Processes

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A two-dimensional depth-averaged model and a three-dimensional model for tide propagation and fine sediment transport are used to determine the respective role of several processes on the turbidity maximum behaviour in the Seine estuary. Consolidation processes have been taken into account in the 2DH model. Despite simplified sedimentological formulations and even without any gravitational effect, a turbidity maximum, close to the observations, is reproduced during spring tides. This result confirms the large contribution of tidal pumping on the turbidity maximum formation. The sediment behaviour (settling, erodability) acts in modifying the concentration and location of the tidal-induced turbidity maximum. The bathymetry influences the tidal propagation, but also the location of deposited sediment patterns and consequently, modifies the location of the turbidity maximum. The three-dimensional model allows accounting for all the forcing while the 2DH model does not include the salinity gradients and thus the density circulation, nor the vertical profile of velocity and concentration, which change the deposited sediment distribution. Density gradients act in maintaining the fine sediment in the estuary and in stretching the dynamical accumulation towards the upper limit of the salinity gradients. The turbidity maximum results from the superposition of both processes: (a) the dynamical accumulation of suspended sediment, related to tidal pumping and river flow, modelled by bathymetry and dependent on sediment behaviour, (b) salinity gradients, only related to river flow and bathymetry, which modify its structure.

\textbf{Keywords:} turbidity maximum; deposit patterns; tidal pumping; sediment behaviour; morphological effects; salinity gradients; modelling; Seine estuary (France)

Introduction

An accumulation of suspended particles, called 'turbidity maximum', often appears in estuaries. This sediment pattern can be due to the bottom residual flow induced by density gradients (Postma, 1967), to an 'internal' tidal asymmetry, in relation with the turbulent mixing that depends on salinity stratification changes during the tidal phase (Jay & Musiak, 1994) or to the asymmetry of the tidal wave propagation (Allen et al., 1980; Uncles et al., 1984). The bathymetry, the river flow and the particle behaviour can affect the location and concentration of sediment patterns. These aspects are being considered in the case of the macrotidal Seine estuary.

Some efforts have been undertaken to analyse and model mechanisms of transport, erosion and deposition of cohesive sediment, which mostly compose the turbidity maximum. Two-dimensional models are often used in order to predict the behaviour of the turbidity maximum for estuarine situations (Teisson et al., 1986; Li et al., 1994; Barros, 1996; amongst others). Due to their large need for CPU (Central Processing Unit) time, few three-dimensional models have been used for cohesive sediment modelling (examples being Markofsky et al., 1985; O'Connor & Nicholson, 1986; Le Normant, 1995).

The Seine estuary is open to the English Channel, on the north-west coast of France (Figure 1) and is about 160 km long. At the mouth, the tidal range reaches 7 m during spring tides. The river has a mean discharge of 480 m$^3$/s, draining a basin of 74 000 km$^2$ where 40% of the French population and industry is concentrated. At the mouth of the estuary, two dykes separate the navigation channel from lateral mudflats. The dynamics of the turbidity maximum have been largely modified in the last decades by the morphological evolution of the estuary, consisting of
natural landfill and man-made modifications for maintaining the navigation channel.

Two models of fine sediment transport are used in order to identify the processes influencing the turbidity maximum behaviour in the Seine estuary, to determine the role of particle behaviour on sediment patterns and to study the possibility of interactions between deposits and suspended sediment. Due to the large tidal range in this estuary, the asymmetry of the tidal wave propagation is supposed to play an important role. This assumption justifies the first use of a depth-integrated model, which does not take into account salinity gradients. However, using a three-dimensional model is the only way to take into account all forcing and to determine the relative influence of the tidal asymmetry and salinity gradients on the turbidity maximum behaviour. Though sand particles also play a role in the sediment budget, only fine cohesive sediments are dealt with, as they constitute the larger part of the suspended sediment and extend increasingly on the bed (Avoine et al., 1996).

The models

SAM-2DH: a depth-averaged model for multivariable advection

Hydrodynamics. In order to calculate water levels and currents, the two-dimensional finite difference model SAM-2DH, which solves the shallow water equations using an Alternated Directions Implicit scheme (Leendertse & Gritton, 1971), has been developed. The Boussinesq approximation and the hydrostatic condition are introduced in the governing equations.

\[
\frac{\partial U}{\partial t} + U(\nabla U) - 2\Omega \times U = -g\nabla \zeta - g\frac{H}{2\rho_0} \nabla \rho - \frac{\tau}{\rho_0 H} + \nabla^2 U
\]

\[
\frac{\partial \zeta}{\partial t} + \nabla HU = 0
\]

Where \( U \) is the fluid velocity (\( \text{m s}^{-1} \)), \( \Omega \) the earth rotational velocity (\( \text{s}^{-1} \)), \( g \) the gravitational acceleration (\( \text{m s}^{-2} \)), \( \zeta \) the free surface elevation (\( \text{m} \)), \( \rho_0 \) the water density (\( \text{kg m}^{-3} \)), \( \tau \) the bottom friction
(N m$^{-2}$), $H$ the water depth (m) and $\nu$ the viscosity (m$^2$ s$^{-1}$).

The model has been calibrated by adjusting the Strickler bottom friction coefficient $\tau$ defined as:

$$\tau = \rho_0 \frac{gU^2}{\kappa^2 (H + H_f)^{1/3}} \quad (2)$$

Where $\kappa$ is the Karman coefficient (=0.4), $H_f$ is for limiting the bottom friction when the water depth vanishes (=2 m).

Meteorological forcing is not considered in the present computation (the terms of pressure gradients and surface friction due to the wind are not included in the equations). Also, in results of the depth-averaged model, density gradients are neglected.

Actually, a specific test shows that the effects of depth-averaged density gradients are negligible in the estuary, especially in the turbidity maximum area and only sensitive in deeper areas, such as downstream from the mouth.

The model covers the eastern part of the Baie de Seine and the estuary up to the first weir at Poses. In order to reduce CPU time but keep a good resolution around the turbidity maximum area (and especially around the dykes at the mouth of the estuary), an irregular rectilinear grid (Figure 1) is used (mesh sizes vary from 200 to 4000 m). Because morphological changes are large in time and space, the most accurate and recent (1994) bathymetric charts, supplied by the Rouen Port Authority in the estuary, have been used downstream of Rouen.

Along the seaward boundary, a real tide is imposed at each node. It is calculated as the sum of 26 harmonic components interpolated from tidal charts which were deduced from a rotating physical model of the English Channel (Chabert d’Hières & Le Provost, 1978) and from a numerical model (Fornerino, 1982). Therefore the model can run for any tidal forcing, allowing the operator to specify any simulated day.

The river flow is introduced at the upstream limit.

**Sediment transport model.** The sediment transport model solves an advection-dispersion equation for the mass conservation of suspended sediment, taking into account the bottom exchanges by erosion and deposition. An explicit advection scheme, based on the Bott (1989) algorithm, which reduces artificial diffusion, has been used. Due to a less restricting stability criterion, the time step for sediment transport processes is larger than for the hydrodynamics one. The equation is given as:

$$\frac{\partial C}{\partial t} + U \nabla C = \nabla (K \nabla C) + \text{erosion} - \text{deposition} \quad (3)$$

Where $C$ is the suspended sediment concentration (kg m$^{-3}$) and $K$ the dispersion coefficient (m$^2$ s$^{-1}$).

The deposition term $D$ (kg m$^{-2}$ s$^{-1}$) is calculated following the Krone (1962) formulation:

$$D = W_s C \left( 1 - \frac{\tau}{\tau_{cd}} \right) \quad (4)$$

Where $W_s$ is the settling velocity (m s$^{-1}$), $\tau$ the bottom shear stress (N m$^{-2}$), $\tau_{cd}$ the critical shear stress (N m$^{-2}$) for deposition (no deposition when $\tau > \tau_{cd}$) and $(1-\tau/\tau_{cd})$ represents the probability for settling particles to remain deposited.

The erosion term $E$ (kg m$^{-2}$ s$^{-1}$) is expressed according to the Partheniades (1965) formulation, using the excess bottom shear stress concept:

$$E = E_0 \left( \frac{\tau}{\tau_{ce}} - 1 \right) \quad (5)$$

Where $\tau_{ce}$ is the critical shear stress (N m$^{-2}$) for erosion (no erosion when $\tau < \tau_{ce}$), $E_0$ the erosion coefficient (kg m$^{-2}$ s$^{-1}$) and $(\tau/\tau_{ce}-1)$ the excess shear stress.

There is a continuous exchange of sediment between the bed and the water column, because the model allows material to settle to the bed throughout the tidal cycle, where it is available for re-erosion, depending on the temporal and spatial variability in shear stress (Sandford & Halka, 1993).

The bottom friction is calculated by the means of the Strickler coefficient (already determined for the hydrodynamics simulation). The dispersion includes the turbulent diffusion, but is mainly due to the vertical dispersion and is parameterized as a function of the total discharge:

$$K_s = K_e = K_0 + K_1 H U \quad (6)$$

Where $H$ is the water level (m), $U$ the depth integrated velocity (m s$^{-1}$), $K_0$ and $K_1$ (m$^2$ s$^{-1}$) parameters which have to be calibrated.

Re-suspension by waves and lateral sliding are not considered in the present model.

**Consolidation model.** Consolidation processes may influence the erodability of cohesive sediments and therefore modify the sediment patterns. A one-dimensional vertical multi-layer sedimentation model is coupled to the 2DH-sediment transport model (Brenon & Le Hir, 1998). According to the Kynch hypothesis (1952), the sedimentation velocity is
assumed to only depend on the local sediment concentration. Effective stresses are supposed to have minor importance, which is reasonable for medium term consolidation. Such a model has been proved to fit settling tests satisfactorily after calibrations (Le Hir & Karlikow, 1992). Horizontal movements are neglected, as they are of minor importance when wave effects are not taken into account.

The consolidation model solves the sediment mass conservation equation between fixed levels at each cell of the 2DH-sediment transport computational grid, according to a semi-implicit finite difference scheme.

$$\frac{\partial C}{\partial t} + \frac{\partial V C}{\partial z} = 0 \quad (7)$$

Where \(V_s\) is the sedimentation velocity (m s\(^{-1}\)) and \(C\) the sediment concentration or dry density (kg m\(^{-3}\)).

In order to simulate the differential movement of several kinds of particles in the little consolidated mud and to keep a fine vertical simulation in the surficial soil structure, where density gradients are high, real co-ordinates have been preferred to material co-ordinates. Such a model can reproduce steps in density profiles just by means of strong variations of the sedimentation velocity (according to the concentration), which correspond to changes in the soil structure.

The sedimentation velocity is calculated according to the soil porosity by using a power law. The porosity itself is related to the dry density, assuming a constant grain density. The shear strength of the surficial sediment is empirically deduced from the dry density of the upper layer through a power law (Hayter & Mehta, 1986; Migniot, 1989; amongst others).

The model computes the bed surface level and the mud density profile. The number of layers, the upper layer thickness and the total bed thickness vary according to deposition, erosion and consolidation.

**SAM-3D: a three-dimensional model for multivariable advection**

In order to calculate vertical structures and take into account density effects, a three-dimensional model SAM-3D (Cugier & Le Hir, 1998) has been used. The model solves the Navier-Stokes equations with a free surface boundary condition, using Boussinesq approximation and the hydrostatic assumption on the vertical. The equations (momentum, continuity and state equations for salinity) to be solved are:

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} + f v &= - \frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{1}{\rho_0} \left( \frac{\partial}{\partial z} \left( v \frac{\partial}{\partial z} \right) \right) \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + f u &= - \frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{1}{\rho_0} \left( \frac{\partial}{\partial z} \left( v \frac{\partial}{\partial z} \right) \right) \\
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} &= \frac{\partial}{\partial z} \left( \frac{1}{\rho_0} \frac{\partial P}{\partial z} - \rho g \right) \\
\frac{\partial p}{\partial z} &= - \rho_0 \left( 1 + aS \right)
\end{align*}
\]

Where \(U\) is the velocity, with \((u, v, w)\) the components (m s\(^{-1}\)), \(f\) the Coriolis parameter (s\(^{-1}\)), \(g\) the gravitational acceleration (m s\(^{-2}\)), \(\rho_0\) the freshwater density (kg m\(^{-3}\)), \(P\) the pressure (kg m\(^{-1}\) s\(^{-2}\)), \(\rho\) the water density (kg m\(^{-3}\)), \(a=0.0008\), \(S\) the salinity, \(v_i\) and \(v_j\) the vertical and horizontal turbulent viscosity (m\(^2\) s\(^{-1}\)).

In order to solve this complete set of equations, barotropic and baroclinic modes are separated. The barotropic 2DH model is used to calculate the free surface elevation and the depth-integrated velocity. The water level is thus introduced into the set of 3D equations, which are solved in order to determine all velocity components. Thus, the actual bottom friction and the vertical dispersion terms are calculated and used by the 2DH model for the next time step, as well as the depth-averaged density gradient terms (Cugier & Le Hir, 1998). The system is fully conservative. The advantage of this method is to allow the calculation of the three-dimensional system less often, as the time step is not constrained by the surface wave propagation. On the vertical axis, real co-ordinates (\(\sigma\) co-ordinates) have been preferred in order to avoid numerical artefacts due to large bathymetric gradients, especially between the deep navigation channel and the shallow mud banks. The vertical discretization is coherent between neighbouring water columns, so that horizontal fluxes are explicitly calculated within horizontal layers. Convective fluxes of salt or suspended sediment are computed by using the Bott (1989) technique.

The horizontal grid, the bathymetry and the sediment transport module are the same in the 2DH and in the 3D models. Due to large CPU time and for a better understanding of basic mechanisms,
consolidation processes are not taken into account in the 3D model.

The turbulent closure uses the turbulent viscosity (and diffusivity) concept following the mixing length theory. In order to reproduce the turbulence decrease by large stratification, the turbulent viscosity (and diffusivity) concept following the mixing length theory. In order to reproduce the turbulence decrease by large stratification, the turbulent viscosity \( v_{iz} \) and diffusivity \( K_{iz} \) are corrected by a damping factor, which is dependent on a local Richardson number \( R_i \) (Cugier & Le Hir, 1998). The classical formulation is from Munk and Anderson (1948), but others have been proposed (see Nunes Vaz & Simpson, 1994, for review and comparison Table 1). Several tests have been conducted (Cugier & Le Hir, 1998) leading to improved efficiency of the formulation of Lehfeldt and Bloss (1988), when simulations are compared to salinity measurements. Consequently, the latter has been applied to the Seine estuary with a good agreement between computed and observed vertical salinity structure (Le Hir et al., 1997).

<table>
<thead>
<tr>
<th>Conditions of simulation</th>
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<tr>
<td>The initial condition for the sediment is set as a uniform quantity of deposited mud, little consolidated and thus easily re-suspended. This quantity is located in the channel downstream of the river but upstream of the expected turbidity maximum area. After a few tidal cycles, this initial supply is totally resuspended. A number of initial deposit locations have been tested, but all lead to similar final sediment patterns, proving the independence of sediment patterns with initial conditions. At the sea boundary, the concentration of suspended sediment is equal to zero during the flood and a free output is introduced during the ebb. At the upstream limit, a constant concentration, closed to the measured value, is given such as 0.04 kg m(^{-3}) for a river discharge of 500 m(^3) s(^{-1}).</td>
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Sediment transport processes are deliberately simplified in order to point out the role of hydrodynamics on sediment patterns. Therefore the settling velocity is chosen to be constant and flocculation processes are implicitly accounted for through a high settling velocity, typically 1 mm s\(^{-1}\). This order of magnitude is in accordance with recent field measurements (Van Leussen, 1995) and has also been observed in the Seine estuary (Dupont et al., 1995; Defossez, 1996). In order to determine the parameters for simulations, ranges of values have been taken from the literature (De Nadaillac, 1985), as these parameters have not been experimentally determined for the mud from the Seine estuary. Therefore, after a sensitivity analysis of the model (Brenon, 1997), they have been calibrated through a trial and error technique, looking for simulated sedimentological patterns closed to the observed one. This set of parameters will be used as the ‘reference’ set of parameters in the 2DH and in the 3D models. When consolidation processes are not taken into account, the mud shear strength is assumed constant and uniform, equal to 0.5 N m\(^{-2}\). This does not mean that the soil settlement is not reproduced but that particles have a given rigidity as soon as they deposit. They keep this rigidity during the whole simulation. Thus, the value of the erosion parameter is equal to \(10^{-3}\) kg m\(^{-2}\) s\(^{-1}\). When consolidation processes are dealt with, the critical shear stress is calculated according to a power law and the erosion parameter is equal to \(5 \times 10^{-4}\) kg m\(^{-2}\) s\(^{-1}\). A strong critical shear stress for deposition (10 N m\(^{-2}\)) has been chosen in order to have deposition always possible. Therefore it becomes not relevant.

### Table 1. Values of eddy viscosity and diffusivity according to Munk and Anderson (1948) and Lehfeldt and Bloss (1988)

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<th>Eddy viscosity</th>
<th>Eddy diffusivity</th>
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<tbody>
<tr>
<td></td>
<td>(a, b)</td>
<td>(a', b')</td>
</tr>
<tr>
<td>Munk and Anderson (1984)</td>
<td>10.0, -0.5</td>
<td>3.33, 1.5</td>
</tr>
<tr>
<td>Lehfeldt and Bloss (1988)</td>
<td>3.0, -1.0</td>
<td>3.0, 3.0</td>
</tr>
</tbody>
</table>

### Influence of tidal dynamics

The two-dimensional model is used to determine the behaviour of turbidity maximum under various conditions of tide and river flow. The fact that the turbidity maximum sometimes occurs landward of the salt intrusion (Avoine, 1981) probably indicates that the vertical gravitation circulation is not the dominant process. This result justifies the first use of a two-dimensional depth-averaged model, which assumes that the effects of density gradients are negligible compared to the effects of the asymmetric tidal propagation.

### Tidal pumping in the Seine estuary

The tidal characteristics of estuaries contain important differences in the capability of tidal currents to move the fine sediments. The Seine estuary is...
classified as a macrotidal estuary (Avoine, 1981): tidal range greater than 4 m and large, relative to the mean water depth.

Considerable asymmetry can occur in the free surface and velocity curves (Figure 2), when the tidal wave propagates upstream in the estuary (Allen et al., 1980). Since the tidal wave celerity is a function of water depth, the crest (at high water) propagates faster than the trough (at low water). The time lag of high water between the mouth and the head of the estuary is smaller than the time lag of low water. This causes the ebb period to become longer and the flood duration shorter, resulting in an asymmetrical tidal curve. In addition, as nearly the same quantity of water should flow in either direction for each tide, this asymmetric tidal cycle induces higher flow velocities than ebb velocities. The deformation of the tidal wave also induces an asymmetry between slacks duration: the high water slack is longer while the low water one is shorter (Postma, 1967).

Since the rate of erosion of cohesive sediment is a function of the bottom shear stress (Partheniades, 1965), the higher flood tide velocities cause a greater bottom erosion and suspended sediment transport than the ebb. This leads to a net upstream movement of sediment near the bed, until the point of the estuary where the velocity due to the river flow is dominant for the transport. Suspended sediment are accumulated beyond this point. Another effect of the tidal asymmetry is to favour sedimentation at high water slack: the slack asymmetry induces a greater settling of particles from the turbidity maximum during high water than during low water. These mechanisms induce a net upstream movement of suspended sediment, which acts in creating tidal sediment trap downstream of the point where the seaward river flow is dominant. This type of transport has been called ‘tidal pumping’ for the Tamar estuary (Uncles et al., 1984).

**Simulations of suspended sediment with the 2DH model**

Due to the non-linear effects of the tide propagation, a turbidity maximum is reproduced in less than 50 hours (almost four high water/low water cycles). During spring tides and for a mean river flow (500 m$^3$ s$^{-1}$), mud concentration of about 1 kg m$^{-3}$ is simulated for about 20 km long. The turbidity maximum is located downstream of Honfleur at low water and it moves upstream (almost 15 km) at high water (Figure 3). The high concentrations extend in the navigation channel, within the two submersible dykes and due to a break in the northern dyke, into the northern shallow channel.

In the following, suspended sediment patterns, computed for recent hydrodynamic conditions (bathymetry of 1993), are compared with data collected in 1979. Avoine et al. (1996) pointed out that, after a long period of seaward drift, the turbidity maximum became stable in the last decade. In order to check this result, simulations have been run with the bathymetry of 1985. Very little difference with previous simulations has been noticed. Therefore, although the study of sediment patterns has been carried out by using the recent bathymetry, a comparison between data of 1979 and computed results seems justified.

For a medium river flow, the agreement between 2DH model results and data is thought to be difficult to judge for the location and for the concentrations of the turbidity maximum (Figure 3). This result points out the important role of tidal pumping on the turbidity maximum behaviour in the Seine estuary. Similar conclusions about the large effect of the tidal dynamics on the turbidity maximum behaviour have been highlighted by Dyer and Evans (1989).
Turbidity maximum sensitivity to the river flow and validation

After the previous study of the turbidity maximum for a mean river flow, the model is run for various river regimes. The location of high concentrations varies according to the river flow. For a better understanding, constant river flows are used for each simulation.

The turbidity maximum area, simulated with higher river flow (1000 m$^3$ s$^{-1}$) is shifted between 5 and 10 km downstream of the location simulated for a mean river flow (Figure 4); conversely, it is about 15 km upstream for a lower river flow (200 m$^3$ s$^{-1}$). Simulated concentrations are higher in the case of low river flow at least for two reasons:

(a) the estuary cross sections are smaller upstream than downstream,

(b) the estuary cross sections are smaller upstream than downstream,

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(a) the estuary cross sections are smaller upstream than downstream,
the quantity of deposited sediment is smaller
(as suspended sediments are far from places where
bottom friction is low).

For similar reasons, the extension of the turbidity
maximum is larger for a low river flow.

In order to validate the model, simulated turbidity
maxima are compared with observations for three
river flows (Figure 4). For a high river flow, simulated
results and observations are in good agreement in
terms of location and concentration. For a mean river
flow, the simulated turbidity maximum is close to
observations for high water while it is located slightly
too much upstream for low water. But for a low river
flow, the turbidity maximum is located extremely
upstream: 5 to 10 km for high water and 10 to 15 km
for low water. This difference could be explained by
the re-suspension of deposited sediment, trapped
along the coast (see ‘Influence of Morphology’). As
these deposits are upstream of the turbidity maximum
area (and especially around Tancarville), the sus-
pended sediments remain upstream and the turbidity
maximum cannot move downstream.

Influence of sediment behaviour

The previous simulations have been performed with a
‘reference’ set of parameters (see ‘Conditions of
Simulation’). Several runs have been performed with
the depth-integrated model in order to determine the
sensitivity of sediment patterns to the erosion and
deposition parameters and thus, on the tidal turbidity
maximum. For a better understanding of the results,
simulations are run without the consolidation process;
that is the mud shear strength is uniform and constant
for each simulation.

Variations of the erosion law

A decrease of the erosion constant to
$5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ induces lower suspended sedi-
ment concentrations. The behaviour of sediment
patterns always depends on the initial supply of
particles: no turbidity maximum is simulated while
deposits are larger and remain longer during slacks.
The initial supply is not re-suspended even after a
four-month simulation. Increasing the erosion
parameter to $10^{-2} \text{ kg m}^{-2} \text{ s}^{-1}$ moves the turbidity
maximum a little downstream [Figure 5(a)]. The
contrast between spring and neap tides is marked: the
concentration of suspended sediment is large during
spring tides while almost all particles deposit during
neap tides. Sediment particles are resuspended at the
early beginning of the flood. This value of the erosion
parameter is asymptotic and for larger values there is
no change. These results point out the relatively low
contribution of this parameter.
A small critical shear stress (0.2 N m\(^{-2}\)) is characteristic of non-consolidated sediments, which can be easily resuspended. Particles remain in suspension even during part of slacks and only little deposition is simulated. The turbidity maximum is located near the mouth during the whole tidal cycle. Therefore, particles can be flushed out of the estuary, concentrations remain low (under 0.3 g l\(^{-1}\)) and the turbidity maximum is non-visible on Figure 5(b). The periodic regime, due to the tidal cycle, cannot be reached after four-month simulations. As the critical shear stress increases to 2 N m\(^{-2}\), the turbidity maximum moves upstream [Figure 5(b)]. Due to the non-linearity of the erosion formulation, the re-suspension of particles during the flood is larger than during the ebb. Thus the downstream transport of particles is low and the sediment trapping along the coast is increased. No real turbidity maximum appears but only some resuspension of particles during ebb and flood at the location of the initial supply. These results show that the critical shear stress and thus the consolidation, plays an important role in the location and concentration of sediment patterns. Reasonable results seem to be given for a critical shear stress equal to 0.5–1.0 N m\(^{-2}\) [Figure 5(b)].

The erosion law mainly acts through the consolidation of the mud and thus, limits the resuspension of the deposited sediment. Thus, the concentration of the turbidity maximum is affected by the variation of these erosion parameters.
Variations of the settling velocity

When the settling velocity decreases to 0.5 mm s⁻¹, the sediment particles are easily transported throughout the estuary. The quantity of sediments deposited downstream on the lateral mudbanks (and which is poorly resuspended) is large. Due to the relationship between deposits and suspended sediment (see ‘Effects of deposits on suspended sediment particles’), the turbidity maximum moves downstream [Figure 5(c)]. As a large quantity of particles is trapped and water volumes increase downstream, concentrations of suspended sediment diminish. Increasing the settling velocity to 2 mm s⁻¹ favours deposition and trapping of sediments. Large shear stress is then necessary to maintain particles in suspension. The effects of asymmetry between ebb and flood, and especially between high water slack and low water slack, are emphasized. Therefore, the turbidity maximum moves upstream [Figure 5(c)] and due to the decrease of sections upstream, sediment concentrations increase. Furthermore, this leads to a diminution in the quantity of deposited mud downstream.

The settling velocity seems to act mainly on deposition patterns and, thus, on the availability of the bottom sediment. Since a functional link exists between deposits and suspended sediment, the variation of this particle characteristic also acts on the turbidity maximum behaviour.

These results point out the strong influence of settling velocity on the behaviour and concentration of the turbidity maximum (Toorman & Berlamont, 1993). Similar results have also been obtained for the Loire estuary, with a one-dimensional model (Le Hir & Thouvenin, 1992). It must be noted that increasing settling velocity and erosion threshold has not the same effect on sediment concentration. A large settling velocity influences the turbidity maximum through deposits during slacks, while the shear stress acts directly on the quantity of resuspended sediment, when currents are maximum. It can be noted that the deposition, parameterized by the settling velocity, is strongly dependent on the water depth for a given deposition period, whereas erosion, which is proportional to the excess shear stress, is related to the non-uniform current distribution.

Influence of morphology

Simulation of deposits with the 2DH model

Suspended sediments settle on neap tides and may not be resuspended when the tidal range increases, due to consolidation processes. Thus, residual deposits are formed, especially in areas of minimum velocities in the vicinity of the turbidity maximum. First computations showed an accretion on the northern bank along the northern dyke and large deposits at the mouth of the estuary, off the navigation channel, where observations indicate 2 to 3 m accretion over the last 10 years (Brenon & Le Hir, 1998). Where the bottom is principally muddy (Lesueur et al., 1997), these features are realistic when compared to the variation of bathymetry between 1985 and 1994 (Figure 6). But the model also simulated excessive deposits along each bank of the estuary, especially in corners of the model coastline. In order to avoid this artefact, the computational domain has been regularized by aligning the banks upstream of the Normandy Bridge, slightly modifying the geometry of the estuary. In addition, an intertidal area has been added on the northern side of this section, as it is observed.

The effect of these changes on sediment patterns is strong: neap tide deposits between Honfleur and Tancarville are strongly reduced while residual deposits are only present on the northern mud bank upstream of Honfleur, where mudflats are in accretion. An agreement between the computed residual deposits and the bathymetric chart evolution is noticeable on Figure 6 at the mouth while excessive deposits disappear along the coastline. Large deposits observed north-west of the mouth are not simulated since they are due to dredging deposits, which are not accounted for in the model.

Effects of deposits on suspended sediment patterns

A functional link between deposit location and turbidity maximum is found. On one hand, neap tide deposits appear in areas of minimum energy close to the simulated turbidity maximum location (related to the tidal propagation and the sediment characteristics, especially the settling velocity and the critical shear stress). On the other hand, the location of the turbidity maximum also depends on deposits that occur during neap tides. This relationship explains the change of the turbidity maximum when the grid is regularized, as the location of trapped deposits is modified (Figure 7).

Numerical results for a low river flow confirm this link between deposits and turbidity maximum. While high-suspended sediment concentrations move upstream and are longer for a low river flow, deposits appear around the same location for low and mean river flow but with a reduced quantity downstream (Le Hir et al., 1997). The location of neap tide deposits does not change so much, but their
distribution between upstream lateral traps and downstream low energy areas is different.

**Effects of mud concentration vertical gradients**

Differences in sediment patterns between 2DH simulations and observations can also be induced by the vertical dispersion, related to the vertical structure of currents and concentrations, which is crudely accounted for in the 2DH model by means of an increased horizontal diffusion.

At the surface, currents are strong while concentrations are low. Near the bottom, currents are low while concentrations are high. The real sediment flux could be quite different than the sediment flux transported in the depth-integrated model. Despite the flexibility provided by the parameter values, the realistic behaviour of the turbidity maximum simulated with the 2DH model (see ‘Simulation of suspended sediment with the 2DH model’) indicates that it is not the case at least in the navigation channel, where the turbidity maximum is located. This is probably because currents are strong enough to mix suspended sediment on the whole water column. But over local troughs, characterized by low velocity, where high concentrations are confined, a depth-averaged computation is likely to overestimate the sediment flux by spreading the suspended sediments in upper layers where velocities are higher.

A second effect is due to the distribution of particles in cross-sections of the estuary. When the latter exhibits a deep channel and shallow lateral areas, the high depth-averaged concentrations in the channel are mainly influenced by very high concentrations close to the bottom, while, near the surface, concentrations are low due to settling. Actually, lateral layers are connected with the surficial layers of the channel and their concentrations are closer. In a depth-averaged model, surficial concentrations are artificially enlarged and thus, lateral concentrations are overestimated. As current intensities are lower close to the lateral banks, deposition is also over-evaluated, with consequences
on the turbidity maximum location, as pointed out in ‘Effects of deposits on suspended sediment patterns’. This process results in an artefact of depth-averaging modelling.

It can be concluded that there is a strong effect of the morphology on suspended sediment patterns and the turbidity maximum location. The latter seems to be attracted by the location of probable deposits, which occur on neap tide. The banks of the estuary between Honfleur and Tancarville are the largest areas of deposition, which may influence the turbidity maximum. Besides, the morphology of typical cross-sections in the estuary, with a deep channel between very shallow lateral areas, entrain strong stratifications in the channel and low concentrations in the upper (and lateral) layers, which are overestimated by the depth-averaged model. As a consequence, the 3D model is more suitable for simulating the lateral deposition, with the effect mentioned on the turbidity maximum.

**Influence of salinity gradients**

The convergence of the bottom residual circulation induced by density gradients can act in trapping the sediments and generate a turbidity maximum. In the Seine estuary, suspended sediment concentrations are less than 1 kg m$^{-3}$ and fluid mud scarce, so that density gradients are mainly induced by salinity and secondarily by suspended sediment concentrations or temperatures, which are not accounted for in this study.

**Residual circulation in the Seine estuary and consequences on sediment behaviour**

The Seine estuary is a partially mixed estuary where the gravitational circulation produces a residual landward bottom flow and a seaward surface residual flow. Suspended sediments can be brought into the estuary either from the river, or from the sea. Particles settle
int into the lower layer in the middle estuary. Then particles are carried landwards by the bottom residual flow, whereas, in the upper estuary, they are transported seawards. Consequently, the maximum concentration of suspended sediment occurs at the bottom near the convergence of bottom residual flow, the so-called ‘null point’ (Glangeaud, 1938). This circulation process can lead to turbidity maximum without the need for consideration of sediment properties other than settling velocity and without sediment erosion, deposition and consolidation.

Compared salinity gradients in the Seine estuary

The 3D model has been first used to simulate the Seine river intrusion. The salinity front (defined by the salinity isoline of 0.5 · 10⁻²) becomes realistic after a simulation of 30 days for a mean river flow with an initial condition of marine water (salinity of 33.0, close to the real value at the downstream boundary) in the whole estuary. In order to reduce CPU time, it has been chosen to begin the sediment transport calculations after this initialization. Vertical structures have been validated by means of observations (Avoine, 1981).

The contrast between bottom and surface salinity patterns shows large stratifications and a very variable dispersion of the river water along the water column. Due to deeper bottom in the northern half of the mouth than in the southern one, the salinity gradient effects are stronger at the north of the estuary. Thus, the fresh water mainly flows to the north-west at the surface while, in deeper layers, it flows along the south-west coast close to the bottom. Salinity gradients are not directly studied here but more details on this can be found in Cugier and Le Hir (1998). Especially, these authors show that the behaviour of the river water at the surface has a large sensitivity to the wind.

Simulations of suspended sediment with the 3D model

In the following section, the respective location of salinity gradients and turbidity maximum will be compared. For this purpose, longitudinal (along the navigation channel) sections of the estuary will be presented, with repetitive scales of grey intensity representing either salinity or suspended sediment concentrations. For this reason, drawings are sometimes few demonstrative, especially when suspended sediment concentrations are low. Only the high water situations will be shown. However, similar results can be observed on the low water situation (Brenon, 1997). 3D simulations with or without salinity gradients will be compared. In the simulations without salinity gradients, the salinity is chosen to be constant in the whole estuary.

Mean river flow, spring tide. For a mean river flow and the ‘reference set’ of parameters (see ‘Conditions of simulation’), the location of the turbidity maximum is close to the salinity front. Moreover, the location of the turbidity maximum is similar in 3D simulations with or without salinity gradients (Figure 8). This result confirms the large tidal role on the turbidity maximum behaviour and minimizes the role of density gradients. Nevertheless, the salinity gradients act on the turbidity maximum concentration. The highest suspended sediment concentrations are simulated with the 3D model when salinity gradients are accounted for (Figure 8). The major effect of salinity gradients is to maintain particles in the estuary and to concentrate these particles around the centre of the turbidity maximum. A similar conclusion had been drawn for the Loire estuary (Le Hir, 1997).

In this simulation, the location of the turbidity maximum seems to be mainly due to tidal pumping, while salinity gradients modify the structure and increase the concentrations of the turbidity maximum (the near bottom landward residual flow prevents the particle spreading off the estuary). These results have to be confirmed for different river flows and various sediment characteristics.

Variation of the river flow. For low river flow, concentrations of the turbidity maximum are higher when salinity gradients are accounted for in 3D simulations (Figure 9). This result confirms that salinity gradients act in maintaining particles in the estuary. The ‘tidal’ turbidity maximum, simulated without salinity gradients, is located upstream of the salinity front, which is the upper limit of the landward residual bottom flow. The salinity gradients also seem to act in stretching the ‘tidal’ turbidity maximum towards the salinity front: the turbidity maximum, simulated with all forcing, extends a little more downstream than the ‘tidal’ turbidity maximum (Figure 9). Both accumulations, due to the tide or to salinity gradients are involved in the turbidity maximum formation. The ‘tidal only’ turbidity maximum seems to explain a large part of the formation of the resulting turbidity maximum while the density gradients act in maintaining particles in the estuary (thus, increasing the suspended sediment mass) and in stretching the turbidity maximum downstream, towards the salinity front.

For a high river flow, concentrations are very low. Therefore, it is difficult to determine precisely what
is the relative influence of hydrodynamic conditions and of density gradients on the turbidity maximum behaviour. The model has been run for such a river flow and the results of the latter simulations (low and mean river flow) are not invalidated (Brenon, 1997).

*Variation of the sediment behaviour.* In order to confirm the effect of salinity gradients on the turbidity maximum, runs have been performed with different values of the settling velocity. Initially, this parameter has been decreased to 0·5 mm s\(^{-1}\). Then, the concentrations are low and the location of the centre of the turbidity maximum cannot be precisely determined. Anyway the action of salinity gradients in maintaining particles in the estuary is largely effective here, and the turbidity maximum is much more concentrated when density gradients are taken into account (Figure 10).

When the settling velocity has been increased to 2 mm s\(^{-1}\) particles settle very quickly and remain naturally in the estuary. Thus, concentrations are not very different in simulations with or without salinity gradients and the turbidity maximum is located upstream of Honfleur and Tancarville.
the salinity front (Figure 11). The ‘tidal’ turbidity maximum seems to be stretched up to the salinity front under the influence of salinity driven circulation.

Others simulations have been run for different sediment characteristics: especially the critical shear stress has been modified (Brenon, 1997). The results confirm the effect of salinity gradients on the turbidity maximum behaviour, as summarized in the next section.

**Synthesis on salinity gradients effect**

The turbidity maximum simulated with the 3D model without salinity gradients is, in terms of location, very similar to the turbidity maximum simulated with all forcing in the 3D model. This result implies a dominant role of tidal pumping.

Nevertheless, the salinity gradients influence the turbidity maximum behaviour. Their major effect is to maintain particles in the estuary. Concentrations of the turbidity maximum simulated with salinity gradients are higher than those of the turbidity maximum simulated without salinity gradients (Figure 12). Their second effect is to stretch the turbidity maximum towards the salinity front. Three cases can be distinguished (Figure 12). In a first case [case 12(b)],

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**Figure 9.** (a) Salinity profile, location of the turbidity maximum for a simulation, (b) with density gradients, (c) without density gradients (kg m\(^{-3}\)). 3D simulation during spring tide, at high water and for a low river flow (200 m\(^{3}\) s\(^{-1}\)).
the ‘tidal’ turbidity maximum and the salinity front are located in the same place. Thus, the resulting turbidity maximum is strengthened there. For the Seine estuary, this situation is reproduced for a mean river flow and the ‘reference’ set of parameters. In a second case [case 12(c)], salinity gradients are located downstream of the ‘tidal’ turbidity maximum. Therefore, the resulting turbidity maximum is stretched downstream. This is the case when the settling velocity is increased, due to the upstream motion of the ‘tidal’ turbidity maximum. In a third case [case 12(d)], inversely to the second one, salinity gradients act in stretching the ‘tidal’ turbidity maximum upstream. It should be noted that the location of the salinity front and induced sediment patterns is independent of the sediment behaviour, whereas the tidally-induced turbidity maximum is dependent on sediment patterns characteristics.

Figure 10. (a) Salinity profile, location of the turbidity maximum for a simulation, (b) with density gradients, (c) without density gradients (kg m$^{-3}$). 3D Simulation during spring tide, at high water, for a mean river flow, $W_s=0.5$ mm s$^{-1}$. 

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These results can be compared to the behaviour of the turbidity maximum in the Gironde estuary (France), where the turbidity maximum location is also related to the interactions between the salinity gradients and the ‘tidal’ turbidity maximum. After observations, authors (Allen et al., 1980) consider that salinity gradient effects dominate for high river flow, while, due to tidal pumping, the turbidity maximum moves upstream of the density gradients for a low river flow. According to our computations in the Seine estuary, where the tidal range is higher, the salinity gradient effects should remain secondary even for high river discharge.

**Conclusion**

Despite simplified sedimentological formulations and without any density gradient, the turbidity maximum
of the Seine estuary has been reproduced during spring tide with a depth-integrated sediment transport model. This result confirms the large role of the non-linear effects of tidal pumping on the turbidity maximum behaviour. The sediment characteristics (settling velocity, critical shear stress) can modify the location and concentration of this tidally-induced turbidity maximum. In addition, a functional link between deposits and turbidity maximum is highlighted: the location and concentration of suspended sediment is related to the location of possible deposits in the area on neap tide. The use of a three-dimensional model shows that salinity gradients mainly act in maintaining the fine sediment in the estuary but also in stretching the turbidity maximum in the direction of the salinity front.

Using these results obtained with the depth-integrated and three-dimensional models, processes influencing the turbidity maximum formation can be identified and classified (Figure 13). The asymmetric tidal wave propagation is characterized by a stronger flood (compared to the ebb currents) and a longer high water slack than the low water slack. This induces a tidal pumping of particles upward, until a decrease of the tide amplitude in the upper estuary where the river flow dominates: a 'dynamical' turbidity maximum is generated by this way. These tidal mechanisms are dependent on the river flow, the sediment behaviour (which has an important role on the concentration and on the location of sediment patterns) and on the bathymetry (which influences the tidal propagation and the location of deposited sediment patterns). Salinity gradients, which are only related to the river flow and the bathymetry, act on suspended sediment patterns by the location of the salinity front and by the influence of the induced gravitational circulation. These mechanisms generate a 'salinity-induced' accumulation of particles, which is free of the sediment behaviour. The turbidity maximum is the result of the non-linear superposition of both accumulations.

The present study is not exhaustive. It could be improved by taking into account consolidation in the 3D model, marine sediment input or wave effects. The wave resuspension acts in supplying particles from mud-banks to the turbidity maximum. The sensitivity analysis has to be carried on by using more sophisticated formulations to express sedimentological processes. Especially, a formulation of the settling velocity according to the concentration, the salinity and the turbulence could be introduced in order to simulate flocculation and deflocculation. Finally, but not only, the classification of processes influencing the turbidity maximum behaviour could be compared by
similar investigations to others estuaries, macrotidal or not.

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