Conference Paper, Published Version

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Abstract— Previous attempts to model sediment transport and morphodynamics in complex estuarine conditions have been limited by the use of simplifying methods in order to reduce computational cost. Thanks to tremendous progress in numerical methods and extensive use of parallel processors, the open source finite element Telemac system (release v6p1) is applied to represent the medium term bed evolution in the largest estuary in France, the Gironde macro-tidal estuary. After calibration, the 2D hydrodynamic model (Telemac-2d) is validated by comparison with some recent data set, combining tidal flow and velocity measurements at different locations along the estuary. For morphodynamic modeling, the effect of sand grading is incorporated into Sisyphe, in order to represent schematically the high variability in the sediment bed composition. The effect of cohesive sediments is also examined using a recently developed model of consolidation.

I. INTRODUCTION

The objective of this work is to develop a realistic morphodynamic model which can be applied to predict accurately the sediment dynamics and medium term bed evolution in the central part of the estuary, where drastic bed evolutions have been reported as a result of sand banks formation and secondary mid-channel deposit. Bed evolutions can be either due to human activities or to natural origins, and may also be attributed to dredging activities. This model can be used as an operational tool by end-users and engineers to test solutions to prevent unwanted erosion or depositions in strategic areas.

Our framework is the finite element Telemac system (release 6.1), where the 2D approach is selected as a good compromise between model accuracy and computational cost. A local morphodynamic model was previously developed for the central part of the estuary [13]. An embedded model strategy was chosen to impose the hydrodynamic boundary conditions under schematic forcing conditions, for a single neap-spring tidal cycle and constant mean flow rate. This method allows saving computational time, but induces additional uncertainties related to the treatment of boundary conditions.

Thanks to tremendous progress in the numerical method and use of parallel processors, the computational domain is here extended and represents the whole 150 km long estuary, including the Dordogne and Garonne main tributaries, while the maritime boundary conditions are now imposed at a distance of approximately 30 km from the coast line. We also include a more realistic representation of the hydrodynamic forcing (including seasonal variations in the river flow rates) and sediment transport processes (including sand grading effects, bed roughness prediction, consolidation algorithm).

We start in Part 2 with a general description of the Gironde estuary, its hydrodynamics and sediment characteristics. In Part 3, we present the coupled 2D hydrodynamic and morphodynamic models: the method of Van Rijn [11] implemented in release 6.1 is applied in order to predict the bed roughness. The advantage of this method which can be applied as an alternative to a calibration procedure for the bed friction coefficient, is to reduce the possible inconsistency between morphodynamics and hydrodynamics [15]. In Part 4, the model is applied to reproduce the effect of grain size distribution on bed evolutions and variability in the flow rate. Finally in Part 5, the effect of cohesive sediments is examined by using a recently implemented multilayer algorithm for consolidation [12]. We present here a preliminary model comparison with 5-years of measured bed evolution (1995–2000) and also with some recent data sets including velocity and turbidity measurements at different points along the estuary (September, 2009).

II. DESCRIPTION OF THE GIRONDE ESTUARY

A. *Study area*

The Gironde estuary, located southwest of France, extends from the confluence of the Garonne and Dordogne rivers to the mouth on the Atlantic coastline (Figs 1&2). Its width ranges from 3.2 to 11.3 km downstream. The Gironde can be subdivided into three parts: the upper river part, the central part and the downstream maritime part. The central part is characterized by a complex geomorphology, with different channels separated by elongated sand banks. The estuary can be classified as macro-tidal, hyper-synchronous and with an asymmetric tide (4 h for the flood versus 8 h 25 for the ebb). The ocean coast line induces a strong forcing with tidal amplitude at the mouth of the estuary ranging from 2.2 m to 5.4 m during a fortnightly spring-neap cycle. The cumulated river discharge from both rivers (Dordogne and Garonne) ranges from 50 to 2000 m^3/s. During flood events, the river flow rate becomes occasionally greater than 5000 m^3/s. The centurial average value of the fluvial flow rate reaches 1000 m^3/s, 65% of it coming from the Garonne River.

B. Hydrodynamic data

The tide propagation can be analyzed through water levels, which are measured every 5 min at nine hydrometric stations along the estuary from the Verdon station at the mouth to the harbour of Bordeaux, located 10 km upstream of the confluence between the Dordogne and Garonne rivers (Fig. 2). Measurements of flow rates are available every hour at the upstream boundary.

Velocity measurements are sparser in comparison to the water level data. For instance, ADCP velocity profiles were measured by EDF R&D in August 2006 at 3 points located along the same cross section, approximately 5 km downstream Pauillac station (Fig. 2) and at 5 points along the estuary from September to October 2009 (7 points were measured, as shown on Fig. 1, but only 5 of them were successful). Both events are used to calibrate and validate the hydrodynamic model [5].

C. Bathymetry surveys

The bed evolutions are measured through bathymetry surveys made every 5 years, since it takes about 4 years to cover the whole estuary from Bordeaux to Verdon station. As mentioned in the introduction, a better accuracy is expected in the central part of the estuary and model validation will be focused on this part. A rather coarse grid is applied in both maritime and fluvial parts, where the bathymetry will not be updated. In the central part of the estuary, morphodynamic features evolved drastically from 1994 to 2005 and more detailed bathymetric data sets are available for years 2000 and 2005. The 1995 bathymetry is used as an initial condition of the morphodynamic model whereas the 2000 data is used to compare the measured bed evolutions with model predictions. The 2005 bathymetry is prescribed.

D. Characteristics of bed material

The bed composition is highly variable in space: gravel and sand can be found at the mouth of the estuary whereas, in the tributaries, the bed channel is dominated by the presence of mud. Information concerning the bed material is generally provided qualitatively: areas of sand, mud or gravel are reported on maps (see Fig.3). At the mouth of the estuary, the median diameter of the bed material ranges within 0.25 and 0.38 mm (Port Autonome de Bordeaux, 2002).

More quantitative information on the bed composition is available in the central part of the estuary. Two measurement campaigns were performed in 2006 and in 2009 by EDF R&D. In 2006, bed samples were collected downstream of the Patiras island (see Fig. 3). Analysis of these samples reveals that 55% of the bed material is cohesive (finer than 0.063 mm) and 45% non-cohesive, with median diameter d_{50} = 0.21 mm. The second campaign provides more detailed quantitative information on the spatial variation of the bed composition. According to Boucher (2009), three types of sediment bed composition can be identified with mud only, sand only (63µm < d_{50} < 2mm) and sand mud mixtures, as shown on Fig. 2. Sand is dominant in the deeper channels, whereas the tidal banks are dominated by the presence of mud.

D. Turbidity measurements

The suspended load and related water quality parameters have been measured at various stations along the estuary (www.magest.u-bordeaux1.fr) since 2005. This yearly monitoring gives some qualitative information on the turbidity variation along the estuary as a response of seasonal variation in the river flow rates.

During the September-October 2009 survey, the attenuation of the ADCP velocity signal is interpreted in terms of turbidity level and converted in g/l using the linear relation proposed by [2] Measurements are summarized in Table 1. The turbidity level is very high upstream in the Dordogne tributary with maximum values up to 8 g/l (Point 7), and progressively reduces to less than 1.05 g/l in the central part and to less than 0.05 g/l at the mouth of the estuary (Point 1). Those observations qualitatively match the observations reported in [2]: for instance, the turbidity level at Pauillac station fluctuates with maximum values of the order of 3 g/l (July 2005).

To the authors' knowledge, no information is available on the bed load transport rates, although the presence of mega ripples and dune in this zone is an indicator of active sand transport.

Figure 1. Location map (indicating ADCP velocity measurement).

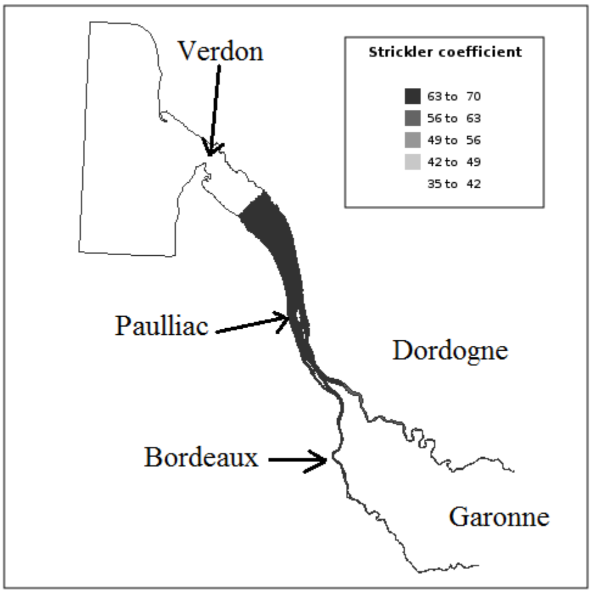

Figure 2. Large scale hydrodynamic model distribution of calibrated Strickler coefficient.

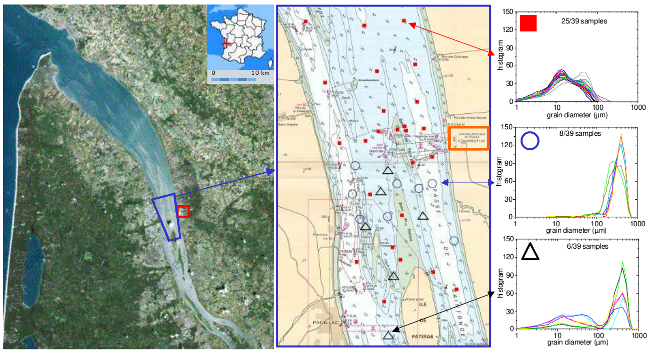

Figure 3. Sediment repartition in the central part (see location of Patiras island). The typical granulometry distribution of the three different types of sediments is shown on the right (red squares for mud only, circles for sand only, triangles for sand/mud mixture) after [1].

TABLE I. TURBIDITY MEASUREMENTS AT DIFFERENT STATIONS ALONG THE ESTUARY. A CONVERSION FACTOR OF 0.0023 IS APPLIED TO CONVERT THE TURBIDITY IN CONCENTRATIONS [2].

	Measurement point			
	Point 1 (depth 32m)	**Point 4 (depth 6m)**	**Point 7 (depth 7m)**	**Magest July 2005 Pauillac**
C(g/l)	0.023–0.046	0.12–1.03	6.9–8.05	0.5–3.25

III. MODEL SETUP

A. *Hydrodynamic model*

Numerical computations are performed with the open source TELEMAC finite element system (see the site www.telemacsystem.com) developed at EDF R&D [3]. The use of unstructured meshes and finite elements methods is well adapted to cover large scale domain and allows to refine zones of particular interests (e.g. the central part of the estuary), while the upstream maritime and downstream river part is more coarsely represented (300 m between nodes in the streamwise direction).

The numerical domain covers the whole estuary: from the Bay of Biscay (mouth near Verdon, Fig. 2) to La Reole and Pessac, considered as the limit of the tide influence in the tributaries. The unstructured triangular mesh comprises 22650 nodes [5]. The cell lengths extend from 50 m in the refined central part and up to 2 km in the maritime boundary. The current release 6.1 of Telemac-2d is used to solve the shallow water equations. This version benefits from optimized finite element schemes and a full parallelization of the code. Moreover, a recently developed algorithm for tidal flats allows to ensure both mass conservation and positive water depth [4] . The numerical domain is extended into the coastal zone (30~40 km from Verdon station) in order to impose the tide height in deep water. The tidal components are issued from a global oceanic model [7] .

B. *Sediment transport model*

The morphodynamic model (Sisyphe release 6.1) solves the Exner equation and splits the total load into bed- and suspended-load. The bed load is estimated by a semi-empirical formula (e.g. Meyer-Peter Muller [8]) whereas the suspension load is calculated by solving an additional transport equation for the depth-averaged sediment concentration. The erosion and deposition fluxes, which enter both the Exner equation and the transport equation, are expressed as a function of an equilibrium concentration, which is also calculated using a semi-empirical formula [16].

In order to solve the advection term of the suspended-load transport equation, a new algorithm has been implemented, to ensure a fully mass conservative scheme. This new scheme is based on finite volumes methods and allows calculating fluxes of sediment along segments forming the individual triangular elements. The treatment of tidal flats is based on positive water depth algorithm and is fully mass conservative [4].

The depth-averaged velocity field calculated by Telemac-2D needs to be corrected to account for the fact that most suspended sediment is transported by the near-bed velocity field. This correction leads to a reduction of transport rates, as detailed in [6]). The correction of the velocity, which is a multiplication by a space-dependent factor in the range [0;1], must be applied to the fluxes themselves, at the edge level, in order to avoid unphysical results. The average correction of the two points forming the edge is chosen so far. This method is available in the current release 6.1 which is used in this application.

The corrected 2D-velocity field does not obey the shallow water continuity equation and this requires a specific treatment in finite volumes advection schemes. Mass conservation is still ensured but monotonicity is spoiled, and this could threaten the numerical stability, especially in dry zones. Stability is eventually obtained by adding the settling velocity term in an implicit way in the advection. By this way, even places where the water depth is close to zero (dry zone) will come up with a finite value of concentration.

The effect of sand grading is based on Hirano's active layer concept, whose thickness is set to 10 cm, which is of the order of magnitude of bed roughness as predicted in the central part of the estuary [14]. In Part III, the grain size distribution in the model remains here in the non-cohesive range (d_{50} > 60 µm). In Part V, we present some preliminary results on the effect of cohesive sediment which is based on a multilayer consolidation model [12].

IV. LARGE SCALE HYDRODYNAMIC MODEL

A. *Boundary conditions*

Flow rates are imposed at the upstream boundary and the tide height at the maritime downstream boundary for the hydrodynamics. The tide height is composed of 46 harmonic waves [5]. Special attention must be paid to the boundary conditions for the suspended load. When the flow exits from the domain, the concentration of suspended sediment is a degree of freedom and is naturally derived from the knowledge of the concentration inside the domain. When the flow enters the domain, the concentration coming from outside is unknown and it is therefore chosen to apply an equilibrium concentration.

B. *Friction coefficients*

Friction coefficients are calibrated using water levels and velocities measurements of the 2006 survey. The method is explained in details by [5]. The hydrodynamic friction coefficient is first estimated by using a bed roughness predictor [11] and needs to be further adjusted to account for various sources of uncertainty in the model.

The bed roughness predictor takes into account the effect of both spatial and time variation of the friction coefficient. Model results compare reasonably well with the observations of tidal amplitude and velocity, although the velocity were slightly underestimated by the 2d model in comparison to measurements in the central part of the estuary, as discussed in [5]. For this reason, the bed roughness coefficients, converted into Strickler coefficients, were time-averaged and slightly adjusted to get a set of calibrated Strickler values which were applied in the morphodynamic model application.

The estuary is split into four zones of constant friction coefficients (Fig. 2): 37.5 $m^{1/3}/s$ in the mouth, 67.5 $m^{1/3}/s$ in the central part, 70 $m^{1/3}/s$ for the Garonne River and 60 $m^{1/3}/s$ for the Dordogne River.

C. *Model validation*

Two sets of data have been used for model calibration and validation. Figure 4 shows the comparison between velocity measurements and tidal measurements at the mouth of the estuary (Verdon station) and at the centre (Pauillac) for the 2009 survey (October spring tide).

An accuracy of less than 10 cm in the water level is obtained.

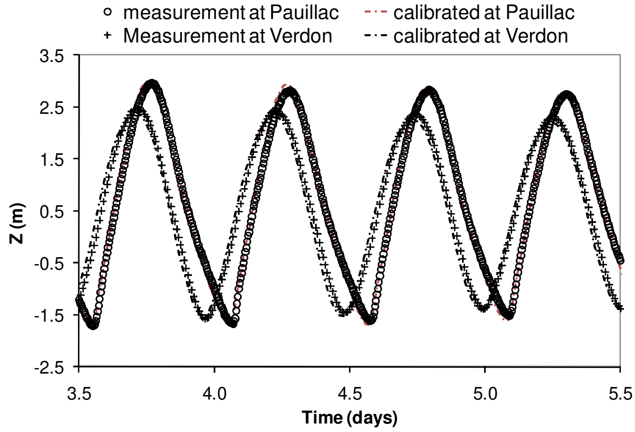

Fig. 4.a. Comparison between model results and tidal height measured at Pauillac and Verdon stations.

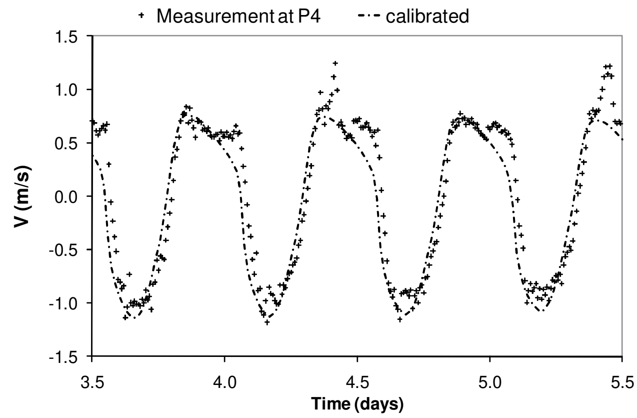

Fig. 4.b. Comparison between model results and velocity measured at P4.

Figure 4 Hydrodynamic model results (full line) in comparison to measurements (dots). $t = 0$ corresponds to October the 3[rd] at 0h UT (spring tide).

V. LARGE SCALE MORPPHODYNAMIC MODEL

A. *Multi-grains sand transport model*

Sediment transport predictions are highly sensitive to the sediment granulometry and bed composition as well as to the choice of transport formula. In the present application, transport rates are dominated by the presence of very fine particles in suspension. The suspended load is highly sensitive to the choice of settling velocity, which can be deduced from the grain diameter using a semi-empirical formula [10]. The reference length delineating the bed-load and suspended load is taken at 0.5 k_s as suggested by van Rijn, where k_s is the equivalent bed roughness. Influences of the ripples on the skin friction and thus on the transport rates are incorporated for all the performed computations.

The variability of the sediment distribution along the Gironde estuary is schematized by assuming an initial uniform sediment distribution for each geo-morphological unit. In the upper river part, the bed sediment is composed of silt (d_{50} = 60 µm), whereas the maritime part is made of medium sand (d_{50} = 310 µm). In the central part, the bed is made of a mixture of 50% of fine sand (d_{50} = 210 µm) and

50% of silt (d_{50} = 60 µm). The grain size distribution calculated by the model after one year is shown on Fig.5.b. In the maritime part, the fine sediment is flushed out and deposited offshore, which is in qualitative agreement with observations (see Fig. 5.a). In the central part, very fine (cohesive) sediment is dominant downstream of the Patiras island and deposits area, whereas coarser sediment is predominant in the deeper channels, as observed by [1].

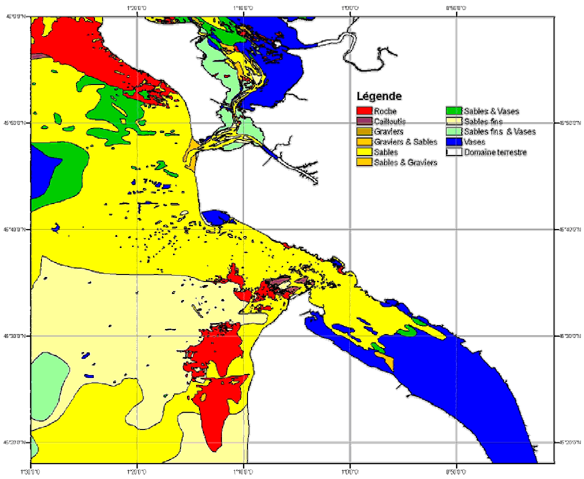

Fig. 5.a. Measurements of the granular distribution in the maritime estuary.

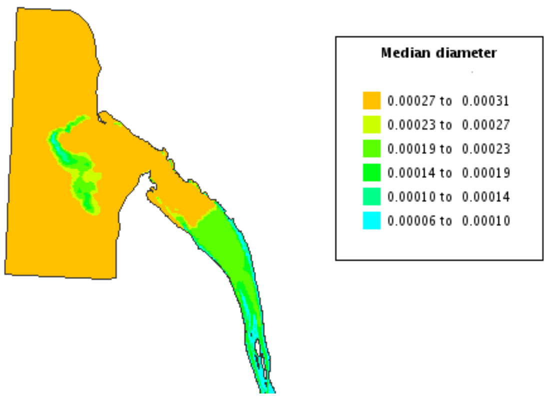

Fig. 5.b. Calculated distribution of sediment grain size in the maritime and in the central parts (units are in m).

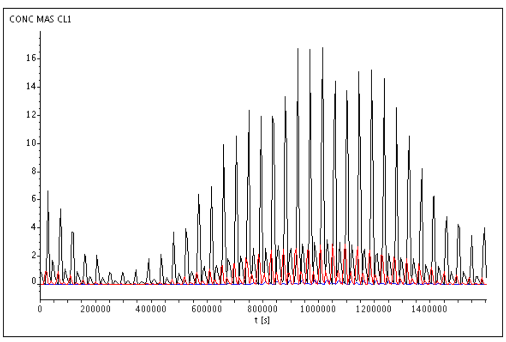

Figure 6. Time-varying concentration in g/l calculated at the 3 stations (P1 is in red, P4 in blue and P7 in black). t = 0 corresponds to the 24[th] of September 2009 (0h TU).

Model results are in qualitative agreement with turbidity measurements from the September 2009 campaign. Time-varying concentrations calculated at point P1 (mouth of the estuary), P4 (central part) and P6 (Dordogne) are shown in Fig. 6. In comparison to the data (see also Table 1), the model tends globally to overestimate the peaks in concentrations by approximately a factor 2 to 5. Best agreement in the central part, both at P4 and at Pauillac station, is obtained by adjusting the settling velocity to 1.8 mm/s for the finer grain size and by lowering the empirical coefficient in the van Rijn formula (0.05 instead of 0.15). These model parameters are retained for the morphodynamic simulation.

B. Medium term bed evolution

In the large scale morphodynamic model, the sequence of dry or flood seasons can be imposed at the upstream boundaries based on measured flow rates. Variation of river discharges from January 1[st] 1995 to December 31[st] 2000 is shown on Fig. 7. On this figure, the sequence of dry and flood seasons is clearly seen. For instance in the Garonne River, the flow rate decreases down to 60 m^3/s during the dry season and reaches its maximum, up to 4000 m^3/s, during winter floods.

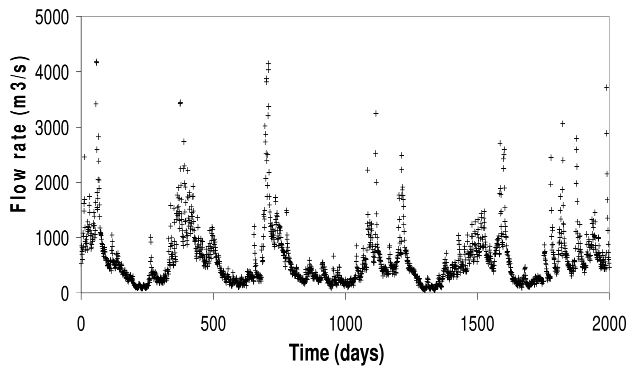

Figure 7. Seasonal variation of the flow (Garonne) from 1995 to 2000.

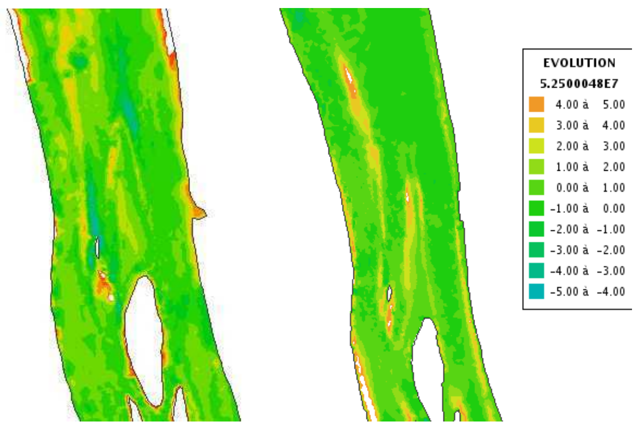

Figure 8. Bed evolutions in the central part. The left part shows the differential bathymetry (1995-2000). The right part shows the 2.5-year bed evolution.

The predicted bed evolution (Fig. 8.b) is overall, in both qualitative and quantitative agreement with the 5-year differential bathymetry, shown in Fig 10a. The growth rate of the Patiras island and associated deposition rates of the fine particles downstream of the island are over-estimated by roughly a factor 2, which is consistent with sediment transport rates estimations.

VI. Cohesive sediment processes

Non-cohesive sediments, consisting of sand, are characterised by their diameter and exhibit stable properties in time, while cohesive sediments, consisting of mud, silt and clay, are subject to consolidation and obey different laws of transport, erosion and deposition.

A. *Erosion and deposition laws*

Cohesive sediments are transported in suspension (no bedload) and the erosion and deposition fluxes are calculated according to Partheniades' erosion law. The erosion rate E is zero except when the bed shear stress τ_0 exceeds the critical erosion rate τ_e:

$$E = M\left[\left(\frac{\tau_0}{\tau_e}\right) - 1\right]$$

The erosion parameter is a user defined empirical parameter. The critical erosion rate depends on the sediment bed concentration and is defined for each layer as a function of concentration. For soft mud (C_s = 100g/l) we use τ_e = 0.055 N/m^2, whereas for consolidated mud (C_s = 500 g/l), τ_e = 2.61 N/m^2. The deposition rate D is a function of settling velocity W_s:

$$D = W_s C$$

Where C is the depth-averaged suspended sediment concentration. Empirical model parameters are determined based on literature review of existing models and experimental work on the Gironde mud [17]. In this application, we used W_s = 1.78 mm/s and M = 0.003 Kg/m^2/s.

B. *Consolidation multi-layer algorithm*

A multi-layer consolidation algorithm has been implemented in release 6.1. This model has been validated by the use of a 'home-made' RX-settling column, sedimentation and consolidation tests are performed. The X–ray scanner (equivalent to a commercial CatScan© facility) gives access to the time-evolution.

The sedimentation-consolidation « multi-layer » model is based on an original technique to solve Gibson equation isopicnal model, developed in [18] (1DV model). The advantage of this representation is that the flux of sedimentation and consolidation is based on the Gibson theory. If there is erosion, the thickness of the uppermost layer decreases, and vice versa, when there is deposition, this increases.

In the case of pure cohesive sediment, the self weight consolidation is finely described by the equation of Gibson:

$$\frac{\partial e}{\partial t} + \underbrace{\left(\frac{\rho_s}{\rho_f} - 1\right)\frac{d}{de}\left(\frac{k}{1+e}\right)\frac{\partial e}{\partial z}}_{\text{sedimention (advection term)}} + \underbrace{\frac{\partial}{\partial z}\left(\frac{1}{\gamma_f}\frac{k}{1+e}\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right)}_{\text{consolidation (diffusion term)}} = 0$$

where k is the bed permeability, e the void ratio, σ' the effective stress, ρ_f and ρ_s the fluid and sediment densities, g the gravity. K and σ' are determined form constitutive equations, in order to reproduce observations. The accuracy of the concentration profiles depends on the number of layers. Finally, we set the concentration as $C = \rho_s / (1 + e)$.

We use 10 sediment layers (with fixed concentrations) and time-varying thickness. The model results are in good agreement with measured profiles, as shown on Fig. 9.

C. *Model set-up*

In order to initialize the bed structure, the model is run for one month of pre-simulation. In zones of deposit (North of Patiras island, tidal flats) the top layer increases (C_s = 100 g/l) and the bed is covered of soft mud (see Fig. 10.a). The deeper navigation channel (Fig. 10.b), where the currents are stronger, the top layer is eroded and the sediment bed is made of consolidated mud (3[rd] layer becomes the top layer: C_s = 200 g/l).

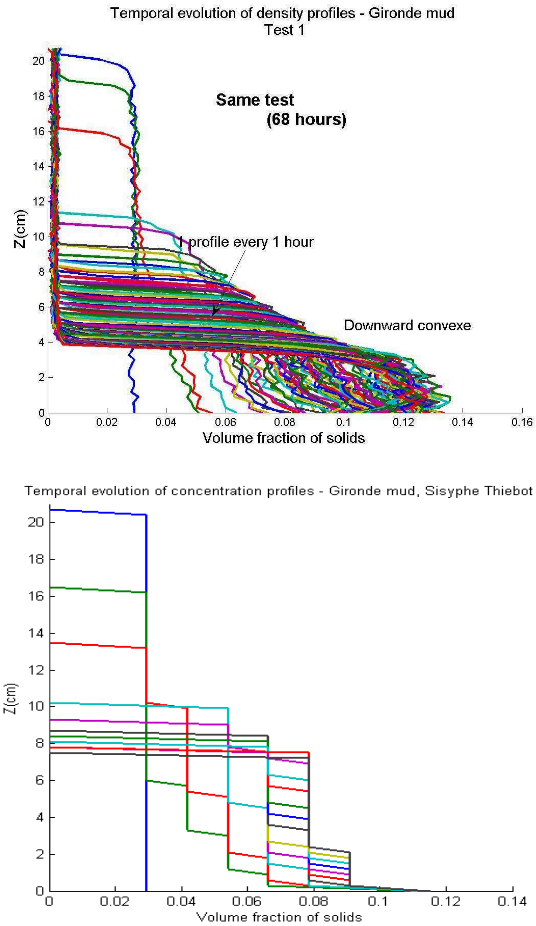

Figure 9. Comparison between measurements(top) and model results (bottom).

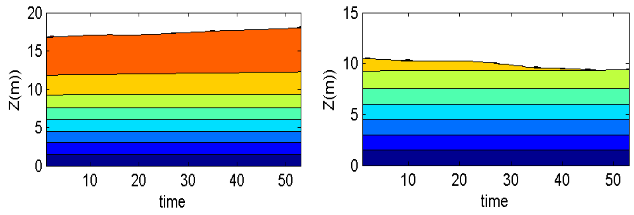

Figure 10. bed structure at different points in the estuary. Left: navigation channel. Right: lee of the Patiras island (tidal flat formation).

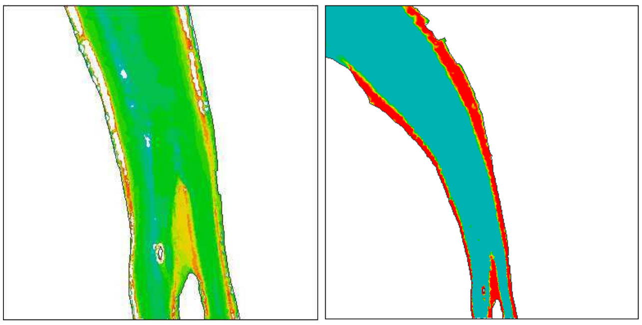

Figure 11. Calculated bed evolution (left) and tidal flats formation after one year (right). Red is for soft mud C_s (100g/l).

D. Preliminary morphodynamic model results

The cohesive sediment transport model is now applied to simulate the bed evolution in the period 1995–1996. The preliminary results show quite drastic bed evolutions and reproduce the formation of the Patiras bank in the lee of the central island (Fig. 11). This feature is clearly observed in the data (Fig. 8.b). However it is overestimated in the model predictions. Model parameters still need further validation.

VII. CONCLUSIONS

The Telemac finite element system, which has been applied to predict the medium term bed evolution (5 years) in the Gironde estuary (150 km long). The model includes a more detailed representation of physical processes: bed friction factor, sand grading, realistic hydrodynamic forcing. For 3 grain sizes (non-cohesive sediment) the CPU time is approximately 10 hrs for 1 year (using 4 processors).

The high variability in the sediment distribution (mixed sediment in the center part of the estuary) has been schematized by assuming non-cohesive sediments with variable grain size (Part IV) and cohesive sediments (pure mud) with variable properties (Part V). This is a rather schematic representation and the effect of mixed sediment still needs to be accounted for.

In Part IV, he grain size distribution is schematized by setting fine sediment in the river tributaries, coarser grains in the maritime part and mixture of fine and very fine sediments in the center part. The morphodynamic model has been validated against observations (turbidity measurements and differential bathymetry from 1995 to 2000). The best agreement is obtained by use of the van Rijn reference concentration formula, associated with a bed roughness predictor. Despite the fact that the suspended load transport rates of the finer sediment class are overestimated (by roughly a factor 2), results for the medium term bed evolution are in qualitative agreement with observations.

Cohesive sediment transport processes have also been introduced and change quite drastically the model predictions. Qualitatively, the multi-layer consolidation algorithm is able to reproduce the observed spatial variation in the bed structure (soft mud in the deposit area and tidal flats). However, bed evolutions are overestimated and further validation is required.

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