COUPLED 3D MODELING OF TURBIDITY MAXIMUM DYNAMICS IN THE LOIRE ESTUARY, FRANCE

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Comprehensive 3D modeling efforts to understand salt intrusion and fine sediment dynamics in the Loire estuary started in 2006 and first results about the role of fluid mud on the hydrodynamic circulation through the bottom roughness was reported by Hamm and Walther during ICCE 2008. Recent progress since 2008 includes a) the coupling between the three modules (hydrodynamic, salinity, fine sediment transport) in order to let the fluid mud control the bottom roughness, b) the improvement of the vertical turbulence model enabling to reproduce strong stratifications observed during neap tides, c) a new empirical consolidation model calibrated against lab measurements and including the quantification of the erosion rate over a large range of bed dry densities and d) a new parameterization of the settling velocity function of the turbulence level of the flow. These developments have been validated over a period of five months in winter against field measurements of salinity and turbidity acquired through a permanent network of fixed sub-surface turbidimeters established in 2007. Additional validation against bathymetric measurements of the position of the fluid mud layer in the navigation channel is also presented.

Keywords: estuary, maximum turbidity, salinity, vertical turbulence, 3D modeling, TELEMAC system

INTRODUCTION

The Loire estuary is one of the three major french estuaries. It is a macro-tidal estuary with a mean spring tidal range of about 5 m allowing the tide to propagate up to Ancenis, 90 km upstream from Saint-Nazaire (fig. 1). The long-term mean discharge of the Loire river is 825 m3/s with considerable variations ranging from 60 and 6,000m3/s. The water quality of the estuary is considered as relatively bad with a salt intrusion limit locating 70 km upstream and a large maximum turbidity due to significant developments over the two last centuries including a deep-water port development downstream in the Saint-Nazaire area with an outer navigation channel down to -12.5mCD and the calibration of a unique inner navigation channel at -5m CD up to the city of Nantes located 55 km upstream from Saint-Nazaire (fig. 2).

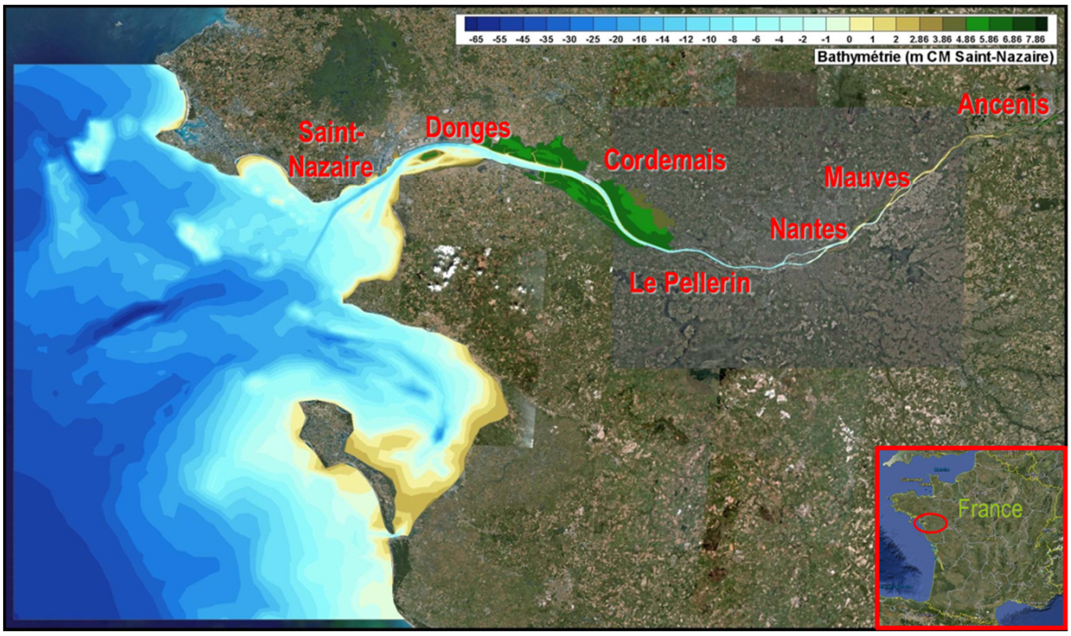

Figure 1. Site location

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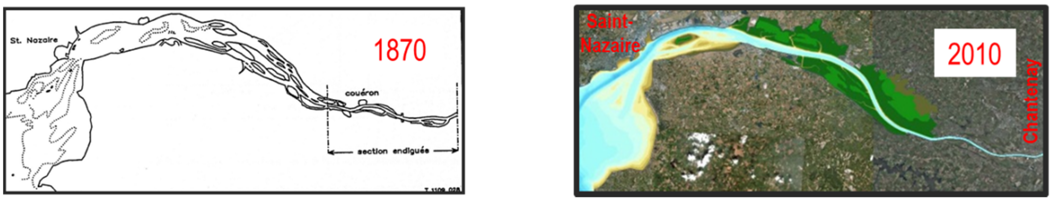

Figure 2. Bathymetric evolution of the Loire river between 1870 and 2010.

OBJECTIVES OF THE MODEL

The goal of this work was to set-up a reliable numerical model able to simulate at least one year of evolution of the hydrodynamic, salinity, and maximum turbidity in the estuary for several configurations including past and present situations and several scenarios aiming at improving the water quality. Due to the large number of simulations to be performed, it was requested to build this model with the constraint of running a 1 year simulation in a few days. As a consequence, the development of this model is a compromise between the computation time and the refinement in the equations used to pick-up the key physical processes. Reliability was obtained thanks to the large effort devoted in the collection of field measurements. It permits to get a better understanding of the processes and to calibrate several parameters related to the mechanical properties of the mud in the Loire river.

MODEL DESCRIPTION

The model is based on the Telemac-3D system. The simulated area is about 90 km inland and 40 km offshore. It includes laterally not only the tidal flats but also large parts of submersible areas. The horizontal mesh is composed of about 7100 nodes with a maximum size of 2.5 km offshore and 50 to 150 meters in the area of interest. The vertical mesh is composed of 16 planes, with a strategy of fixed planes (red) and sigma planes (black) to get a proper refinement near the bed (2 at 5 planes of 0.25m to catch the strong gradients of currents, salinity and SSC) and near the surface to properly integrate the wind effect. The model is forced with the daily discharge of the Loire river, the astronomical tide level, variation of mean sea level due to meteorological conditions, waves and wind conditions.

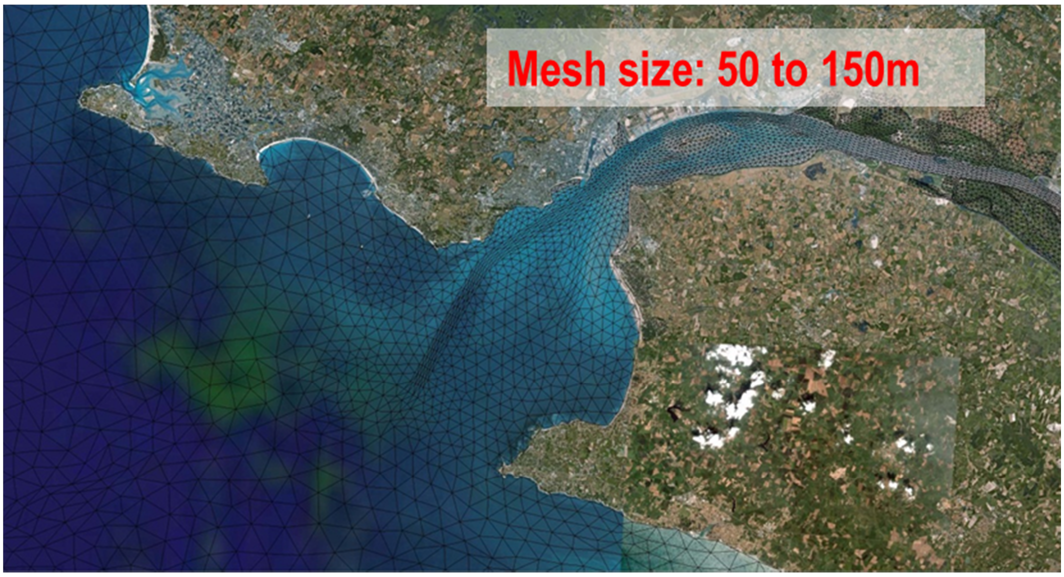

Figure 3. Horizontal mesh

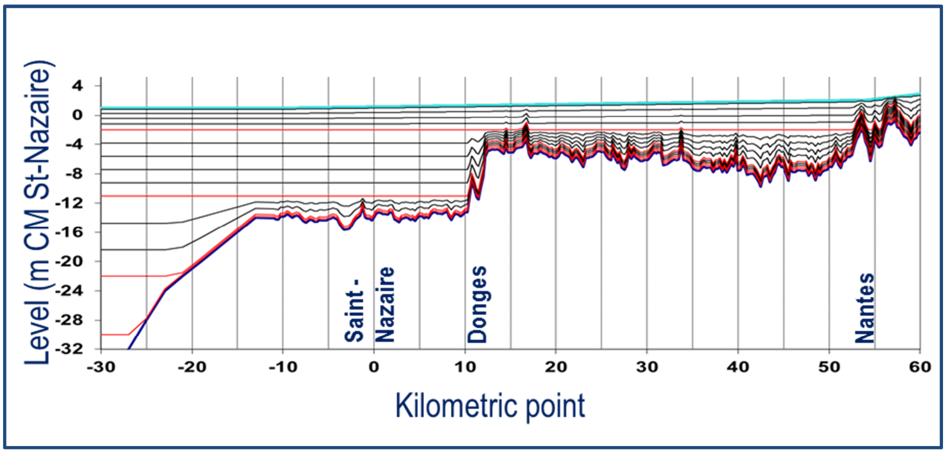

Figure 4. Vertical mesh

HYDRODYNAMIC CALIBRATION

The set-up of the roughness map was based on 8 tidal gauges. As reported in Hamm and Walther (2008), the good agreement of computed water levels and measurements in the inner estuary can only be obtained by taking into account the instantaneous position of the fluid mud deposit through the roughness.

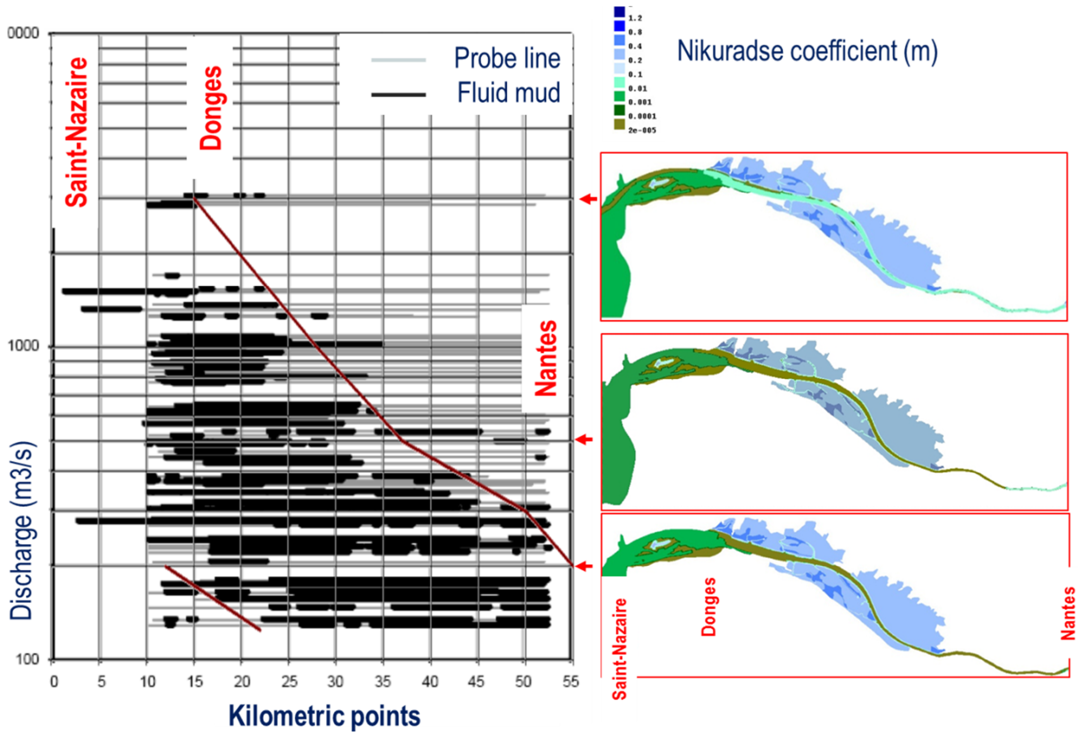

Figure 5. Measurement of mud deposit in the navigation channel and map of roughness for three discharges

A first approach, named the decoupled approach, was used in the beginning. It considers that the position of the mud deposit is known in advance as a function of the river discharge (fig. 5). Accurate results were obtained when simulating the present situation but it appears that this method was no more valid when testing new estuary developments. This is the reason why a second approach, named the coupled approach, was developed in which the computation of the fluid mud evolution on the bed at each time step and every node is used to update the map of roughness.

SALINITY CALIBRATION

The choice of a proper vertical model of turbulence is crucial for simulating the dynamics of the salinity. Three models have been tested in this work, including the classical mixing length model, the k-epsilon model and a new multilayer mixing length model developed during this study.

A strong event of salt intrusion was observed in October 2000 during a field campaign including measurement of salinity at 2 levels at the sites of Montoir and Cordemais (fig. 6) against which the three models were tested.

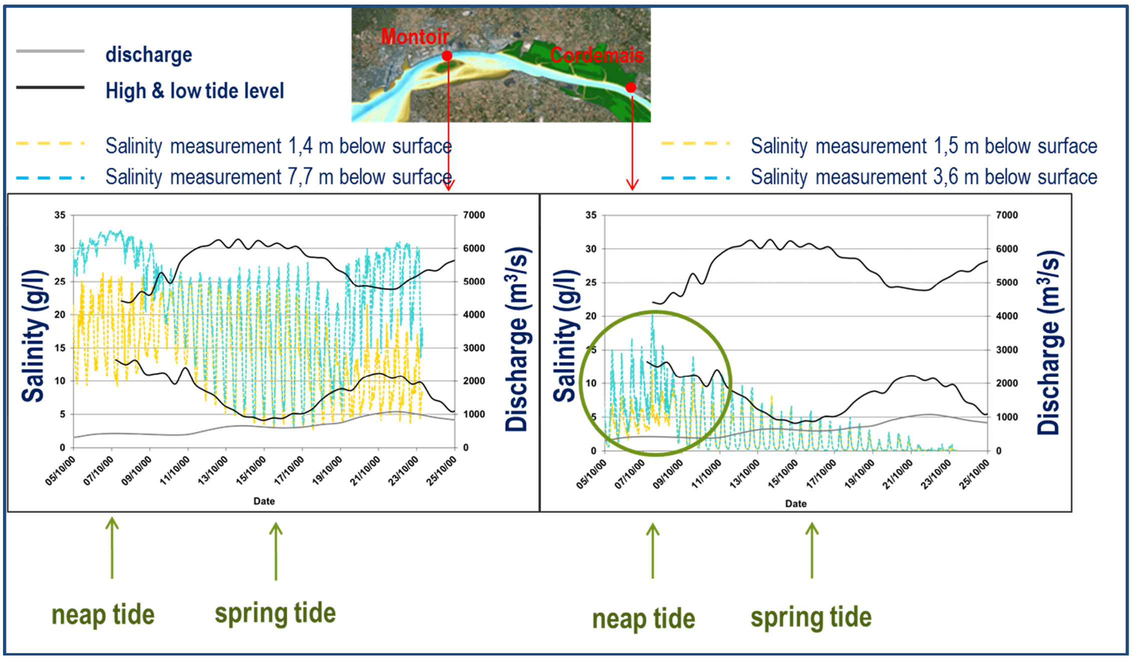

Figure 6. Measurements of salinity at Montoir and Cordemais in October 2000

Classical mixing length and K-epsilon models

The characteristic length of a classical mixing length is based on the water depth, and the damping function acts locally in function of the Richardson number. Many mixing length (Prandtl, Tsanis, Nezu &Nakagawa, Quetin) coupled with three different damping functions: Munk & Anderson, Lefeldth & Bloss and Toorman were tested.

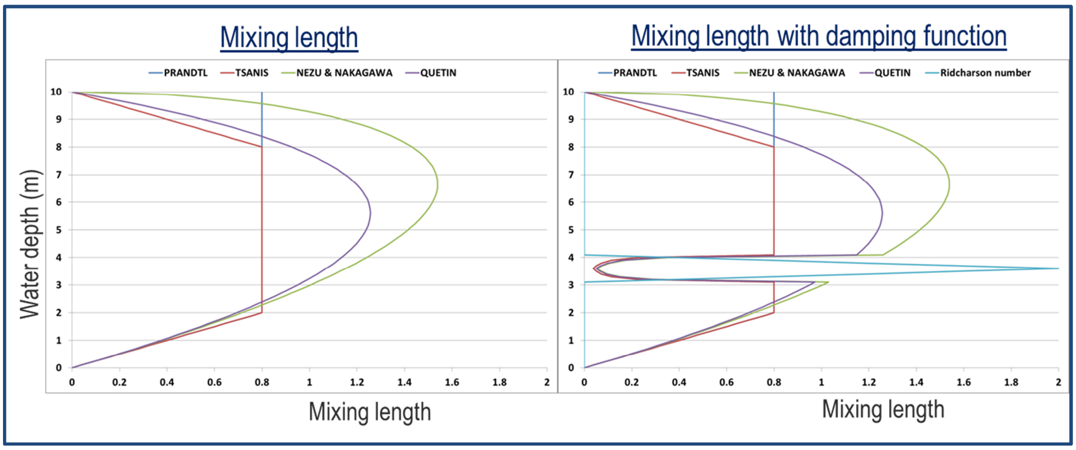

Figure 7. View of mixing length and mixing length coupling by a damping function

On the figure 8, the results of the run with the Nezu & Nakagawa mixing length coupled with Lefeldth and Bloss damping function shows a good agreement in salinity evolution during spring tide, but the position of salinity gradient is not correct during neap tide. We can't observe the intrusion of salinity in Cordemais during neap tide.

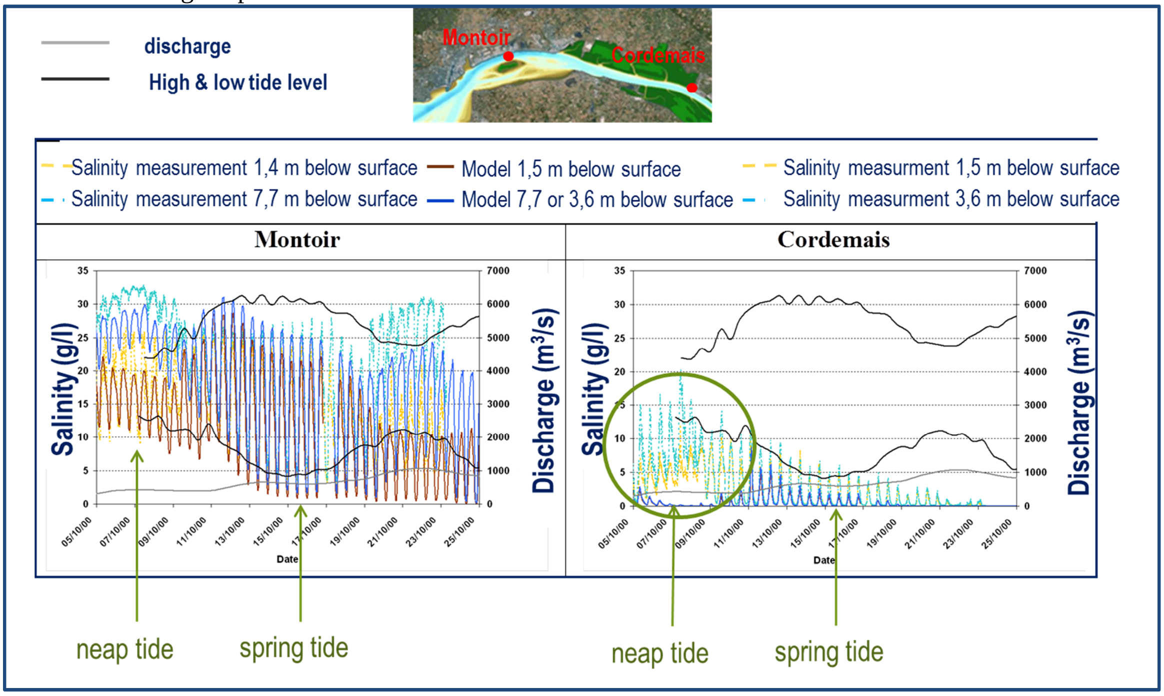

Figure 8. Comparison of measurement and model using Nezu & Nakagawa mixing length coupled with Lefeldth and Bloss damping function

Results obtained with the K-epsilon model (with Rody coefficients) are presented on figure 9. A better agreement was observed at Cordemais between measurement and model during the first neap tide period.

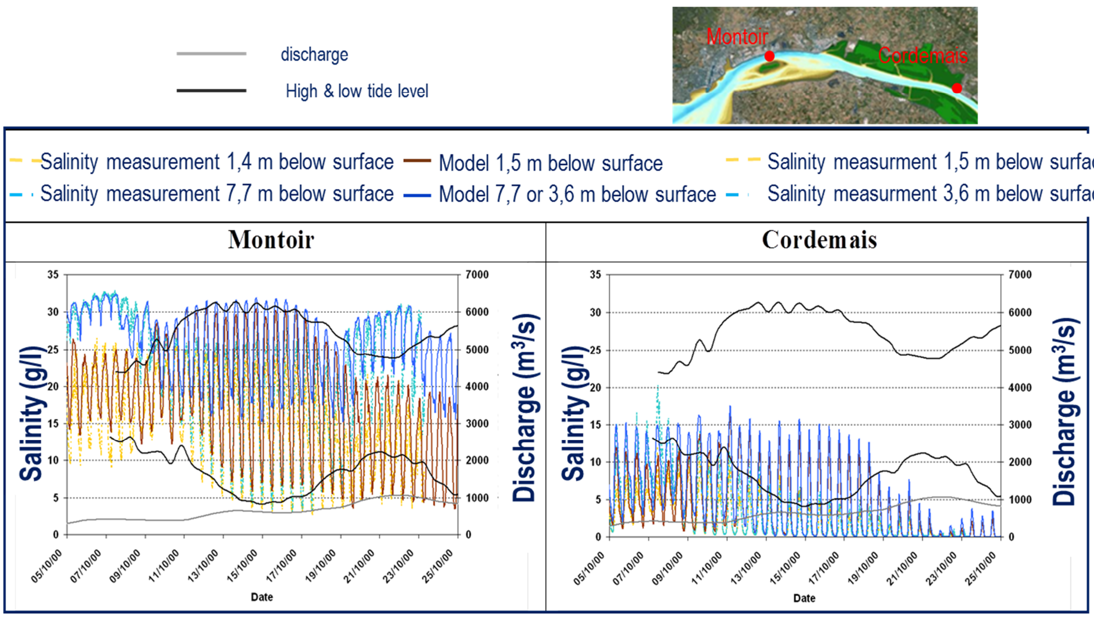

Figure 9. Comparison of measurement and model with the K-epsilon model

In our case, the disadvantages of this method were that the computation time was multiplied by two and wind forcing gave unrealistic results. In addition, the advantage of the transitional approach of the K-epsilon model had a limited interest in our case, because the transitional solution was masked by the large mesh size. This is the reason why we decided to develop a new turbulence model expanding the classical mixing length concept to a stratified flow.

The multilayer mixing length

The idea comes from oceanic models where the characteristic length of mixing is not based on water depth, but on the thickness of uniform layers. A layer is defined by looking at the variation of Richardson number over the depth. When this number is greater than 0.2, a new thickness is defined (fig. 10). With this approach, the maximum value of mixing is decreased in comparison with the classical method. The concept was validated against laboratory experiments of turbulent mixing in a two-layers stratified shear flow performed by Viollet (1980).

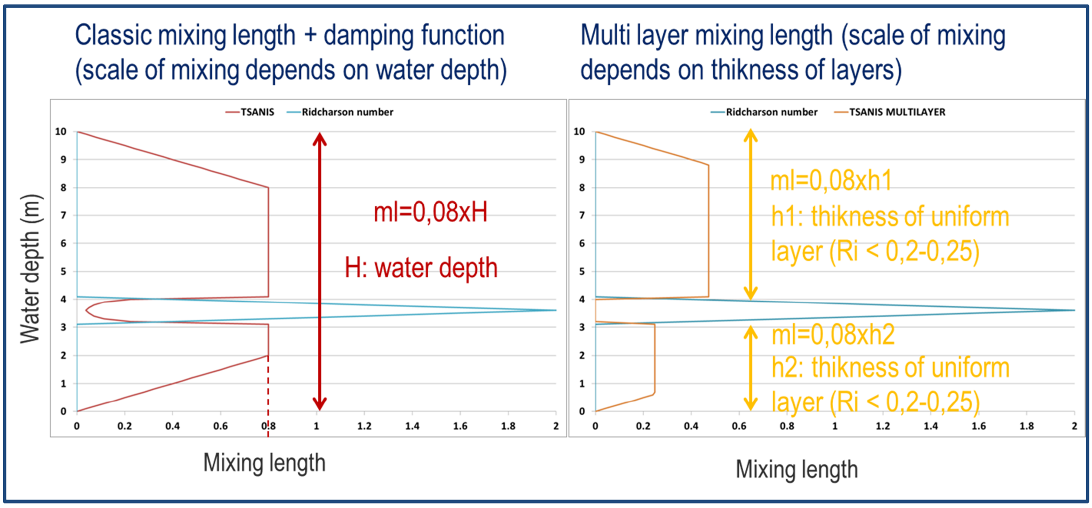

Figure 10. View of classic mixing length and multilayer mixing length

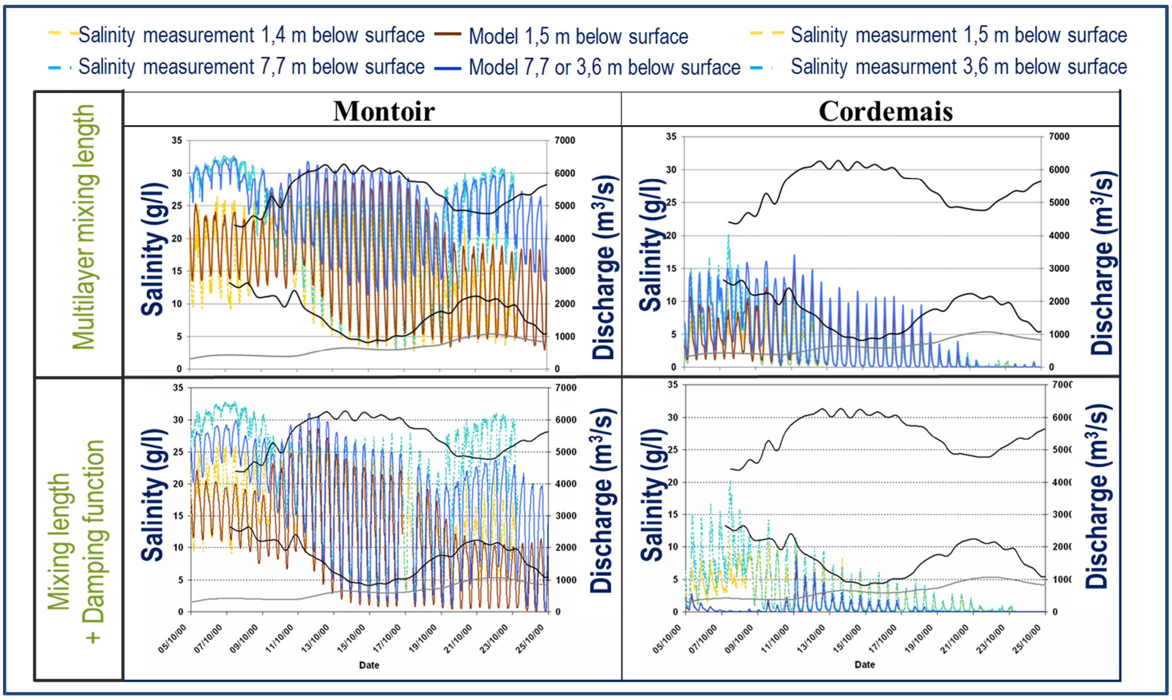

Figure 11. Comparison of measurement with classical and multilayer mixing length models

We can see that the result obtained with the multilayer model on figure 11 is of the same quality as the K-epsilon model with the advantage of a smaller computation time.

An additional validation test was performed on a flood period of the river with discharges peaking over 4000 m^3/s. Figure 12 shows a good agreement between measurement and simulation, with an important stratification in the navigation channel. A mixing of the stratification at 26/01/2004 due to wind effect is also observed.

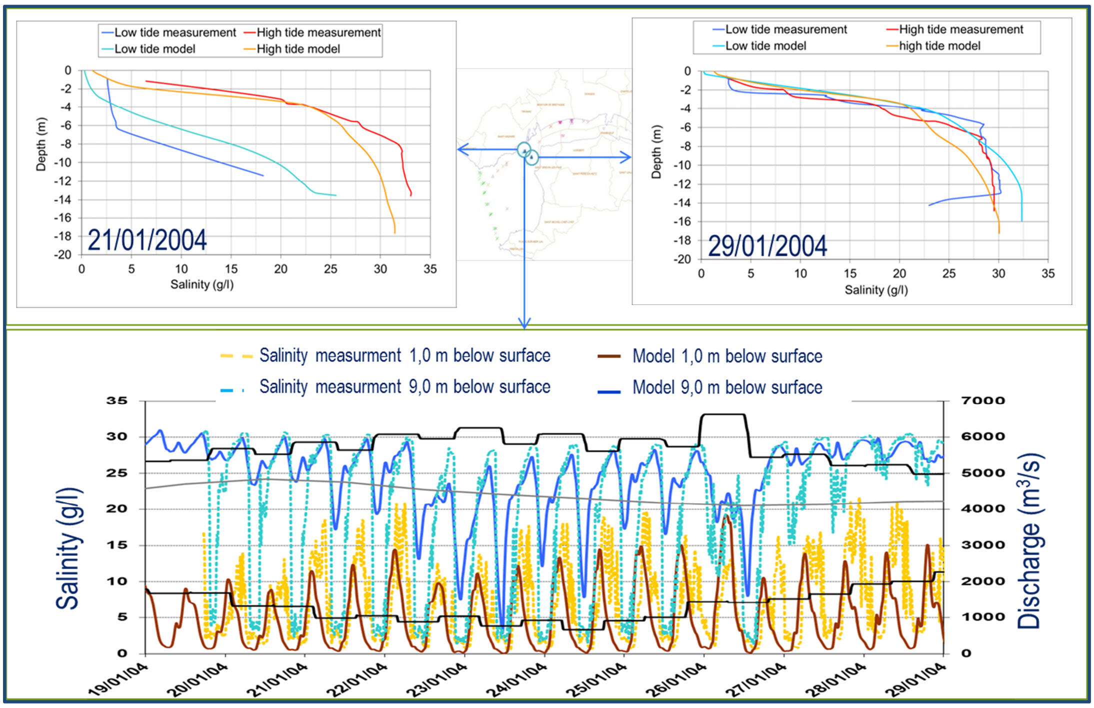

Figure 12. Comparison of measurement and model with the multilayer mixing length for flood conditions

SUSPENDED SEDIMENT TRANSPORT AND BED CONSOLIDATION MODEL

This module includes the transport of the suspended sediment in the water column with a concentration up to 40 g/l and an empirical bed consolidation procedure. The exchange between the bed and the water column is realized through classical erosion and deposition laws.

Consolidation model

The empirical consolidation model is composed of 16 layers. Each layer is defined by 3 constant parameters: a dry density (Cs in g/l), a critical shear stress for erosion (Toce in N/m²) and a transfer rate (parameter a in s^{-1}). At each time step the mass of sediment to be transferred from one layer to another depends on the thickness of layer and on the transfer rate (fig. 13).

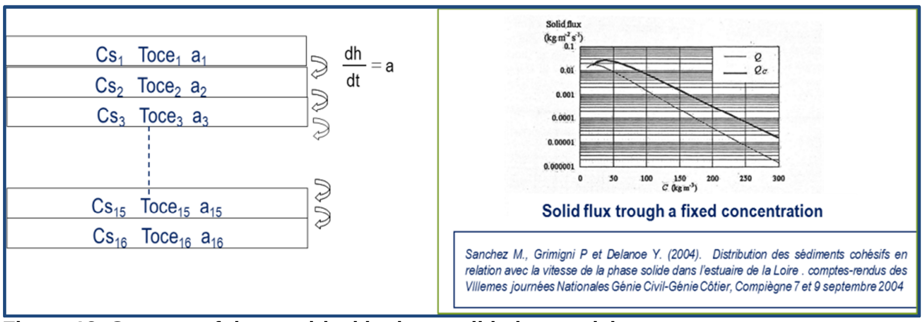

Figure 13. Concept of the empirical bed consolidation model

The transfer between the bottom layer of the water column and the top layer of the bed is carried out when the suspended sediment concentration exceeds 40 g/l. The parameter ‘a’ was calibrated with laboratory measurements performed by Sanchez et al. (2004). A validation of the model was carried out against settling tube measurements. Figure 14 presents an example of such a comparison.

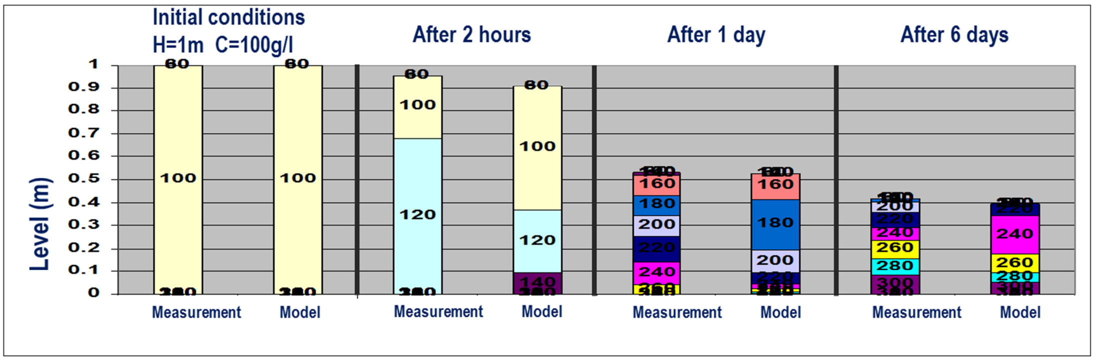

Figure 14. Comparison of settling tube measurements and model of consolidation

Deposition rate and settling velocity

The deposit rate is calculated by the product of the near-bed suspended sediment concentration by the settling velocity. Two empirical settling velocity laws have been established (fig. 16) based on one part on laboratory experiments performed in a deflocculated environment (law 1) and on the other part on field measurements performed with an Owen’s tube in a flocculated environment (law 2).

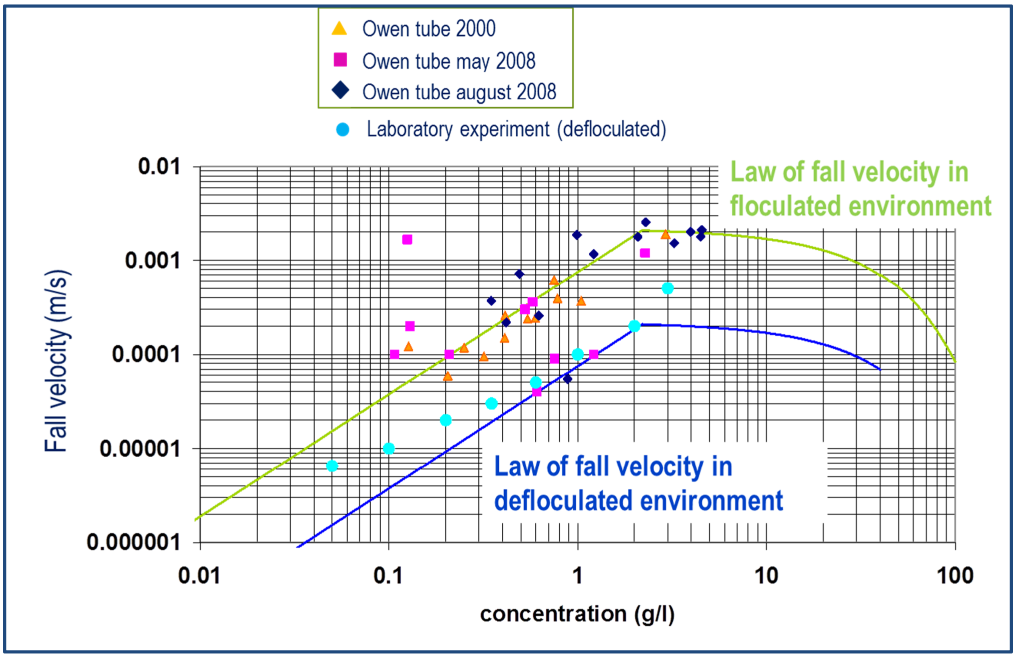

Figure 15. Calibration of empirical settling velocity laws

As a first approach, we used a simplified procedure to adapt the settling velocity to the turbulence intensity of the flow as follows: when the velocity speed is over 1.1 m/s, it is assumed that flocs are broken and law1 is applied. On the other hand, law2 is applied when the velocity speed is under 0.5 m/s. Between these two limits, a linear interpolation between law1 and law2 is applied.

Erosion rate

An empirical erosion rate law was calibrated for different dry density of the bed on laboratory measurements performed by Sanchez and Levacher (2008) as shown on fig. 16.

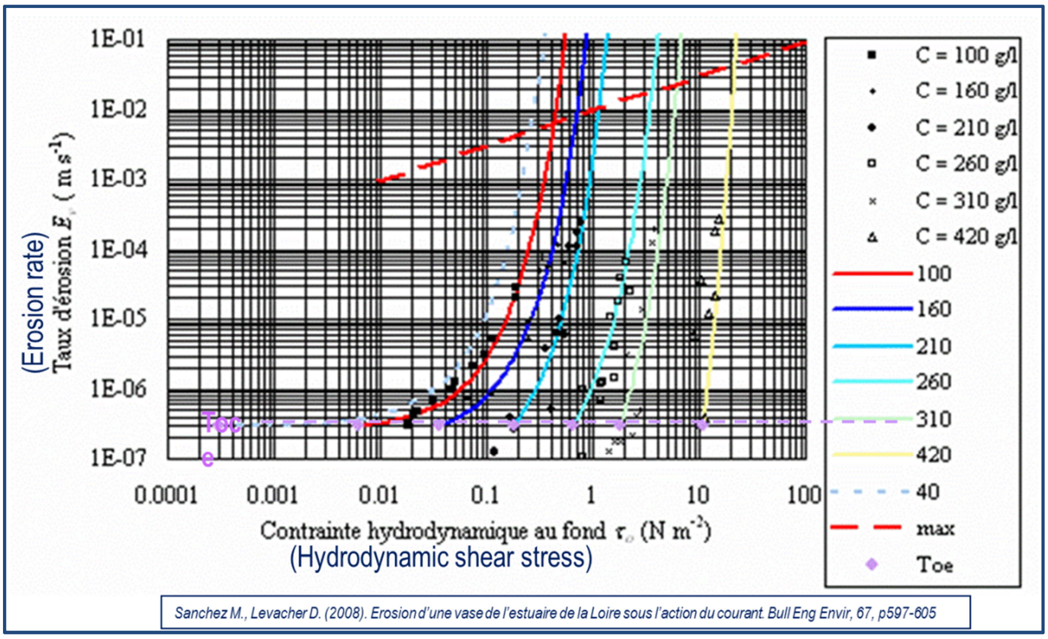

Figure 16. Calibration of the erosion rate law on laboratory measurements

Verification of the suspended sediment transport

The comparison of the model and suspended sediment concentration measured at two fixed points during five months (figure 17) shows that the model is able to reproduce the dynamic of the maximum turbidity.

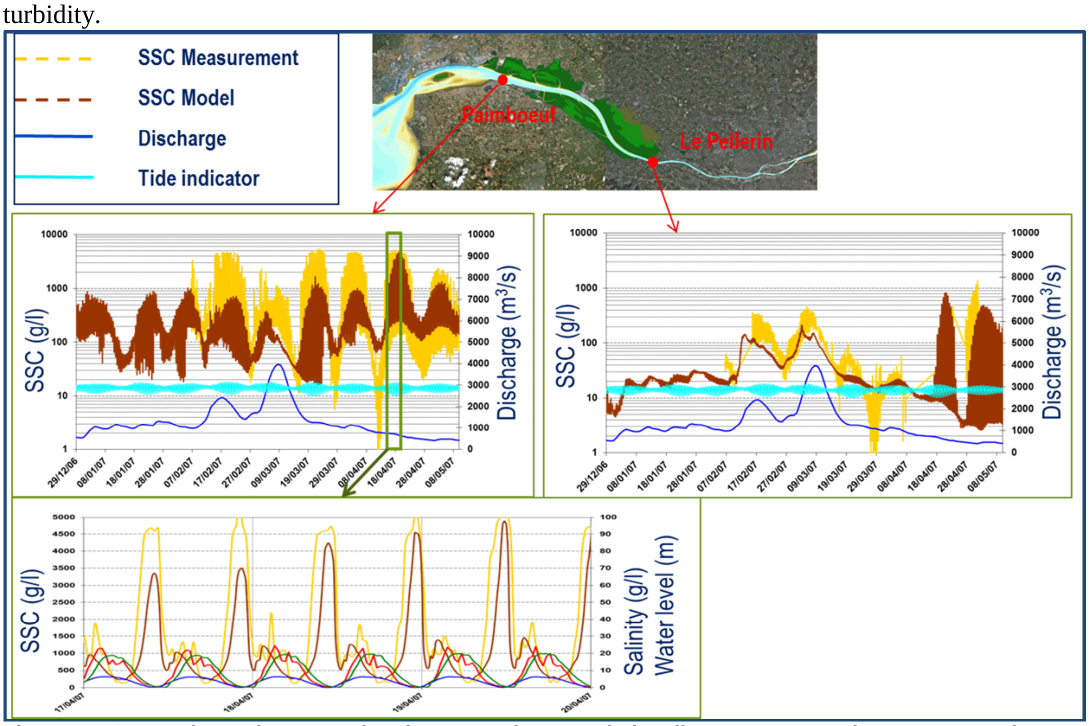

Figure 17. Comparison of measured and computed suspended sediment concentration over 5 months

It is worth to note that after the flood of March and the expelling of the maximum turbidity downstream, the model is able to build a new maximum turbidity that we can observe at Le Pellerin in April-May.

Verification of the bed dynamics

Measurement of fluid mud deposits are regularly performed by the port authority along the navigation channel. These data have been sorted in relation with the river discharge as shown on fig. 18. This graph indicates that there is no mud in the channel navigation upstream of the kilometric point 30 for a discharge of 500 m^3/s (mean discharge of the ten last days). This remarkable feature was reproduced with the numerical model during an 8 months simulation shown. We can see on fig. 19 that during flood conditions the mud is located downstream and then moves up to the kilometric point 30 when the discharge of the ten last days is less than 500 m^3/s. The gap in time between measurement and model is about 15 days.

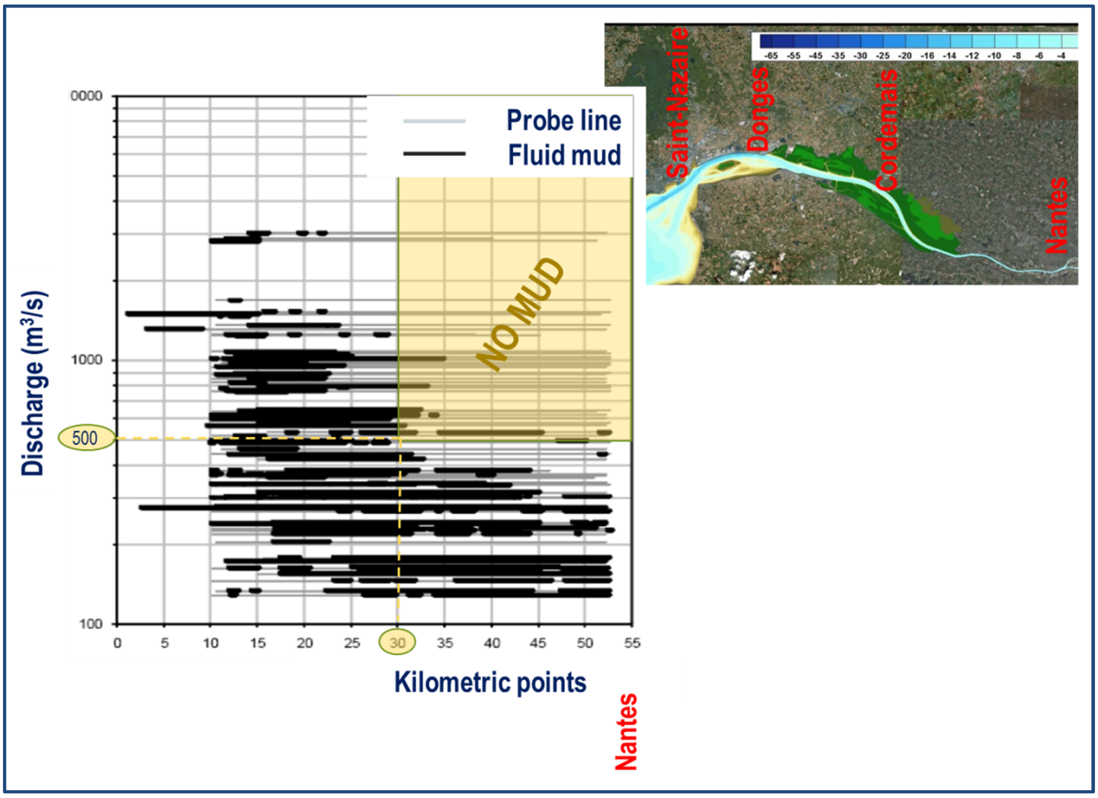

Figure 18. Measurement of mud deposit in function of discharge of Loire river

FUTURE WORK

At that point, the model proved to be able to reproduce a full annual cycle of the dynamics of the maximum turbidity in the Loire estuary without any assumption regarding the bathymetric state of the estuary. Numerous sensitivity tests performed in the course of this work show the importance of an accurate modeling of the settling velocity induced by the flocs dynamics. Efforts are put on this topic at the moment to improve that part of the model.

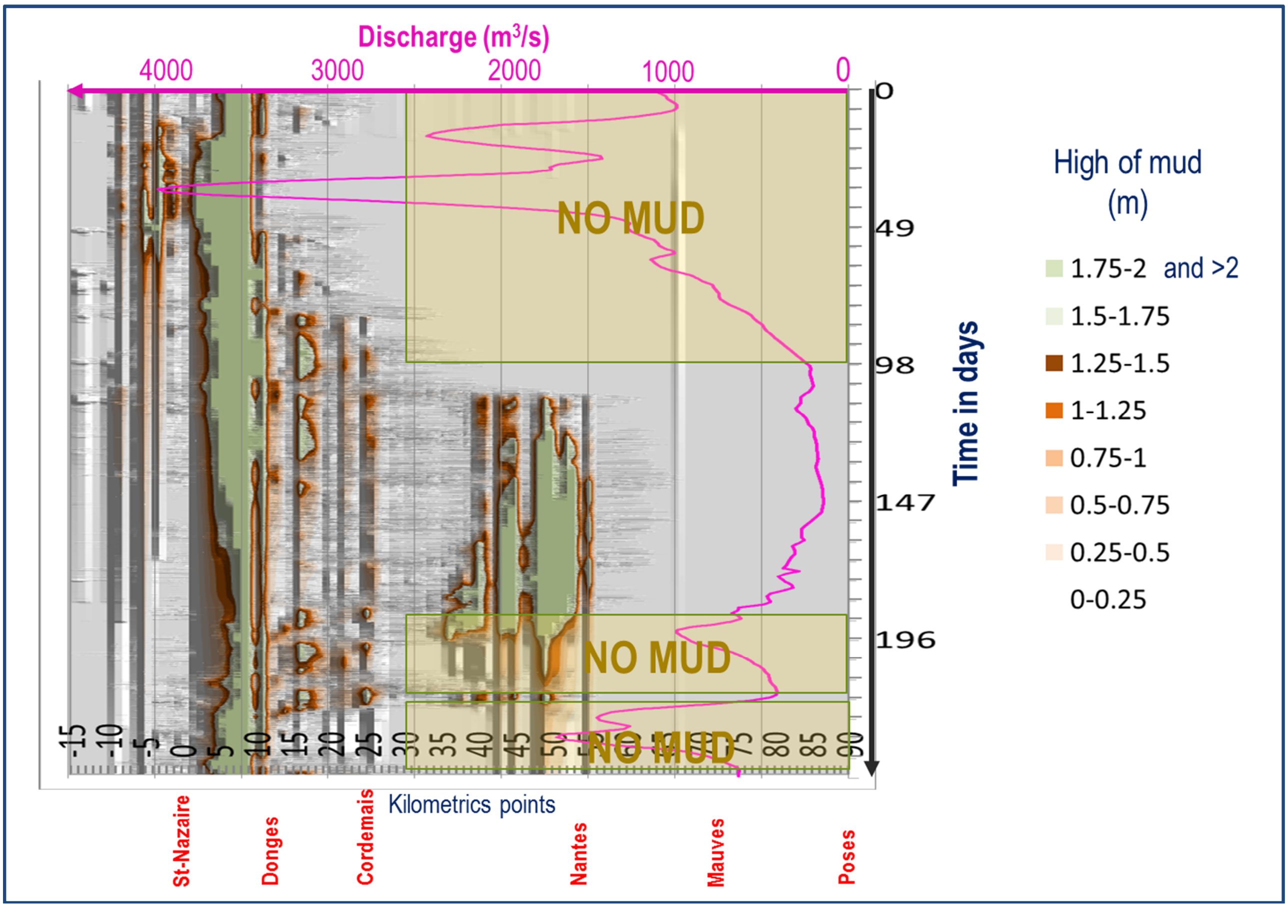

Figure 19. Simulated map of mud deposit in the channel of navigation during 8 months

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