EVALUATION OF AN OFFSHORE DISPOSAL SITE IN THE LOIRE ESTUARY THROUGH FIELD MONITORING AND 3D NUMERICAL MODELING

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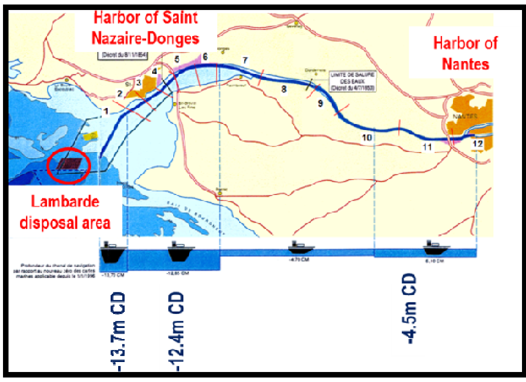
This communication presents the assessment of an offshore disposal site, named La Lambarde, located in open water offshore of the mouth of the Loire estuary in France. The site is used since 1986 by Port Authority of Nantes-Saint-Nazaire (GPMNSN) to relocate fresh sediment dredged for maintenance purposes in the access channel and port installations located along the estuary. A six-year study, commissioned by GPMNSN authorities to ARTELIA, started in 2007 to optimize the location of the disposal site and improve the knowledge of the suspended sediment regional dynamics.

Keywords: 3D, hydro-sedimentary, sand mud mixture, estuary, dredging, dumping

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. The long-term mean discharge of the Loire river is 825 m^3/s with considerable variations ranging from 60 and 6,000m^3/s. A dredged navigation channel serves Saint-Nazaire Harbor at the mouth of the estuary and Nantes Harbor 55 km upstream. Between 2004 and 2010, 36.6 million m^3 was dumped in the disposal area of Lambarde (Fig.1). The Site of Lambarde (3000 m x 2000 m) is divided into 15 sub-zones (Fig.2). Sub-zones: 0, 1 and 2 have been used between 2004 and 2010.



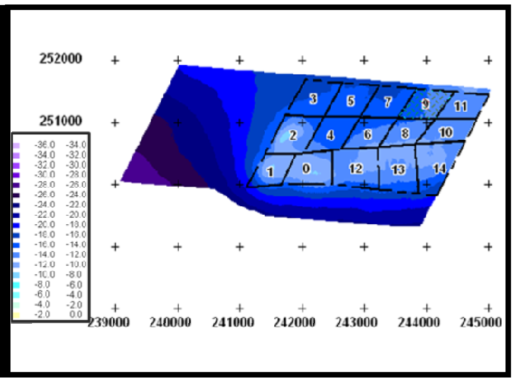


Figure 1. Map of navigation channel and disposal area. Figure 2. Bathymetry of Lambarde disposal site.

Assessments performed in 2001 and 2007 have shown that the disposal site is strongly dispersive with about 80% of the 5 million m^3 of very fine sediments dumped annually (mixture of 88% of silt and clay and 12% of sand; in situ density of 1.4) were remobilized by waves and currents and dispersed regionally. This conclusion raised questions among the administration and the stakeholders about the impact of this source of fine sediments on the neighboring coast and activities and about the ways to reduce it. A six-year study, commissioned by GPMNSN authorities to ARTELIA, started in 2007 to solve these questions, optimize the location of the disposal site and improve the knowledge of the suspended sediment regional dynamics. The study was divided into three parts:

1. Preliminary study (2009)
2. Field campaign (2010-2011)
3. 3D hydro-sedimentary model (2011-2012)

The third part is the main object of this paper.

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PRELIMINARY STUDY

A classical 3D hydrodynamic model was first set-up and trajectories of particles with a critical shear stress from Lambarde site was calculated on the hydrological year 1999. 10 representative sequences of oceano-meteorological conditions were selected. Fig.3 is an example of results for two typical sequences. From these results and statistical weighting, the first annual short-term dispersion pattern was established (Fig.4).

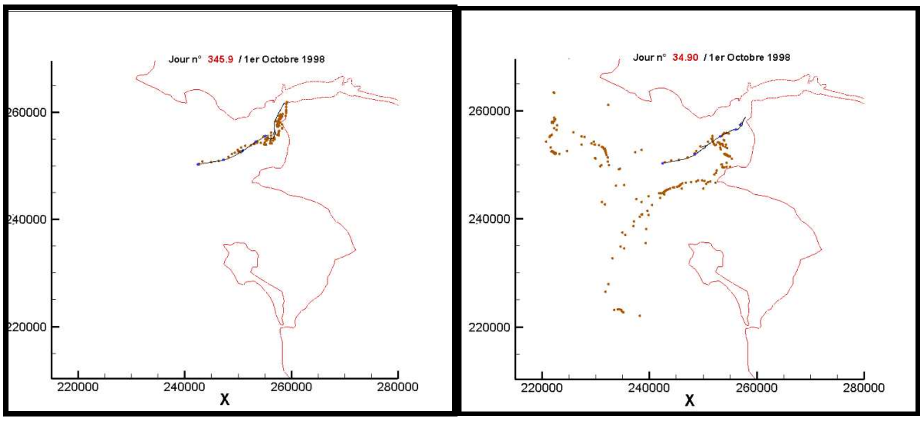

Figure 3 :Period 1: Field of particles after 15 days of low flow, low wind (NE ->W) and low waves and Period 3: Field of particles after 15 days of mean-> low flow, strong wind (W->NW), mean -> strong waves.

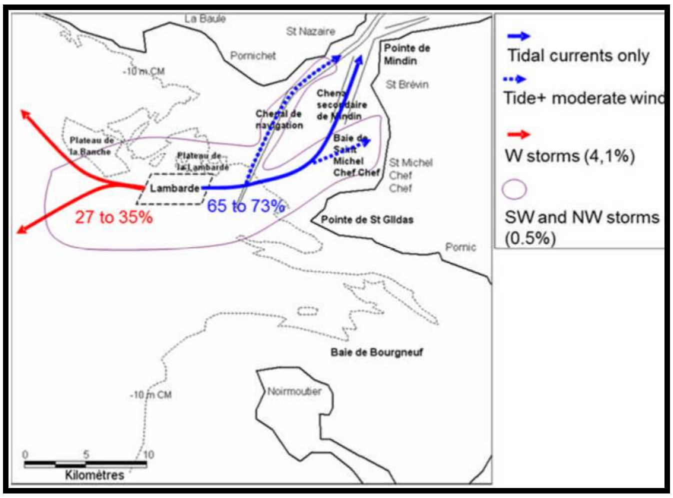

Figure 4: Preliminary study: establishing a first dispersion pattern

The study of patterns of dispersion and time cards exceeded several critical shear stresses allowed to propose three alternative disposal sites. The location of these three alternative disposal sites (Fig.5) is a compromise between different parameters as stability, dispersion, economic, biological, fishing, shipping and others…

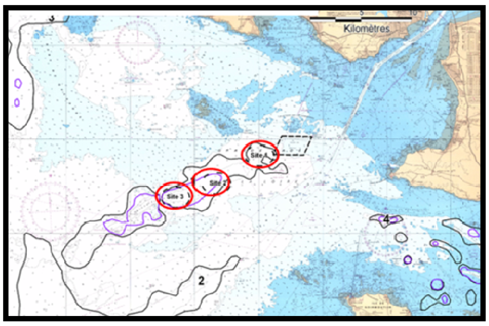

Figure 5: Location of 3 sites for an alternative disposal

FIELD CAMPAIGN

This initial understanding enabled the preparation of a large field campaign, carried out in September and October 2009 and April-May 2011 by IMDC, covering hydrodynamic conditions, short-term local monitoring of placing events and medium term regional monitoring of suspended sediment fluxes and deposition (N. Zimmermann et al. ,2010).

Field campaign at fixed point

Three fixed stations measurements are implemented, near the actual dumping area, near the site 1and between site 2 and 3 (Fig.6). The objective of the fixed stations measurements is to provide the hydrodynamic and sediment transport conditions prevailing during the field survey for the results analysis. Additionally it should help characterizing the alternative disposal sites, and help to determine the dispersion and re-suspension of sediments on the medium- to long-term. Each station measured during three weeks, starting from the beginning of the dredging campaign. Each station was composed of a series of instruments measuring turbidity, salinity, current velocity and direction, wave characteristics and for Lambarde station: erosion-sedimentation (Fig.6).

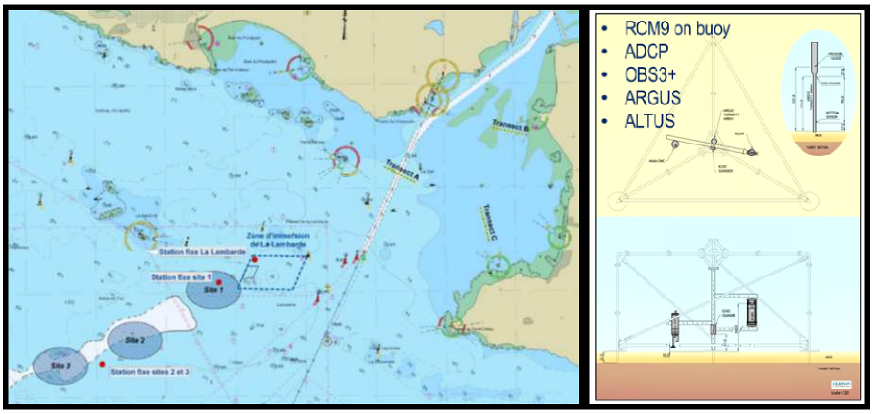

Figure 6: locations of fixed stations (red) and transects (green) and scheme of Lambarde fixed station

Field campaign: Instruments on a survey vessel

A vessel was equipped with an ADCP and a Siltprofiler, for measurement of plume tracking and measurement of Sediment fluxes through transects. The objective of the plume tracking (Fig.7) is to determine the behaviour of the sediments immediately after dumping, both in the water column and near the sea bed, under different hydrodynamic conditions and according to the sediment characteristics. The objective of transects measurements (Fig.6) is to determine the fluxes of dispersed sediments in direction of the estuary through predetermined transects during a complete tidal cycle. Three transects are situated at mid-distance between the disposal site and the city of Saint-Nazaire, respectively perpendicular to the navigation channel (A), the secondary channel of Mindin (B) and in the direction of the bay of Saint-Michel Chef-Chef (C).

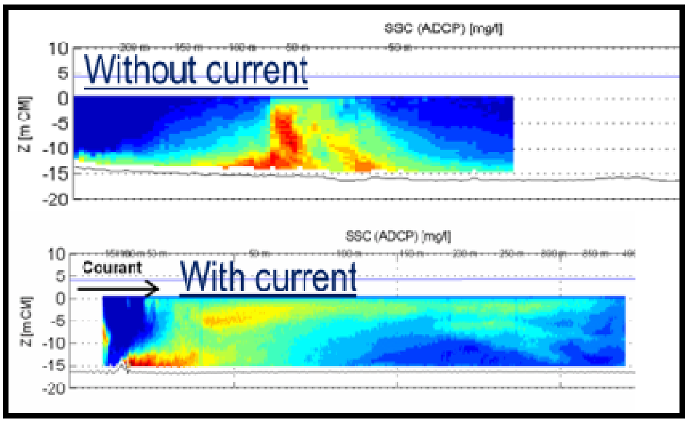

Figure 7: dispersion of the plume under the influence of the current during a Lagrangian protocol measurement

Field campaign with fluoresent tracer

Fluorescent tracer with the same characteristic as sediment mixture was mixed and dumped, during ebb and during flow the 1rst April 2010 on the Lambarde site. This was followed by two sediment sampling campaigns in targeted areas of the estuary which took place at mid-April and at the end of May. The objective of a campaign with fluorescent tracer is to measure dispersion end recirculation in the bay.

Bathymetric surveys

Regular six-monthly bathymetric surveys over the period 2004-2011 were also analysed to establish the stability of the disposal site (Fig.8).

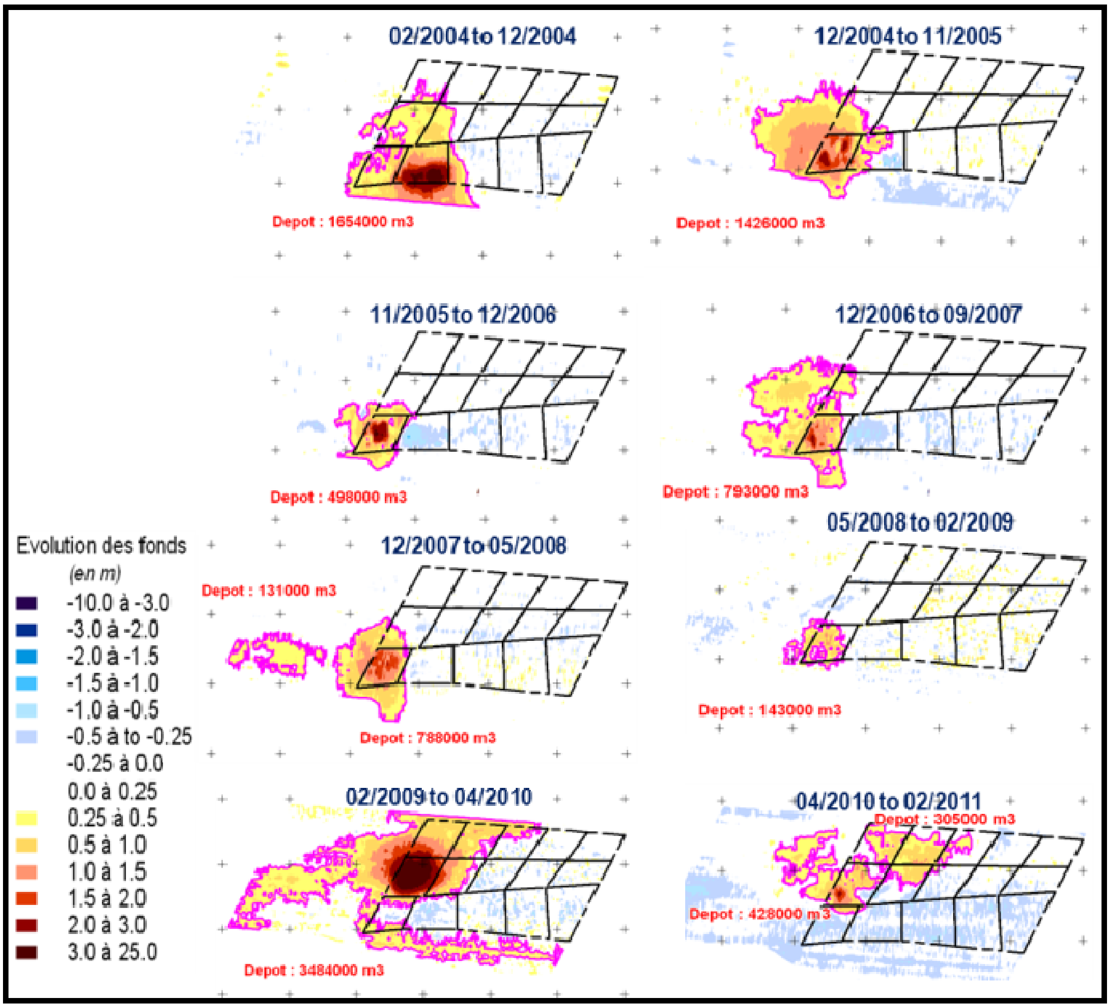

Figure 8: Evolution of Bathymetry

3D HYDRO-SEDIMENTARY MODEL

Using an existing Telemac 3D model of Loire estuary

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 (Fig.9). 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.

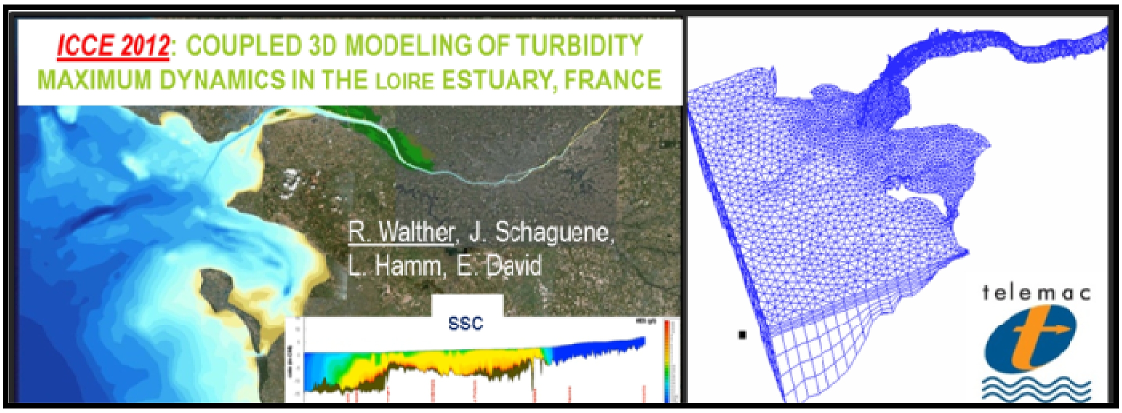

Figure 9: View of Telemac-3D model of Loire estuary

This operational 3D model is calibrated and validated in the inner estuary: sea levels, currents, salinity, sedimentology including turbidity of mud transport and bed level evolutions in mud (R. Walther et al. ,2012).This model included particularly:

- New law of erosion (M.Sanchez and D. Levacher,2008)
- New law of consolidation (M.Sanchez et al.,2004)
- Flocculation effects on fall velocity
- Sliding effect
- Development of a multilayer mixing length for a better calculation of stratification effect (R. Walther et al.,2009)
- Morphodynamic coupling of bottom roughness and fluid mud (L. Hamm and R. Walther,2008)

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 (R. Walther et al. ,2012).

Adaptation and validation of the model in the study area

The mesh of the model was refined by reducing the mesh size of about 100m horizontal grid in the area of the deposit site and 250m around. The model simulated the 2009-2010 hydrological year and compared to the measurements on the period from 24 September to 14 October 2009.

The model correctly represents the water levels and currents in the outer estuary (Fig.10).

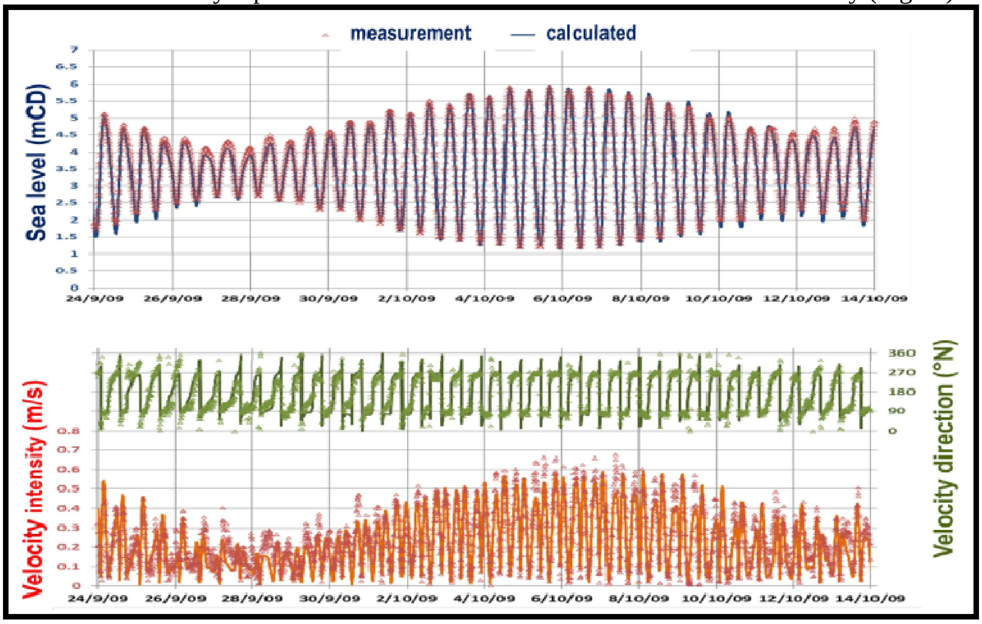

Figure 10: Sea level and velocity comparison

The model correctly represents the magnitude of the salinity measurement at the bottom as at the surface. In particular we identify the effect of low tides allowing a little stratification between the bottom and surface. The effect of high tides tends to homogenize the bottom salinity and surface (Fig.11).

The 3D model uses a library of waves propagation that was pre-calculated for different water levels, directions, and periods. A total of 1920 wave propagation are pre-calculated. At each time step a spatial interpolation is performed, from the waves measured at the maritime boundary and the library. This relatively simple and very fast method of calculation time gives good results (Fig.11) as bathymetry does not change too much.

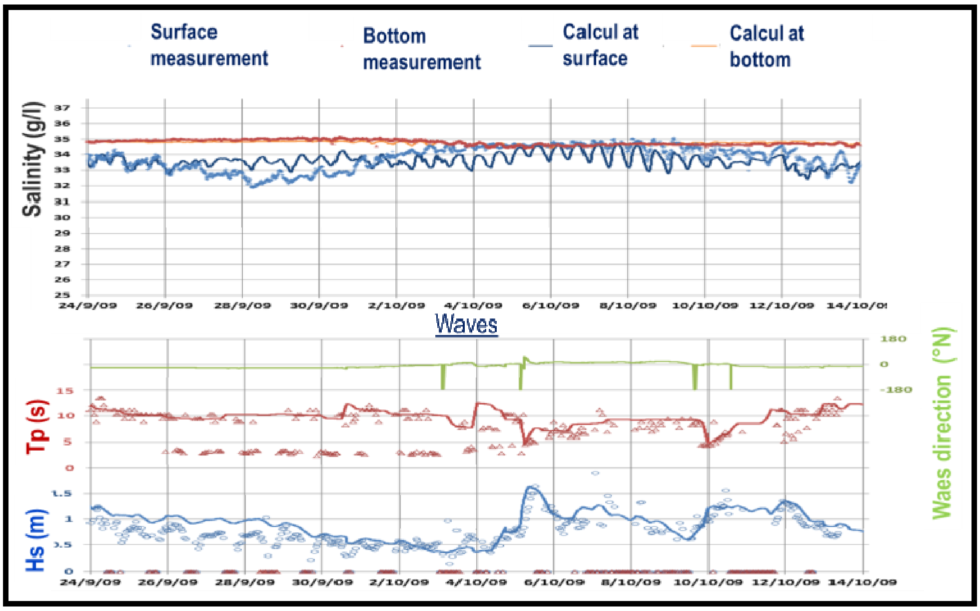

Figure 11: Comparison of salinity at bottom and surface and comparison of waves in amplitude an period

Introduction of a mixed sediment in Telemac-3D

It was added in Telemac-3D a sand sediment tracer, in addition to the mud sediment tracer.

In the water column, both sediments do not interact, both of them have their own fall velocity and thus their own deposition flux.

However, they interact in the consolidation model, in which mud and sand are mixed in each layer of the consolidation model. The percentage of the mixture then modifies critical shear stress of layer and flow erosion.

When the mass fraction of mud in the mixture (Fig.12) is below ~ 0.3, the critical shear stress is larger than that of pure sand. Mud infiltrate into the pores formed by the assembly of sand brings cohesion mixture (b). When the mass fraction of mud in the mixture is higher than ~ 0.3, mud that have infiltrated the pores between not allow contact of the sand grains together. The critical stress decreases (c).When the mass fraction of mud in the mixture is higher than ~ 0.5, it can be considered that the mixture behaves like pure mud.

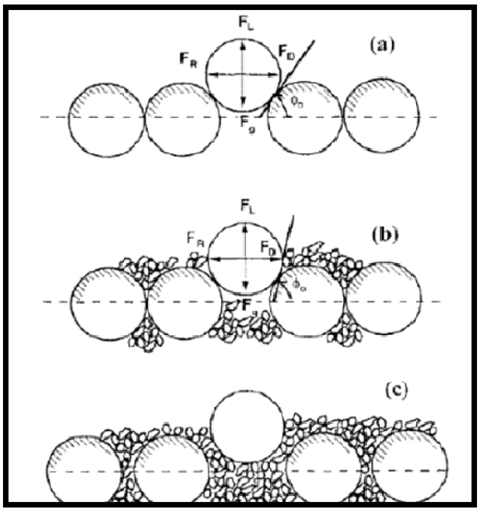

Figure 12: Conceptual diagram showing the implementation mechanism in motion, Panagiotopoulos et al., 1997

In terms of flows, the code computes a flow of pure sand and a flow of pure mud. The equilibrium concentration at the reference level for pure sand is calculated at each point of the model by model 1DV TRANPOR 2004(Leo.C. van Rijn, 2007), taking into account the combined effect of wave and current.

Depending on the mixture in the treated layer, a mixture flow is derived and based on the mass fraction of each class of sediment (Fig .13).

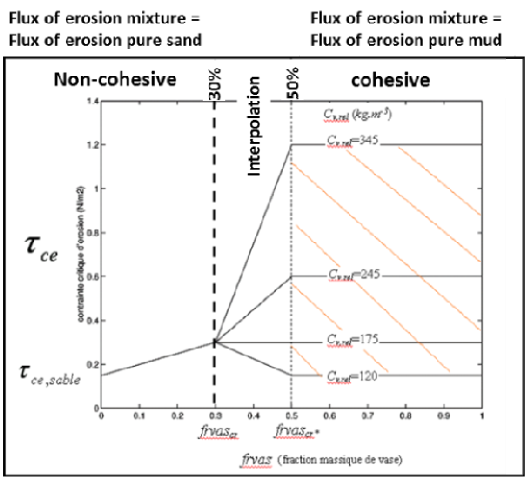

Figure 13: Variation of critical shear stress as a function of mass fraction of mud (Frvas) and relative concentrationof mud (Cv,rel), (B. Waeles, 2005)

Hydro-sedimentary 3D model of stability

The purpose of the model of stability is to correctly reproduce the evolution of the disposal site over 7 years.

Description and Boundary condition

The real time series from 2004 to 2011 will be imposed in tide, mean sea level, wind, wave and dumping (position, time and mass distribution in sand and mud).

Given the significant time calculation, it was decided to create a model in 3D, forced by the general model of the Loire estuary (Fig.14).

Every 3 months the library of wave propagation in the stability model is recalculated to take into account the evolution of the bathymetry site.

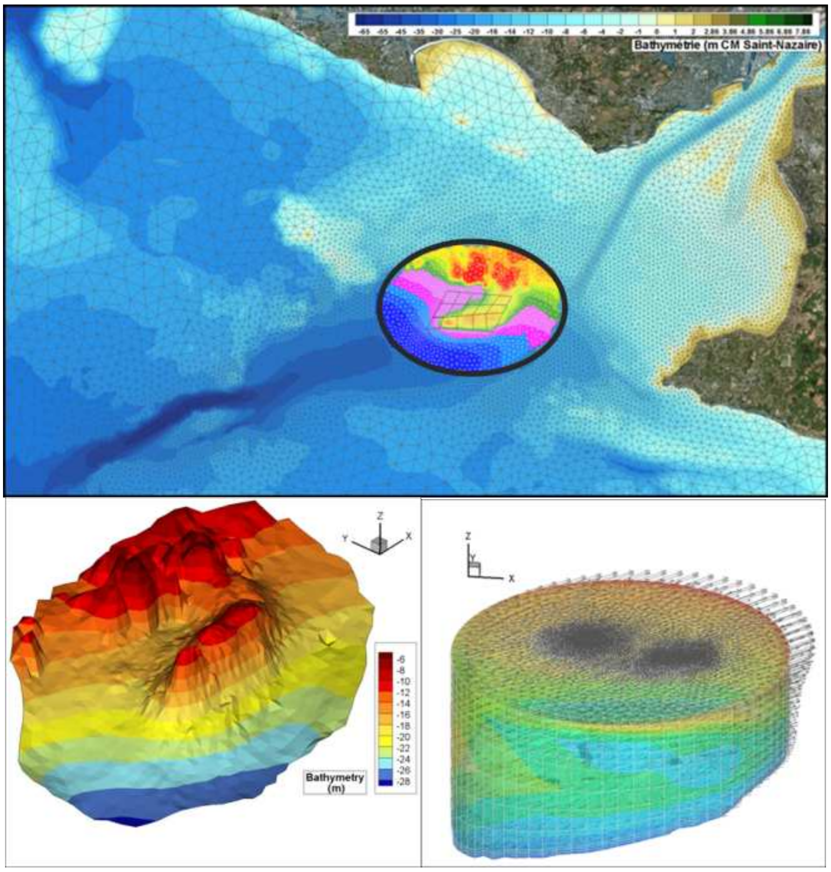

Figure 14: 3D sub-model of stabilty

Hypothesis for the near-field

The near field of sediment release is not calculated (time and space scale are not adapted), it is approached by assumptions regarding the distribution of masses from the measurements 5-10 minutes after the start of dumping.

The mass of each sediment release is distributed uniformly over 10 minutes and sub-divided into three phases:

- The suspension dissolved in the entire water column
- The bottom turbid plume,
- Part deposited on the bottom

The bottom turbid plume that has a lifespan of 10 to 15 minutes from the measurements is put in the bottom layer of the model less concentrated: 40g/l. The mass is distributed with in 500m around the central position of the point of dumping.

The part deposit in the bottom is divided into the layers of concentrations between 40 and 100g/l. The sandy part of the dumping is set entirely in the layer 100g/l. The masses are also distributed within 500m around the point of dumping.The radius of dumping was a calibration parameter and the value of retaining 500m corresponds to the empirical result of calibration. It remains consistent with measurements.

The mass distribution in the three phases is based on the speed of the ambient current (Fig.15).

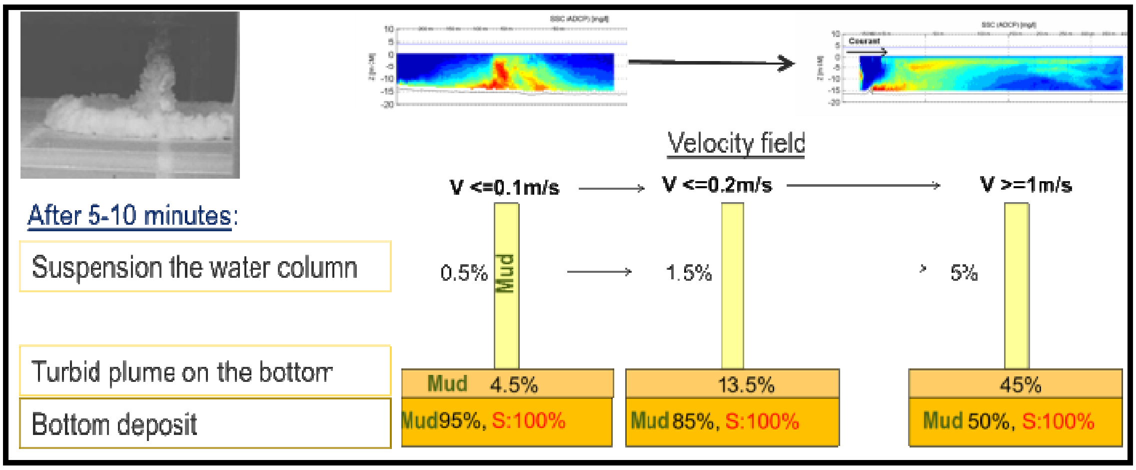

Figure 15: Hypothesis of mass distribution in the near field

The measures of plume tracking reinforce laboratory experiments of R. Boutin (R. Boutin, 2000) and also designed to provide a balance between bottom turbid plume and suspension dissolved in the water column.

Calibration and validation of hydro-sedimentary 3D model of stability

The model of stability is calibrated and validated on the basis of bathymetry between February 2004 and February 2011. The calibration was performed on measured evolution during the first 3.5 years. The validation consisted to simulate the last 3.5 years.

After the seven years, the deposit measured on the site is 9.8 million m^3 while dumped volumes are in the same period 39.6 million m^3 (calculated volume density up to 1.4). The stability rate in volume (typically used by ports) is 24%.

The main fitting parameters were:

- The choice of layers of concentration mud in which the mud are initially deposited.
- The radius on which is deposited the mass of each dumping around the centre point
- The critical stress for erosion for highly concentrated mud: it was decided to limit the critical stress 1.53 N / m2, which corresponds to a vase of 300g/l
- The parameter value of sliding effect

Calibration was performed initially on the volume remaining in place on the site throughout the 7 years. Also, as can be observed in graph (Fig.16), the average stability of the deposit around 25% is well reproduced by the model.

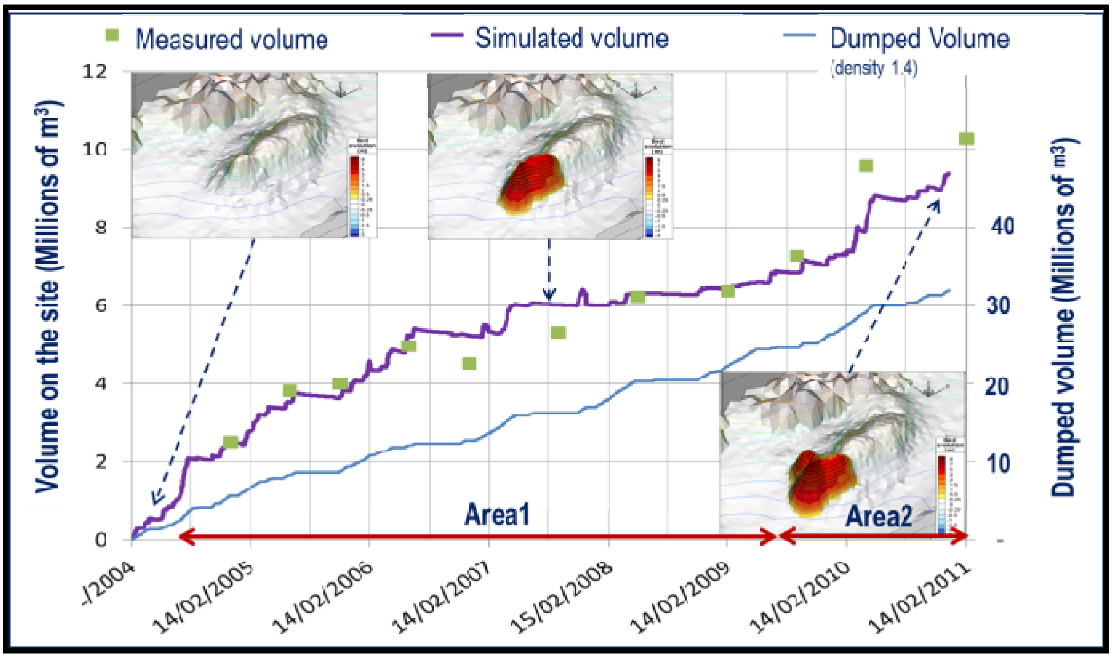

Figure 16: Comparison of the volume on the site

For area 1 and 2, maps of bathymetric evolution are provided (Fig.17). Volumes find on site were found with less than 3% of error but with a little less spreading in the model.

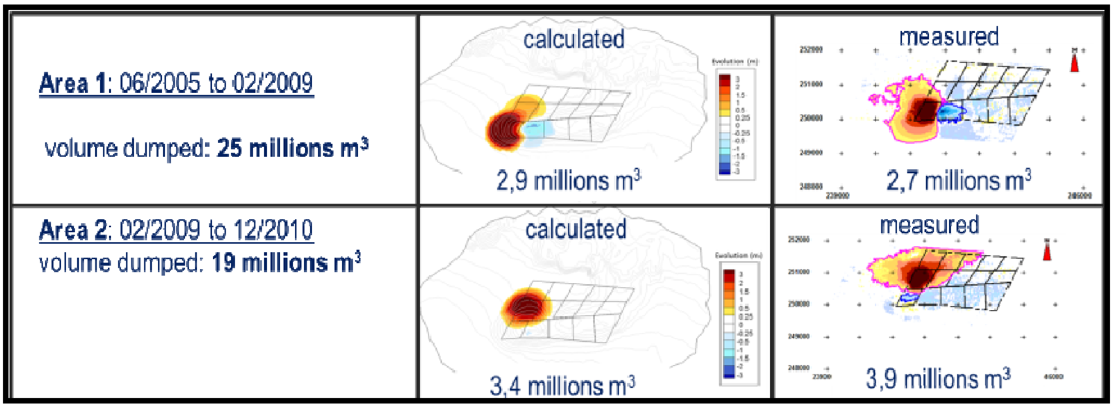

Figure 17: Bathymetry evolution

For each bathymetry, we calculated an average bottom level per area, in order to assess the temporal and spatial distribution of deposits on the site. Changes in average bottom level of each area are relatively well represented (Fig.18). This good agreement was obtained by fitting the radius of dumping. Indeed, this radius has an important role on the distribution of dumped volume between the target area and neighboring area.The sliding effect plays an important role on the area 3 or no dumping is made and for which we see a significant bathymetric evolution between 2010 and 2011 (Fig.18). The critical shear stress of consolidated sediment plays an important role in the evolution of the area 0, where there is no dumped after 2005 (Fig.18).

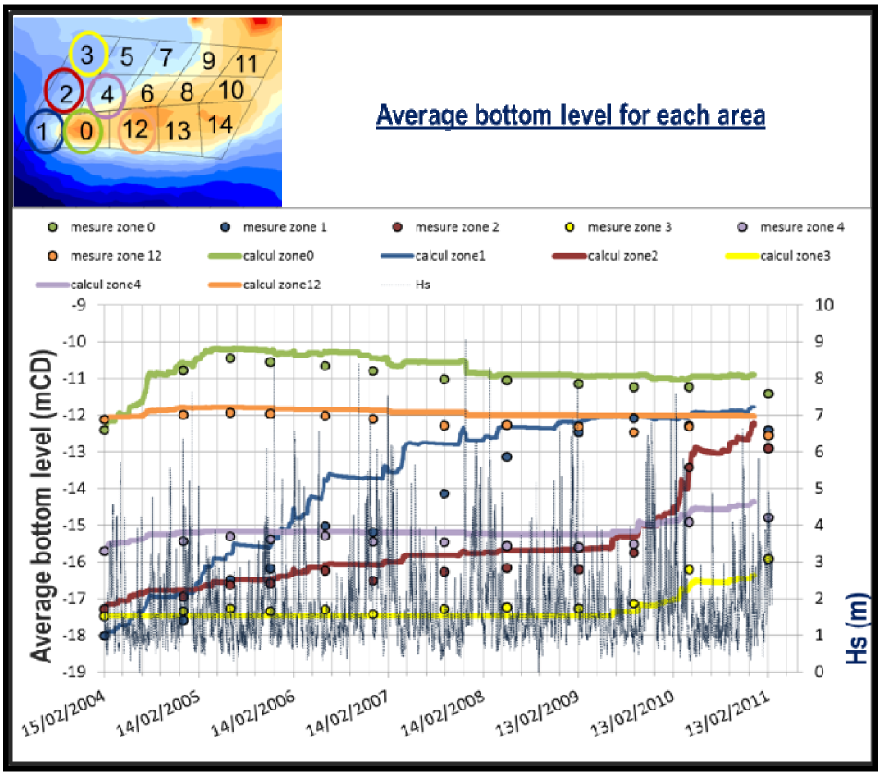

Figure 18: Average bottom level for each area

Influence of waves

With a focus on the graph of volume at bottom evolution (Fig.19), we can see the strong influence that may wave during dumping on the site stability. In this example, if sediment is dumped with more than 2 meters of waves, there is no stability.

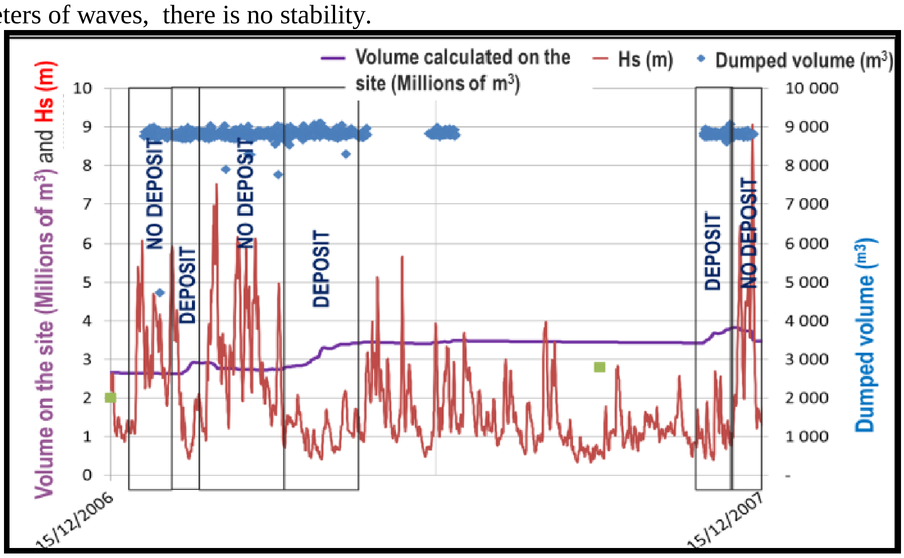

Figure 19:Influence of waves on the stability

Hydro-sedimentary 3D model of dispersion

Once all sedimentological parameters have been calibrated in the sub-model of stability, it is reintroduced into the overall model (Fig.20).

The goal of the 3D dispersion model is to follow over a year the dumping in the far field. The data used here include 1371 dumping from 21 September 2009 to 21 September 2010. Mass of sediment are respectively 0.33 million tons of sand and 4.12 million tons of mud for a total of 4 45 million tons dumped in area 2.

Calibration of hydro-sedimentary 3D model of dispersion on measurement of Suspended Sediment Concentration

In this simulated year, we have a series of measurements of Suspended sediment Concentration at Site 1 (Fig.20) in September 2009 which is about 3km from the dumping area.

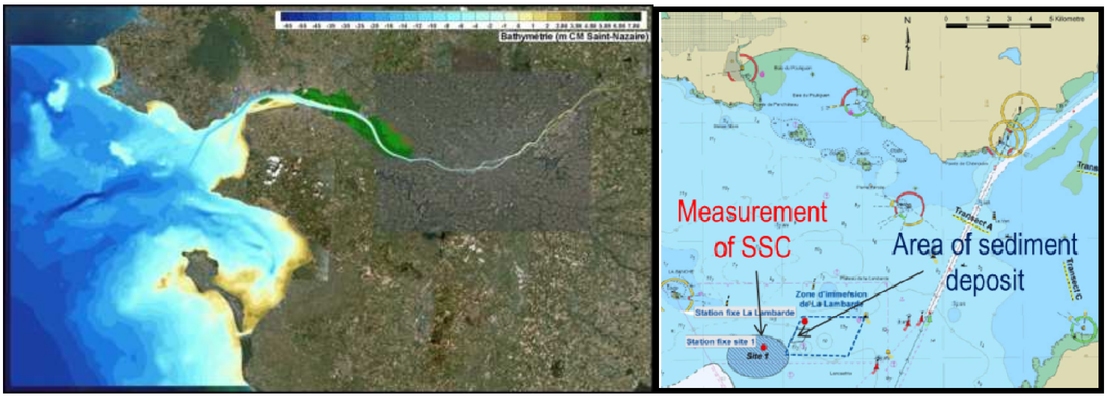

Figure 20: General view of the dispersion model and Location of Suspsended Sediment Concentration measurement

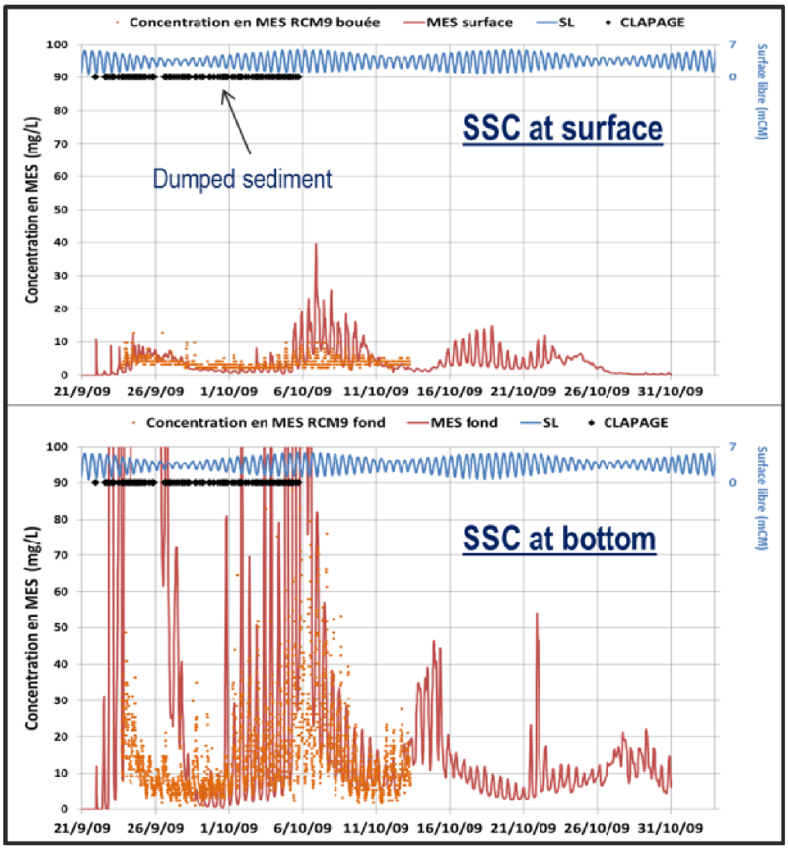

Figure 21: Comparison of suspended concentration at the surface and at the bottom

Correspondence with the model is reasonable, even though peaks are more important in the model (Fig.21). Measurements are quite close to the area of dumping, where assumptions are made on the forms and distributions of sediment release, but quality of the result is very correct. To obtain these results, particularly on the surface, fall velocity for low concentrations has been adapted over the original law. Indeed the Original fall velocity law had been calibrated on the dynamics of the turbidity maximum, which is more related to the dynamics of higher concentrations.

Comparison with flusorescent tracer campaign of April and May 2010

The April-May 2010 campaign, consists of two sediment releases on the 1rst April containing a fluorescent tracer, followed by a campaign sediment sampling in targeted areas of the estuary that took place on 20 and 21 May .

The sediment releases were made during ebb and flow of spring tide (coefficient 106) and just before a storm of Western significant height peaking at 5.5m. The sampling campaign was carried out following northeast established wind (between 5 and 11 m /s).

Map of maximum deposits obtained on the sampling period (20-21 May) is compared to the map of tracer presence in the samples (Fig.22).It was observed that the areas where the tracer was noted are in areas where the model had deposits. Deposits are more pronounced in the Bay of Saint-Michel-Chef-Chef than in Bay of Bourgneuf. This is in the sense that the tracer concentrations found were higher in the Bay of Saint-Michel-Chef-Chef. Unfortunately, more quantitative comparison is technically difficult.

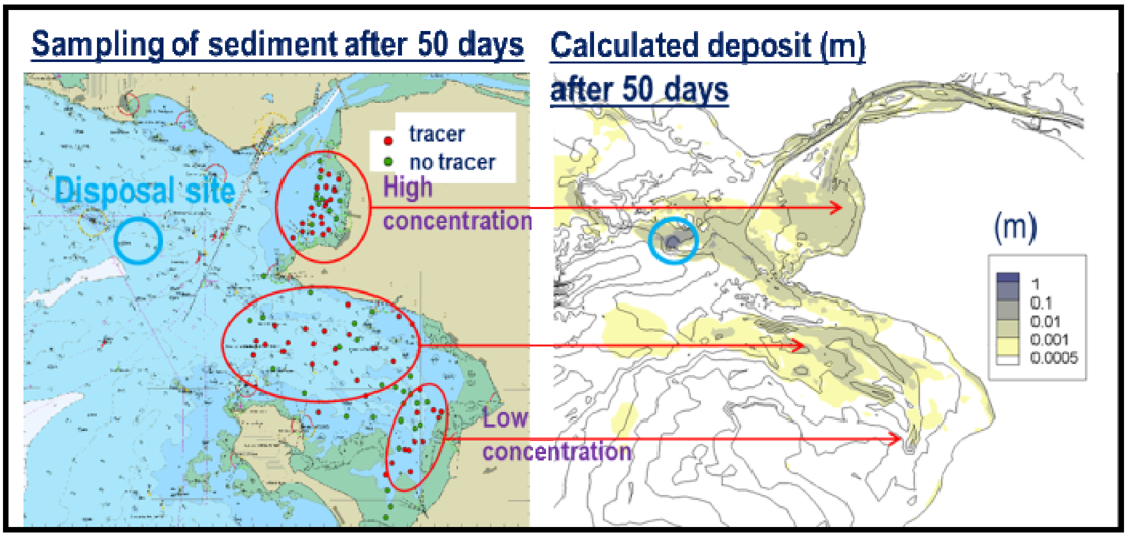

Figure 22: Comparison of tracer meausrement and deposit during 1 April-21 May

Dispersion results after one year

Figure 23 show that annual average (off near field area), dumping induces an excess concentration relative to the natural conditions.

The maxima show with initial directions (that is to say when the plume is concentrated again) that may take the plumes from the following different hydro-meteorological forcing (Fig.23).

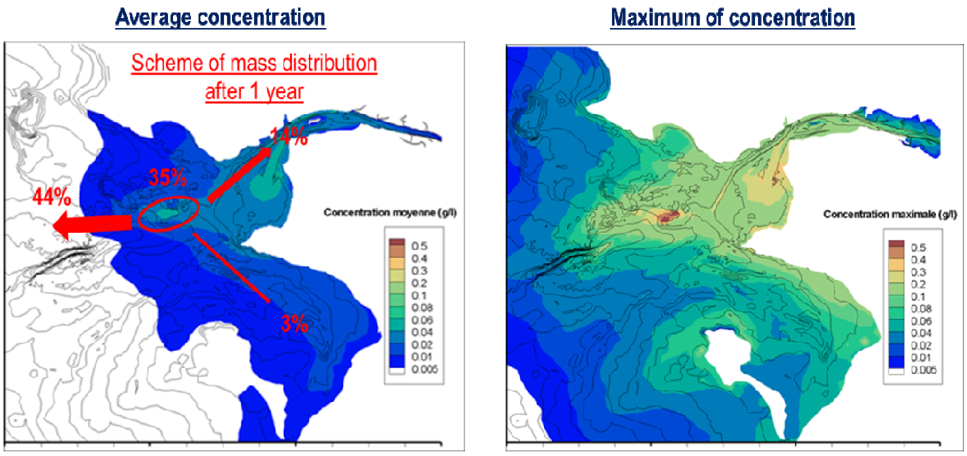

Figure 23: Average concentration of Lambarde sediment dispersion during one year and maximum concentration of Lambarde sediment dispersion during one year

Clearly, there is the area of influence around the Lambarde in east-west axis, the entrance to the “grande fosse” and the entry of the navigation channel and the East Coast: Bay of Saint-Michel-Chef-chef and channel Mindin and the northern entrance of the Bay of Bourgneuf. The inner estuary part is more like a reconstruction of turbidity maximum, as a plume of Lambarde.

CONCLUSIONS

An important measurement campaign, defined from the results of a preliminary 3D model of the Loire estuary, allowed to calibrate and validate:

•A sub-3D model of stability in sand mud mixing that simulate real-time up to 7 years of bathymetric evolution

•A 3D model of dispersion in sand mud mixing, that simulate up to 1 year of dispersion in real time

•These two models were used: to better analyze and understand the current situation, to compare six dumping scenarios in stability and dispersion (Fig.24), to compare dumping strategies (in time and space)

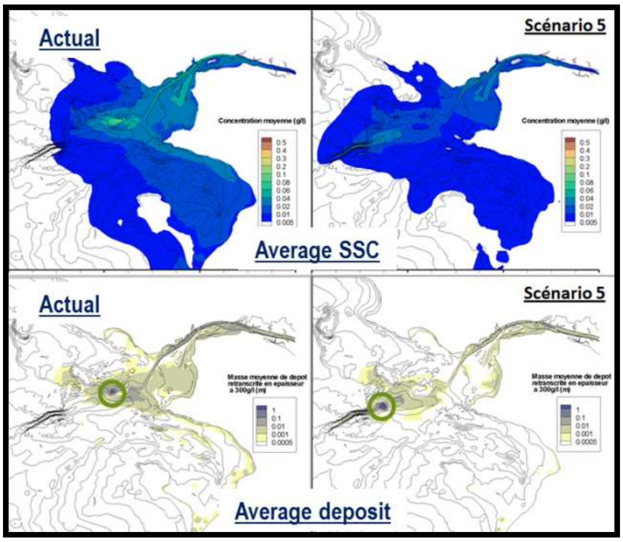

Figure 24: Exemple of comparison of dispersion between current situation and scenario 5

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