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Improvements in 3D sediment transport modelling with application to water quality issues

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***Abstract*— A new vertical scheme has been developed to represent suspended sediment transport processes in the TELEMAC-3D model. In comparison to the existing diffusion scheme, the newly developed advection/diffusion scheme is proved to be more robust. Three large scale test cases have been provided to assess the model accuracy in the presence of tidal flats and its ability to cope with distorted mesh elements. Finally, the 3D model has been applied to represent cohesive sediment transport processes and associated water quality issues in estuarine conditions.**

I. Introduction

In complex situations, involving recirculating flows and stratification effects which are typically encountered in estuarine conditions, 3D turbulent flow models are required in order to capture the vertical mixing processes and turbulent flow structure which determine the suspended sediment transport rates.

A fine vertical mesh resolution is generally required in order to represent accurately sediment concentration and velocity gradients near the bed. In TELEMAC-3D, the distortion between the vertical and horizontal scales leads to divergence of the existing diffusion scheme when dealing with large time steps and large scale domains. A new fully implicit vertical scheme has therefore been developed in order to solve simultaneously the vertical settling and diffusion terms which are, in most applications, the dominant terms in the 3D sediment transport diffusion equation. The efficiency and robustness of the new scheme has been assessed in comparison with the existing diffusion scheme.

A number of theoretical and numerical difficulties arise when dealing with sediment transport, which are highlighted in Section 2. The newly developed sediment transport model is presented in Section 3. Three validation test cases are presented in Section 4, to assess the accuracy and efficiency of the new scheme when dealing with distorted mesh elements.

The final Section(Section 5) presents a recent application of the 3D model to represent sediment transport and related water quality issues in an estuary.

II. 3D Modelling of Sediment Transport

A. *Sediment Transport Processes*

Sediment transport models are generally based on semi-empirical concepts which involve the classical decomposition of transport rates into bed-load and suspended load. For bed-load, the TELEMAC-3D model can be internally coupled with SISYPHE which solves the Exner bed-evolution equation (see Villaret et al., 2011). For the suspended load, the TELEMAC-3D sediment transport library can be applied to calculate the coupled flow velocity and sediment concentration profiles. It is mainly applicable to uniform sediment, cohesive or non-cohesive, characterized by the mean grain size, density and settling velocity as well as sediment bed related properties such as bed porosity.

B. *Governing equations*

The vertical profile of the suspended sediment concentration (SSC), treated as a passive scalar, can be determined by solving a classical transport/diffusion equation, with an additional vertical advection term to represent the effect of the gravitational settling velocity.

$$\frac{\partial c}{\partial t} + \frac{\partial u_j c}{\partial x_j} - w_s \frac{\partial c}{\partial x_3} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_c}\frac{\partial c}{\partial x_j}\right), \quad j = 1,2,3 \tag{1}$$

with $c = c(x_j, t)$ the SSC, $w_s > 0$ the vertical-settling sediment velocity and σ_c the turbulent Prandtl number. At the outlet, the normal gradients of the concentration are set equal to zero.

At the free surface, the net vertical sediment flux is set to zero:

$$\left(\nu_t \frac{\partial c}{\partial z} + w_s c\right)_{z=Z_s} = 0 \tag{2}$$

At the bottom, a Neumann type boundary condition is specified, in which the total vertical flux equals the net erosion (E) minus deposition rate (D):

$$\left(\nu_t \frac{\partial c}{\partial z} + w_s c\right)_{z=Z_b} = D - E \quad (3)$$

In the case of non-cohesive sediments, the erosion flux can be expressed in terms of an 'equilibrium' reference concentration, and the deposition flux is calculated as the product of settling velocity w_s and near bed concentration C_0.

In the case of cohesive sediments, the erosion and deposition fluxes are calculated based on the Partheniades (1965) and Krone (1962) empirical formulae:

$$E = M\left(\frac{\tau_0 - \tau_{ce}}{\tau_{ce}}\right) \;\; if \;\; \tau_0 > \tau_{ce}$$

$$D = w_s C_0 \left(\frac{\tau_{cd} - \tau_0}{\tau_{cd}}\right) \;\; if \;\; \tau_0 < \tau_{cd} \quad (4)$$

Where τ_0 is the bed shear stress, τ_{ce} and τ_{cd} are respectively the critical bed shear stress for erosion and deposition, and M is an empirical parameter defining the erosion rate.

The bed evolution (Z_b) is obtained from the sediment mass conservation as follows:

$$C_b \frac{\partial Z_b}{\partial t} = D - E \quad (5)$$

for a uniform bed of concentration C_b.

C. Numerical difficulties

Assuming the passive scalar hypothesis, the transport equation for the sediment concentration is similar to a tracer, except for an additional settling term. Equation (1) can be solved using the finite element library available in TELEMAC, but special treatment is required to account for the additional vertical settling term.

The main difficulties encountered arise from :

- Sediment concentrations are exponentially larger near the bed which leads to potentially very large vertical gradients. A refined grid may therefore be required to represent the concentration gradients accurately.
- Boundary conditions need to be applied at the bed level, which numerically is located somewhere between the bottom plane the first mesh plane above the bed.
- Possible inconsistency between the schemes used for hydrodynamics (turbulent and mean flow) and sediment transport.

The distortion of the mesh, as measured by the ratio of the vertical mesh to the horizontal mesh, can lead to unrealistic restriction of the time step when dealing with large scale applications. A robust, mass conservative and efficient treatment of the settling and vertical diffusion term is therefore an important requirement.

III. Vertical Diffusion/ Settling Algorithm

Within the restrictions of the shallow water framework $\partial/(\partial x, \partial y) << \partial/\partial z$), the downward settling and upward vertical diffusion terms are the most important terms of the 3D suspended sediment transport equation. These two terms govern the sediment vertical distribution and transport rates.

Both diffusion and settling terms preferably require simultaneous treatment since they should balance. This avoids the possibility of introducing numerical instabilities and thus allows for a longer computational time step.

A. Existing Finite Element Diffusion Scheme

The settling term was previously treated in the diffusion routine by adding the settling term ($W_S C$) to the vertical turbulent diffusion term $\gamma_t(\partial C/\partial z)$. The diffusion matrix was therefore transformed into a non-symmetric matrix, as explained in Le Normand (2002).

B. New Advection-DiffusionScheme

The idea of the new advection-diffusion scheme is to modify the existing advection scheme in order to include the effect of both vertical settling and diffusion:

$$\frac{\partial C}{\partial t} = \frac{\partial (W_s C + \gamma_t \frac{\partial C}{\partial z})}{\partial z} \quad (6)$$

This is done after horizontal and vertical advection of the water and SSC, using the transformed sigma mesh. Only the horizontal diffusion term is now included in the SSC diffusion terms (i.e. the vertical diffusion is switched off).

The vertical settling and diffusion terms are discretized using a finite volume implicit scheme, where the settling term is up-winded and the diffusion terms are space-centred and calculated at the mid-grid level.

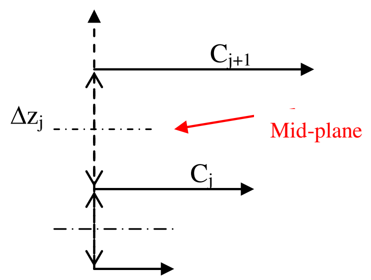

Figure 1. Vertical grid at the bed

The resulting advection-diffusion formulation is written in the form of a tridiagonal matrix as:

$$a(j)C(j-1)+b(j)C(j)+c(j)C(j+1)=d(j) \quad (7)$$

where C is the SSC and the matrix diagonals a, b and c are:

$$a(j)=-\alpha(j)\,dt \quad (8a)$$

$$b(j)=1+\left(\frac{W_s(j)}{dz(j)}+\alpha(j)+\beta(j)\right)dt \quad (8b)$$

$$c(j)=-\left(\frac{W_s(j+1)}{dz(j)}+\beta(j)\right)dt \quad (8c)$$

The coefficients α and β are weighted eddy diffusivity(ε_v) terms, calculated as:

$$\alpha(j)=\frac{\varepsilon_v(j-1)}{dz(j).dz_a(j)} \quad (9a)$$

$$\beta(j)=\frac{\varepsilon_v(j)}{dz(j).dz_b(j)} \quad (9b)$$

With the distance weightings dz_a , dz_b and dz written as:

$$dz_a(j)=z(j)-z(j-1) \quad (10a)$$

$$dz_b(j)=z(j+1)-z(j) \quad (10b)$$

$$dz(j)=\frac{dz_a+dz_b}{2} \quad (11)$$

Equation (7) is solved efficiently using a direct tridiagonal matrix solver using a classical double sweep method.

C. Position of the numerical bed

The "*numerical bed level*" $\delta=\delta(x,y,t)$ corresponds to the elevation where the boundary conditions are applied. In TELEMAC-3D, δ is assumed to be proportional to the first grid point above the bed (j = 2), $\delta=\Delta z_1/\beta$. The position of the *numerical bed level* depends on the details of the numerical discretization.

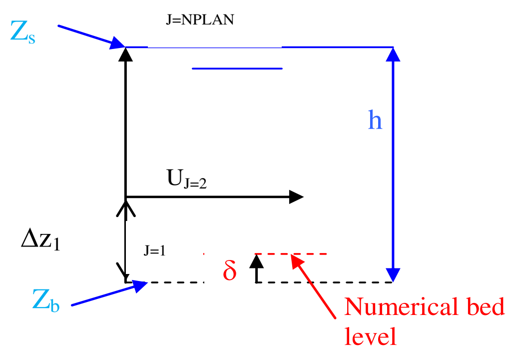

Figure 2. Vertical grid at the bed

1) Hydrodynamic model

The second plane elevation (j=2) is assumed to be in the logarithmic region:

$$\frac{\left|\overrightarrow{U_2}\right|}{u_*}=\frac{1}{\kappa}Log\left(\frac{\Delta z_1}{z_0}\right) \quad (12)$$

Where u* is the friction velocity, κ = 0.4, the Karman constant and z_0 = $k_s/30$, with k_s being the Nikuradse bed roughness. The friction velocity u* is fed into the boundary condition:

$$\left(\nu_t\frac{\partial U}{\partial z}\right)_{Zb}=AU_1+B \quad (13)$$

where $A=u_*^2/U_1$, and B=0.

Different turbulence models are available in TELEMAC-3D. In the mixing length model (OPTION 1 in visclm.f) the eddy viscosity coefficients are calculated at the mid grid level.

Near the bed, the eddy viscosity profile increases linearly with distance from the bed in order to retrieve classical turbulent boundary layer concepts:

$$\nu_t=\kappa u_* z \quad (14)$$

A linear discretization of (13) leads to : $U_2-U_1=2\frac{u_*}{\kappa}$. Using Equation (12), the velocity at the first plane is then:

$$\frac{U_1}{u_*}=\frac{1}{\kappa}Log\left(\frac{\Delta z_1}{e^2 z_0}\right) \quad (15)$$

The 'numerical' bed level for the momentum equation is therefore located at $\delta=\frac{\Delta z_1}{e^2}$.

2) Suspended sediment transport model

In the new advection-diffusion scheme, the thickness of the near bed cell where the boundary conditions are applied is $\Delta z_1/2$, such that the bottom concentrations are calculated at the center of the cell. The position of the numerical bed level is therefore:

$$\delta=\frac{\Delta z_1}{4} \quad (16)$$

D. Finite Element or Finite Volume schemes

Possible inconsistencies when using different schemes for the flow and sediment can lead to erroneous results. Ideally the same scheme should be used to discretise both the hydrodynamic and sediment flux divergence terms. This alleviates the possibility of different fluxes being evaluated at inconsistent points and with different orders of truncation error.

IV. TEST CASES

In order to test the ability of the new scheme to cope with meshes with distorted aspect ratios (h/L = O(10^{-3}), all the test cases presented here were performed on large, estuary scale computational domains. The geometry used for the tests was a 50 km straight long flume with the origin at its centre. The horizontal element size for this mesh varies from 10 m to 100 m. In the last application (tilting flume) the width of the flume was reduced from 5 km down to 1 km to reduce CPU time. The water depths were generally <10 m and varied depending on the particular test case.

A. Rouse Profile

This first test case represents a simple steady uniform flow with a constant water depth of 10 m. A fixed concentration is imposed at the channel entrance. The erosion and deposition fluxes are set to zero to prevent any bed evolution. The objective is to assess the model accuracy in comparison to the classical Rouse concentration profile:

$$\frac{C}{C_{ref}} = \left[\frac{h-z}{h-Z_{ref}} \cdot \frac{Z_{ref}}{z} \right]^R \quad (17)$$

where $R = w_s/(\kappa u_*)$ is the Rouse number. The near bed reference concentration C_{ref} is defined at a distance Z_{ref} from the bed.

In order to reach uniform flow conditions, the flume is inclined to be parallel to the free surface slope. Under equilibrium conditions, the balance between friction and hydrodynamic pressure gradient leads to $u_* = \sqrt{ghI}$, where I is the free surface slope, and g the gravity. For a Nikuradse friction law (k_s = 1 cm), the friction velocity calculated by the 3D model is u_*=4.34 cm/s. The resulting channel slope (approximately equal to the free surface slope) is 1/50000.

Once the concentration profile is established, the model results are extracted at one point downstream of the flume. Concentration profiles are compared to the analytical Rouse concentration solution, where the reference concentration is taken at the first plane above the bed (j = 2).

The model is run with 21 horizontal planes, equally spaced with a time step of 10 to 100 s. The CPU time quoted in Table 1 have been obtained on a PC using a single Intel i3 processor. The total duration of the simulation is 50000 s.

To assess the model accuracy, we calculate the average geometric standard deviation (AGD) (cf. Wu et al. 2009). The results are summarized on Table 1 below.

TABLE I. ROUSE CONCENTRATION PROFILE- COMPARISON BETWEEN THE DIFFUSION AND CONVECTION SCHEMES IN TERMS OF ACCURACY AND EFFICIENCY (DURATION = 80 000S). *FOR SCHEME (1), THE MODEL WAS RUN WITHOUT HORIZONTAL DIFFUSION FOR THE TRACER. THE EFFECT OF HORIZONTAL DIFFUSION WAS FOUND TO INDUCE A MASS ERROR.

Numerical scheme	Dt (s)	CPUTime (mn)	Mass loss (Kg)	Accuracy (AGD)
Diffusion (0)	10s 100s	47mn Divergence	2659 -	1.20 -
Advection-diffusion (1)*	10s 100s	21mn 1mn 38	0.48 0.014	1.20 1.20

The closest AGD is to 1, the more accurate the model results are. For a perfect fit, AGD = 1. Both the existing diffusion and new advection-diffusion schemes are able to reproduce accurately the concentration distribution (AGD = 1.23). However, the new advection-diffusion scheme was found to be as accurate and more rapid, more robust, and able to cope with time steps (x10) greater than with the existing diffusion scheme.

B. Mass conservation on tidal flats

The objective of this second test case is to assess the new vertical settling algorithm and existing diffusion scheme with respect to mass conservation on tidal flats (wetting and drying of mesh elements).

The bathymetry of the flume is -10m MSL across most of the domain, with a linear slope on the eastern end of the domain rising from -10 m MSL to +2 m MSL over a distance of 10 km.

An open boundary was specified at the western end and forced using a sinusoidal tide (1 m amplitude, 0 m MSL mean level, 12 hour period). The initial boundary level was set to 1m in order to make the test harder for the model (i.e. a 1 m wave propagates into the domain at the start of the run).

A uniform SSC of 300 mg/l was initialised throughout the domain in the area to the east of 15 km (i.e. in the bed slope region). This sediment is too far from the boundary to pass out of the domain in the modelled timeframe, therefore boundary fluxes can be ignored in the mass conservation checks.

Here we used the TELEMAC method (OPTBAN=1) for the treatment of tidal flats, which allows to solve the momentum equation on dried or semi-dry elements. We introduce an additional limitation to reduce the erosion rates when the water depth is less than a minimum value of 0.1m.

A settling velocity of 1 mm/s was prescribed. Erosion was parameterised using a critical shear stress for erosion of 0.05 N/m^2 and an erosion parameter of M=5.0 10^{-4} kg/m^2/s. Deposition was assumed to be constant. The concentration of the uniform mud layer is set to 500 g/l.

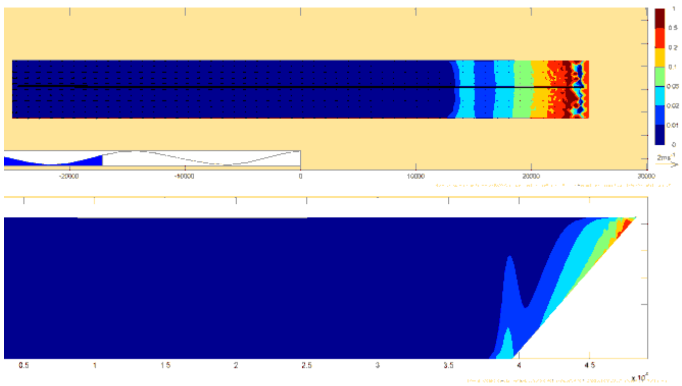

Figure 3. Tidal flats test case – Concentration along the cross section (New Advection-Diffusion scheme (1) – Dt = 2.5s)

Model results are summarized in Table 2. The new vertical advection-diffusion scheme is found to be remarkably stable and mass conservative even when using relatively large time steps, whereas the previous diffusion scheme necessitates a drastic reduction in the time step.

TABLE II. TIDAL FLATS - MASS LOSS AFTER ONE DAY

Numerical scheme	**Dt (s)**	**CPU Time (mn)**	**Mass loss (Kg)**
Diffusion (0)	5 10 50	Divergence Divergence Divergence	- - -
Advection-diffusion (1) **	5 10 50	50 mn 27 mn 5mn30s	-1.7 0.54 -7.6

**The horizontal diffusion terms have been included in scheme (1)

C. Tilting flume

The objective of this last test case is to assess the robustness of the new scheme under very drastic flow conditions using rapidly varying, high depth averaged flow velocity (up to 1.5 m/s) including tidal flats.

In order to reduce CPU time, we use a narrower flume (1 km wide), the same length as in previous test cases (50 km long). The flume is now tilted around its axis, with maximum amplitude at its extremity (+/-25000 m) of +/-3 m. The scale of the model and the period of the tilting motion was chosen in order to represent tidal motion. Also to reduce the CPU time, the number of 3D horizontal planes was reduced to 10.

As in previous test cases, the bed comprises mud, with similar characteristics : τ_{ce}= 0.05 N/m^2, M=5.0 10^{-4} kg/m^2/s. C_{bed}= 500 g/l. The settling velocity is still w_s= 1 mm/s and the critical shear stress for deposition is τ_{cd} =1000 N/m^2 (i.e. constant deposition).

This test case is hydrodynamically unstable due to the large vertical accelerations that are present. This necessitates a time step of less than 2.5 s in order to avoid non-physical, parasitic oscillations of the free surface during the descending phase when peak depth averaged flow speeds in shallow water reach 1.5 m/s.

Starting from a horizontal bed, with a water depth of 2 m, the bed is first tilted over a 3 hour period so that it is gradually lowered on the west side and raised on the east to the maximum offset from the horizontal start position of +/-3 m at each end. The bed then remains in this position for 12 hours allowing the water to flow to the west end. It is then tilted back in the opposite direction over a period of 6 hours until it is at the same slope angle in the opposite direction. A longitudinal cross section of both friction velocity and concentration fields during the first 12 hours is shown on Figure 4 below.

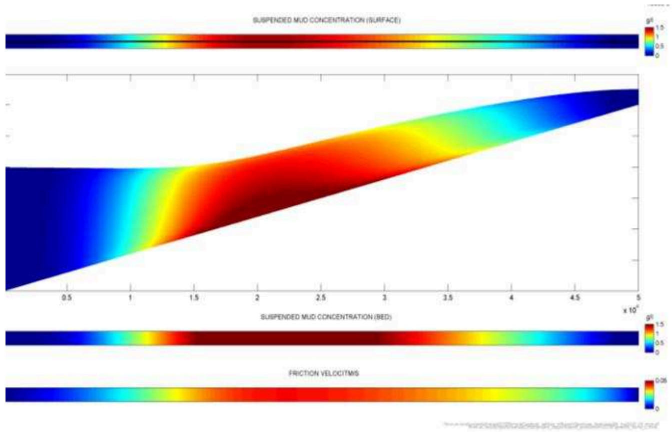

Figure 4. Tilting flume test case – Concentration in the cross section (New advection-diffusion scheme (1) – Dt = 2.5s)

Even with a time step of 5s or more, the vertical advection-diffusion scheme (1), remains stable but the mass loss increases. For a time step of 2.5s, the mass error is 250 kg, which is still only a small portion of the total mass in suspension (>100,000,000 kg).

The previous diffusion scheme remains unstable for a time step of 2.5s. For 1 s, both CPU time and mass error are larger when using the existing diffusion scheme. Results are summarized in Table 3 below.

TABLE III. TILT FLUME EXPERIMENT - MASS LOSS AFTER ONE DAY (108 000ΔT, WITH ΔT=5S).

Numerical scheme P)	**Dt (s)**	**CPU Time (min)**	**Mass loss (Kg)**
Diffusion (0)	5 2.5 1	Divergence Divergence 33mn	- - -489
Advection-diffusion (1)**	5 2.5 1	4mn50s 9mn 30s 23	-1816 -240 -297

**The horizontal diffusion terms have been included in scheme (1)

V. ESTUARINE APPLICATION

The stability and mass conservation of the previously described new scheme for vertical settling and diffusion of sediment implies that it is applicable to a large scale model of a real estuary. This section describes a test case of the Mersey Estuary, UK.

A. Presentation of test case

The Mersey Estuary (north-west England, UK) stretches for a distance of about 40 km and 5 km width (Figure 5). This narrow estuary is characterised by the presence of a meandering channel and extensive intertidal sand and mud flats.

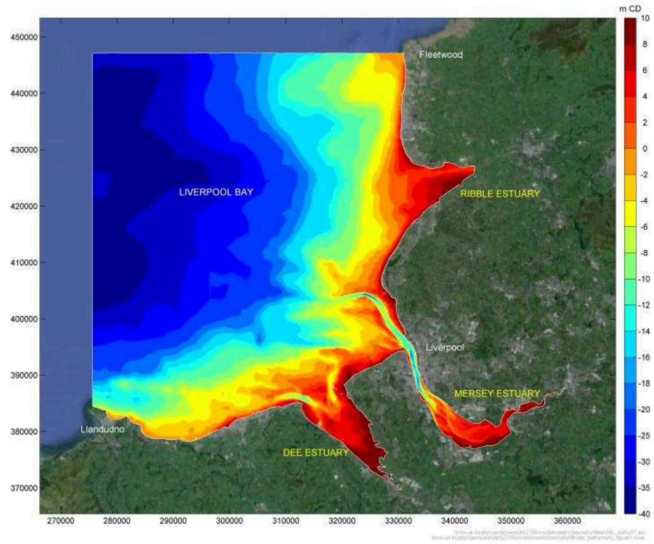

Figure 5. The geometry used for the Mersey model (Bed levels are referenced to Chart Datum at Liverpool)

Past industrial activity means that the sediments in the Mersey are highly contaminated with heavy metals and Polycyclic Aromatic Hydrocarbons (PAHs). Dredging of this material is tightly regulated, requiring the material to be removed to designated landfill sites making it costly and time-consuming. Water Injection Dredging (WID) is a more efficient method but introduces the contaminants back into the water column, thus raising environment concerns.

As part of development works in the mouth of the estuary , a study was undertaken to assess the potential impact and viability of using WID. To this end, a fully coupled 3D hydrodynamic-mud-contaminant model was set up which is described here. The geometry used for the modelling is shown in Figure 5.

B. Sediment processes and parameterisation

1) Suspended sediments

Settling of the suspended mud was parameterised in the model using a recently implemented flocculation formula (Soulsby et al, 2013). In this formula the median settling velocity is dependent upon the time varying diameter of the particle aggregates, which is in turn controlled by the degree of turbulence and the SSC.

Suspended mud concentrations in the Mersey often exceed 1 g/l above which the effect of the density of the mud in suspension starts to become comparable to the effect of the salinity. The suspended mud therefore contributes to the buoyancy effect and introduces additional damping of the vertical diffusivity. This mechanism is included in the model using the formulation of Munk & Anderson (1948).

The SSC in the model was initialised to zero everywhere. The time taken for the concentrations to spin up was observed to be of the order of two or three tidal cycles.

C. Bed deposits

A two layer bed model was used for modelling the bed exchange processes in the model. In the bed model, the uppermost sediment layer represents the mobile sediment that is picked up, advected and deposited during each tide. Deposition is assumed to occur continuously into this top layer by setting the critical shear stress for deposition, τ_{cd} =1000 N/m^2. Net erosion occurs in the model if the erosion flux from the bed is greater than the deposition flux. For the top bed layer, a critical shear stress for erosion of 0.2 N/m^2 was set everywhere. When this threshold is exceeded by the flows, erosion is initiated and material erodes from the top bed layer at a rate predefined by the erosion rate constant (Partheniades, 1965).

The erosion rate constant is a key calibration parameter and determined iteratively to be 1.10^{-4} kg/m^2/s (set equal for both bed layers). This value is within the range generally found in the literature (Whitehouse et al., 2000).

The underlying bed layer represents the in-situ sediment that has experienced previous consolidation and bed armouring. The critical shear stress for erosion for this layer was parameterised spatially with values equal to the tidally averaged bed shear stress for a mean spring tide, then limited to at least 0.4 N/m^2.

The dry density for both of the bed layers was nominally assumed to be 500 kg/m^3. More precise estimates of density for each layer is considered unfounded since in reality the lower layer is likely to be entrained with sand.

At the start of the model run, mud deposits were initialised everywhere except in shallow areas higher than -1 m CD in the offshore area. These regions are predominantly sandy and therefore unlikely to be a source of much fine sediment. In the other areas, the upper and lower bed layer thicknesses were set to 0.01 m and 0.2 m respectively.

1) Dredging of contaminated sediment

Mud released by Water Injection Dredging (WID) was included in the model as a near bed point source with a release rate of 113 kg/s located approximately in the centre of the region to be dredged (Seaforth Triangle in Figure 6). For realism, the dredging was assumed to occur when the water level was above MSL so as to allow enough depth for the dredger to operate.

Much of the modelled released mud was found to form a density current which flowed into the outer dredged area that had already been excavated. Flushing of the outer area was therefore also simulated for a period of 2 hours each ebb tide. In order to capture the detail of the plume a mesh resolution of 5 m was used within Seaforth Triangle. Elsewhere within the estuary the mesh elements were approximately 100 m or smaller. Offshore the element size increased gradually up to a maximum element size of 3 km in Liverpool Bay.

Contaminants released during dredging were modelled using *partition coefficients* derived from laboratory experiments. A partition coefficient (K_d) describes the equilibrium ratio of contaminant concentration between their adsorbed (C_s) and dissolved (C_w) phases.

$$K_d = \frac{C_s}{C_w} \quad (18)$$

The rate of transfer of contaminant between phases was modelled by assuming that the equilibrium represented by K_d would be reached within a period of approximately an hour (T_{eq}=3600 s). Assuming exponential decay, at each computational time step (dt=2 s) the exchange (Q_c) of contaminant from dissolved to adsdorbed phase (negative if in the other direction) was calculated as:

$$Q_c = \frac{C_{eq} - C_s}{T_{eq}.\exp(-1)} dt \quad (19)$$

Where C_{eq} is the long term equilibrium adsorbed concentration, determined from the total contaminant concentration (C_{tot}=C_s+C_w) as:

$$C_{eq} = C_{tot}\left(1 - \frac{1}{K_d+1}\right) \quad (20)$$

In order to determine the fate of the released contaminant, the background mud and contaminated mud were treated as separate tracers in the model, but the effect of the mud on the 3D processes (e.g. buoyancy and flocculation) was modelled in terms of the total mud (background + released). This method allowed mixing of the released contaminant with background levels, but also allowed the fate of the released contaminant and mud to be determined.

The described model was run for a period of 4 weeks. The bed sediments were then scaled to the full period of dredging (10 weeks) so as to represent the full dredged volume of 375,000 m².

Figure 6. Locations of the proposed Water Injection Dredging (Seaforth Triangle) and the sediment flux measurements (ADCP transect) in the Mersey Narrows.

D. Main results

1) Mud model calibration and validation

The results from the mud transport model were calibrated against ADCP flux measurements, using the SEDIVIEW method (Wither et al, 1998) at a transect in the Narrows, the location of which is shown in Figure 6. Sediment fluxes were collected throughout a spring tide in November 1995 and the comparison with the modelled fluxes is shown in Figure 7. As can be seen the model reproduces the observed fluxes to a good degree of accuracy throughout the tidal cycle.

As a validation exercise, the model was re-run for a neap tide in January 1996 for which similar measurements were also available, shown in Figure 8. This indicates that the same model calibration is valid for different periods and tidal ranges.

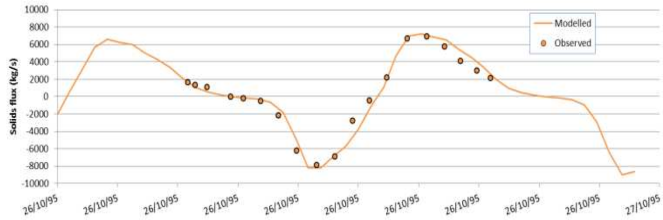

Figure 7. Modelled and observed sediment fluxes for a spring tide

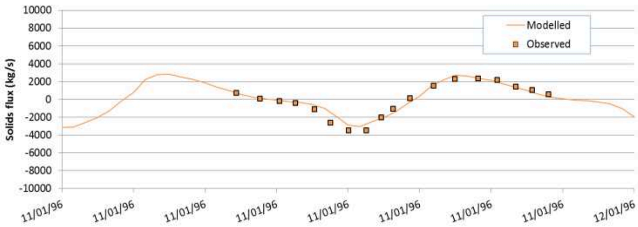

Figure 8. Modelled and observed sediment fluxes for a neap tide

2) Preliminary contaminant results

As part of the study, numerous contaminants including heavy metals and PAHs were modelled which are described in detail elsewhere (HR Wallingford, 2014). Just one PAH will be described here which is Naphthalene. This contaminant was modelled with a partition coefficient, K_d=2.2 and a source concentration of 119 µg/kg.

The results show that there is a tendency for the released plume to be carried offshore, with 65% of the mud ending up spread thinly over a wide area outside the mouth. About 30% of the material is deposited within the Narrows and the remaining material was deposited further upstream in the estuary.

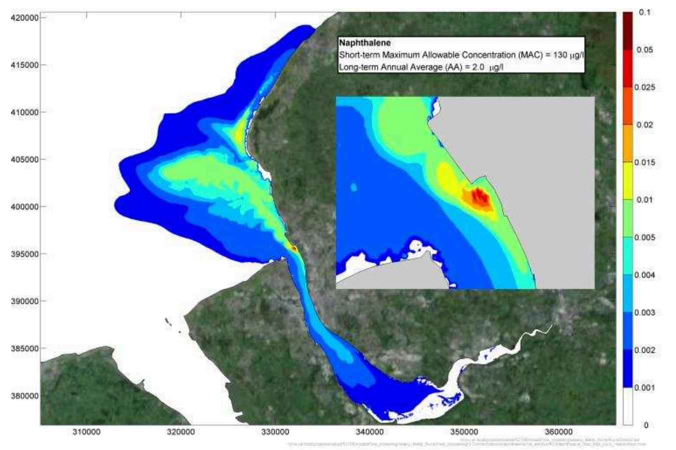

Figure 9. Maximum released Naphthalene concentration in dissolved phase, near surface waters, over the 4 week simulation

The maximum near surface concentrations of dissolved Naphthalene modelled over the 4 week simulation are shown in Figure 9. Comparing these concentrations against Environmental Quality Standards (EQS) for marine waters as defined under the EU Water Framework Directive, it is found that the maximum predicted dissolved concentration of Naphthalene which might occur during the dredging activity will not exceed the short term Maximum Allowable Concentration (MAC=130 µg/l) and the predicted mean concentrations are an order of magnitude below the long term Annual Average (AA=2.0 µg/l).

Figure 10 shows the concentration of Naphthalene in the bed deposits, ignoring deposits less than 1 mm thick. Due to the strong flows in the estuary mouth, the released mud and associated contaminants are dispersed over a wide area. Hence the increases in bed contaminant concentration are relatively low, especially away from the point of release.

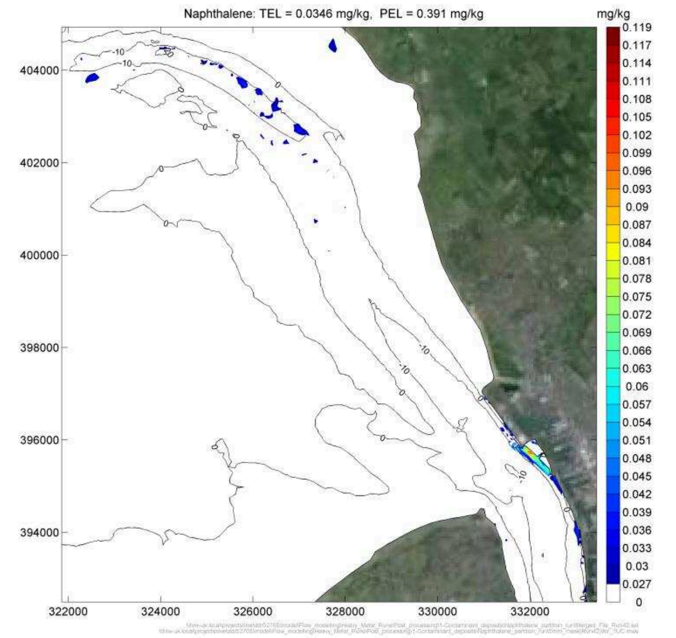

Figure 10. Increase in Naphthalene concentration in fine sediment deposits associated with proposed WID, scaled up to full period of dredging.

For Naphthalene, the Threshold Effect Level (TEL) advocated by the UK Environment Agency, below which there is considered low risk to benthic organisms, is stated as being 0.0346 mg/kg. The TEL is found to be exceeded in only a small number of localised areas, primarily in the bed deposits located within 100 m of the dredger.

VI. CONCLUSIONS

A new numerical scheme has been developed for TELEMAC3D for modelling the vertical sediment processes of settling, vertical diffusion and exchange with the bed. A range of difficult test cases show that the new scheme offers improvements in terms of the stability, mass conservation and model run-time.

The new scheme has also been applied to a fully coupled hydrodynamic-mud-contaminant model of the Mersey Estuary to assess the likely impacts of Water Injection Dredging on the ambient concentrations of a range of contaminants. The mud model was calibrated and validated to a good degree of accuracy against available in-situ measurements of discharge and sediment flux obtained in 1995-6. Preliminary results suggest that the model is valuable for providing supportive information to Environmental Impact Assessments into the dispersion of dredged muds and their associated contaminants.

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