Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/104235

Vorgeschlagene Zitierweise/Suggested citation:
Daou, Mehdi; Larroudé, Philippe; Cartier, Adrien; Hequette, Arnaud (2011): Comparison of sediment transport formulae with simulation of several storms on a Mediterranean beach and with in-situ sedimentary flux on a North Sea beach. In: Violeau, Damien; Hervouet, Jean-Michel; Razafindrakoto, Emile; Denis, Christophe (Hg.): Proceedings of the XVIIIth Telemac & Mascaret User Club 2011, 19-21 October 2011, EDF R&D, Chatou. Chatou: EDF R&D. S. 28-34.

Comparison of sediment transport formulae with simulation of several storms on a Mediterranean beach and with in-situ sedimentary flux on a North Sea beach

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***Abstract*— This paper discusses the abilities of numerical models to predict the morphodynamics over loose and rigid beds. In the first part the sediment transport model is presented which solves the bed evolution equation in conjunction with sediment transport formulas. The flow field and the water depth are calculated using the depth-averaged hydrodynamic model TELEMAC-2D developed by Électricité de France.**

I. INTRODUCTION

The work consisted in setting up the methodology of calculation (De Vriend (1987) [9], De Vriend and Stive (1987) [10], Smit et al., 2008 [19]). The principle is to make an external coupling of three codes. This coupling consists in enchained Artemis for swells, Telemac2d for the currents and Sisyphe for the morphodynamic evolution (Hervouet, 2007[12]). The basic principle of this external coupling is to make this loop on the codes with a step of morphodynamic time depending essentially on weather conditions and on the environment hydrodynamics of the studied beach. These models were used in the framework of a simulated meteorological cycle describing the seasonal evolution of hydrodynamic factors.

This paper discusses the abilities of numerical models to predict the morphodynamics over sandy and rigid beds. In the first part the sediment transport model is presented which solves the bed evolution equation in conjunction with sediment transport formulas. The flow field and the water depth are calculated using the depth-averaged hydrodynamic model TELEMAC-2D and simplified model called Multi1dh. This model was already used and tested in Camenen and Larroudé, (2003b) [3].

The objectives which we want to reach during this study are multiple. First, we are going to set up a procedure for linking the three codes to be able to simulate realistic climates. This procedure is validated from the point of view of the hydrodynamics and morphodynamic evolution (Larroudé, 2008 [14]). This technique of simulation will then use to compare and to study the contribution of various sediment transport formulae (as in Camenen, 2002 [1], on the site of Sète during two specific storm (see Robin et al., 2010 [17]).

We improve this methodology to simulate the Rising-Apex-Waning of a Storm event. We also look at the comparison of the current during these different periods of the storm. To calibrate all these sediment formulae, we also compare our simulations with in-situ data of longshore and cross-shore sediment transport measured on several beaches of the North sea and of the English Channel (Cartier and Héquette, 2011 [4] and 2011b [5]).

II. DESCRIPTION OF THE STUDIED SITES

A. Site 1

The "Plage de la Corniche", located near Sète on the Mediterranean coast, France, was selected as the first study area (Fig. 1). Located in a microtidal, swell-dominated coastal environment, the "Plage de la Corniche" is a linear beach of about 2.5 km length. The mean near shore bed slope is 0.04, while the median grain size in the surf zone is 0.25mm.

The mean significant offshore wave height is about 1.5 m increasing to 3–6 m during storms, while the predominant wave direction is from SSE with occasional SE swells. There is no significant seasonal variation in the offshore wave climate.

Certain and Barusseau (2006) [7] showed that the morphodynamic evolution of offshore bars in a microtidal environment and bimodal moderate wave regime follows two different conceptual models, the main one being a seasonal pattern in line with the observed cycle of hydrodynamic conditions (see also Certain, 2002 [6]).

B. Site 2

The second studied area consists of three intertidal sandy beaches on the coast of Nord-Pas-de-Calais (northern France) located at Zuydcoote, Wissant and Hardelot Plage (Fig. 2). Zuydcoote site, located east of Dunkirk, is characterized by a beach of fine sand (D_{50} = 0.2 mm), 350 to 400 m wide, with an average slope of about 0.014. The tidal range varies from 3.4 m during neap tide to 5.2 m during spring tides on average, and this site can therefore be considered as meso-to macrotidal. The coast, oriented NE-SW, facing the North Sea, is characterized by fetch-limited short waves.

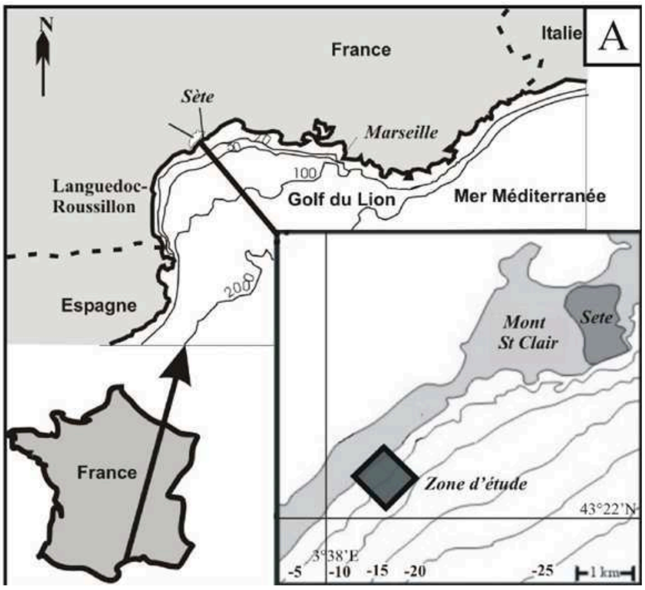

Figure 1. Localisation of the "plage de la Corniche" at Sète in Mediterranean Sea.

The Wissant site is located in a bay that extends over 6 km, bordered on the south by the Cap Gris Nez and the north by the Cap Blanc Nez. The hydrodynamics is more powerful due to the exchange of water mass between the North Sea and The English Channel which is particularly intense. The test site is located in the eastern part of the bay, characterized by a beach of fine sand (D50 = 0.22 mm) and an average slope of 0.012. The coast is subject to a tidal range from 4.2 m to 6.7 m for neap and spring tides.

The third site is located at Hardelot beach, at the Dune du Mont St-Frieux. The beach consists of fine sand (D50 = 0.23 mm) and has an average slope of 0.026. The tidal range reaches 4.8 m at neap tide on average and 8.0 m in times of great water. Oriented N-S, the coast is facing the English Channel.

Tidal currents on the three beaches flowing parallel to the shore and are characterized by a flood-dominated asymmetry. This dominance of flood currents, combined with a system of winds and swells from the SW, generates a hydrodynamic circulation and sediment transport directed eastward on the coast of the North Sea and northward on the shores of the Channel (Sipka and Anthony, 1999 [18]).

The purpose of the study is to estimate the longshore flow in the surf zone (and sometimes in the shoaling zone). Sediment transport rates were estimated using streamer traps following the method proposed by Kraus (1987) [13], allowing to measure suspended and near bed transport.

Kraus structures capture the sediment in suspension over a depth range of about 1m, they are composed of five nets with a mesh size of 63 microns to trap sediment at 0.05, 0.26, 0.46, 0.66 and 0.86 m above the bed. During high wave energy conditions, the sediment trap has to be deployed in shallower water and the two upper nets (0.66 and 0.86 m) are then removed. The structures are placed for 10 minutes, facing the mainstream, which is determined visually by the operator. The sampling time may vary depending on the conditions of agitation and/or the rise/fall more or less quickly of the sea level so this sampling time could be from 5 to 10 minutes.

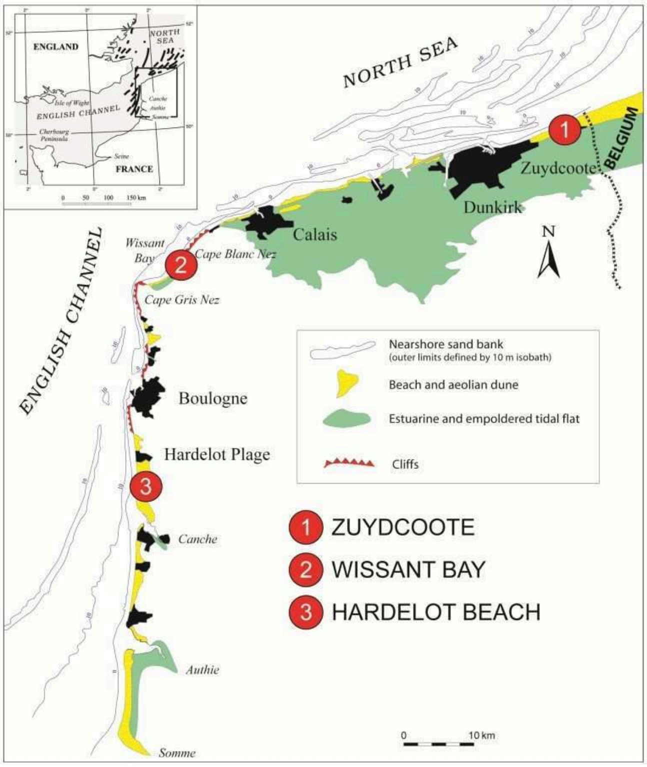

Figure 2. Location of studied sites for the sediment fluxes measurements.

Current meter devices are also deployed on the foreshore. The instruments are routinely placed on the outer side of intertidal bars. Three devices were used, ADCP, S4 and ADW Valeport (electromagnetic current meter). It saves data to hydrodynamic 2Hz, a burst of all the 9min and 15min. Only Valeport S4 allows us to have data at 2 Hz.

Morphological monitoring of each zone was carried out each sampling day using a high precision DGPS, for detail see Cartier and Héquette (2011b [5]).

Sediment fluxes are obtained at a given point in the littoral zone and at given time of a tidal cycle. The Flux is integrated in the water column ($kg.s^{-1}.m^{-1}$). Trapping was carried out in different directions in order to measure longshore, onshore and offshore sediment flux.

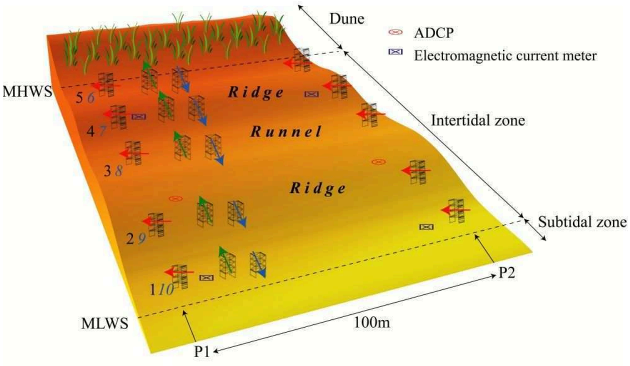

Figure 3. Field methods. Arrows indicate the direction of transport; the figures on the right correspond to the different positions of trapping during the flood and ebb.

III. MODEL AND METHODOLOGY

The sedimentary evolution is modeled under the action of the oblique incident waves and is coupled with different numerical tools dedicated to the other process involved in the near shore zone. We can mention the following modules:

The wave module takes into account the surge energy dissipation (hyperbolic equation of extended Berkhoff), (LNHE, Artemis, 2002). The Artemis code (Agitation and Refraction with Telemac2d on a MIld Slope) solves the Berkhoff equation taken from Navier-Stokes equations with some other hypotheses (little camber of the surface wave, little slope, etc.).

The main results are, for every node of the mesh, the height, the phase and the incidence of the waves. Artemis can take into account the reflection and the refraction of waves on an obstacle, the bottom friction and the breakers. One of the difficulties with Artemis is that a fine mesh must be used to have good results whereas Telemac2d does not need such a fine mesh.

The hydrodynamic module calculates currents induced by means of the surge of the waves, from the concept of radiation constraints obtained according to the module of waves, (LNHE, Telemac2d, 2002). Telemac2d is designed to simulate the free surface flow of water in coastal areas or in rivers. This code solves the Saint-Venant equations taken from Navier-Stokes equations vertically averaged.

Then, the main results are, for every node of the mesh, the water depth and the velocity averaged over the depth. Telemac2d is able to represent the following physical phenomena: propagation of long periodic waves, including non-linear effects, wetting and drying of intertidal zone, bed friction, turbulence, etc.

The sedimentary module integrates the combined actions of waves and currents (2D or 3D) on the transport of sediment The Sisyphe code solves the bottom evolution equation which expresses the conservation of matter by directly using a current field result file given by Telemac2d. (Fig. 4). Several of the most currently empirical or semi-empirical formulas are already integrated in Sisyphe. In this paper we show only the simulations with the Bijker formulas. The main results are, for every node of the mesh, the bottom evolution and the solid transport. The equations of the three modules are detailed in Hervouet, 2007 [12].

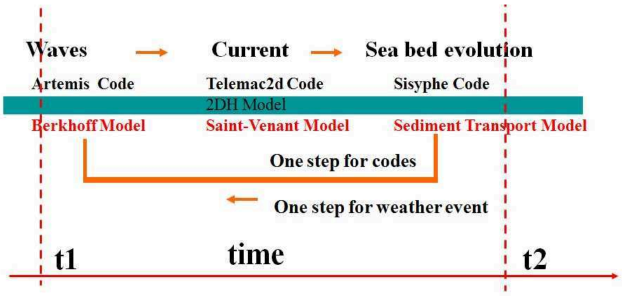

Figure 4. Diagram of the model ATS (Artemis-Telemac-Sisyphe) loop over one weather event time step (between t1 and t2) used for our simulations.

A hydrodynamic simplified model (called Multi1DH) uses the following assumptions: a random wave approach, in a 1DH (cross-shore) direction. An offshore wave model (shoaling + bottom friction + wave asymmetry) is used with the break point estimation. The waves in the surf zone are modeled with the classic model of Svendsen (1984) [20] with an undertow model (roller effect, Svendsen, 1984 [20], Dally et al. 1984 [8]). The longshore current model is the Longuet-Higgins's model (1970) [16]. The model is included in the Sysiphe code to calculate the sea bed evolution with several sediment transports formulas.

IV. RESULTS

We set up a procedure to use the coupled codes Artemis-Telemac2d-Sisyphe and more particularly we improved the treatment of the boundary conditions in order to be able to work on fields of calculations close to the coastal zone and equivalents in dimension for the three codes. The wave module grid is equal to the flow and morphodynamic grid. The waves are incidents on both the lateral and seaward boundaries of the grid. The lateral boundaries of the flow model are defined as zero water levels.

The morphological evolution in the near shore region, including its large-scale features, was first investigated using a combination of a commercial 2DH model (Camenen and Larroudé, 2003 [2], 2003b [3]). Simulation of the wave-driven currents was carried out with Telemac, a finite elements model, and the Sisyphe sand transport module served to compute sediment transport rates and bed evolution. This methodology of morphodynamic modeling for sandy beaches was already improved in terms of mesh, time step and convergence in Camenen (2002) [1], Larroudé and Camenen (2004) [15] and in Falquès et al. (2008) [11] and Larroudé (2008) [14].

We first present results for Site 1 ("Plage de la Corniche"), focussing on the month of December 2008 and February 2009 for the validation and the first test of the different sediment transport formulas. During these months, we had two similar storms in term of significant wave height, period but in December the outer bar moved offshore and during the storm of February this outer bar moved onshore (see Figs. 5a and 5b).

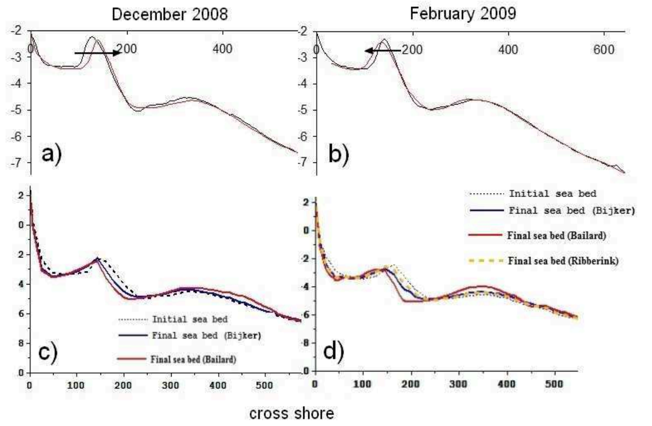

Figure 5. Morphodynamic evolution at site 1 in December 2008 a) measured in situ (initial bathymetry in black) and c) with simplified model Multi1DH and several sediment transport formulas and in February 2009 b) measured in situ (initial bathymetry in black) and d) with simplified model Multi1DH and several sediment transport formulas.

In the case of February, the Multi1dh model reproduces very well the onshore migration of the bar with all the sediment transport formulas (Figs. 5b, 5d). On the opposite, the off shore migration is not so well simulated but the results seem to be acceptable (Figs. 5a, 5c). For the 2DH model ATS, in these cases of cross shore migration of these sand bodies, the modeling of the cross shore current (undertow) is missing. The results for both storms are thus not well representatives (Fig. 6).

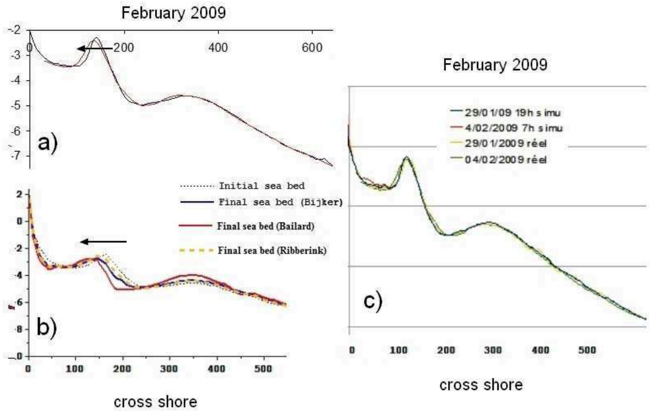

Figure 6. Morphodynamic evolution at site 1 from the 29 01 09 to the 04 02 09, a) measured in situ (initial bathymetry in black), b) with simplified model Multi1DH and several sediment transport formulas and c) with the 2DH model ATS.

Our results show that the different formulas of transport did not correctly reproduce what was observed in reality. During the storm of February, the onshore displacement of the inner bar was not represented by the majority of formulas. We can see through this case that the Bijker formula and Soulsby-Van Rijn overestimate~~s~~ sediment transport, while the other formulas underestimate. The modeling of the December storm, however, shows that some formulas are more robust than others, the formulas of Ribberink, of Soulsby-Van Rijn and Egelund Hansen being the least robust. For the same storm, the Bijker formula seems to overestimate the sediment transport, while the Watanabe & Dibajnia formulae coded in the Sisyphe code has a tendency to overestimate the sediment flux when there are strong velocities.

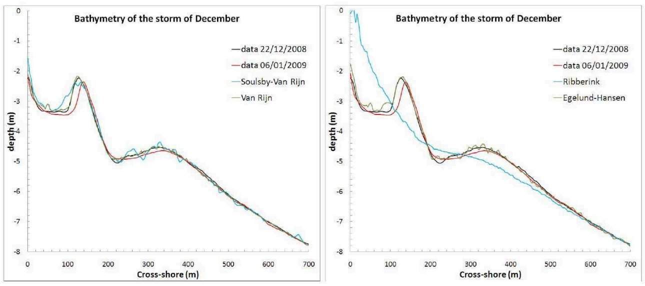

Figure 7. Comparison of a cross shore profile evolution between different sediment transport formulae for the December storm at site 1.

The second part of the study is to compare the solution obtained with different sediment transport formulas directly with in situ measurements of sediment transport. We use a set of data obtain on the North Sea and the English Channel beaches.

There are three calculations per site with the formulas of Bijker, Einstein and Van Rijn with the first approach of simulation and there are two calculations per site with the formulas of Bijker and Dibajnia-Watanabe for the second numerical approach.

TABLE I. IN-SITU DATA (ZUYDCOOTE) AND SIMULATED (SECOND APPROACH) LONGSHORE SEDIMENT FLUXES

DATE and TIME	Measured Longshore Flux (kg.s^{-1}m^{-1})	Calculated Longshore Flux (kg.s^{-1}m^{-1})
13/11/2008 15:50	4.5×10^{-4}	3.6×10^{-3}
14/11/2008 10:45	4.8×10^{-4}	1.1×10^{-3}
17/11/2008 13:17	9.9×10^{-4}	1.3×10^{-3}
13/11/2008 15:50	4.7×10^{-4}	0.0
14/11/2008 10:45	6.2×10^{-5}	0.0
17/11/2008 13:17	1.2×10^{-4}	0.0
24/11/2009 14:22	7.8×10^{-2}	2.4×10^{-2}
27/11/2009 12:07	8.2×10^{-4}	6.3×10^{-4}
30/11/2009 14:37	4.2×10^{-4}	5.7×10^{-3}
03/12/2009 11:22	6.0×10^{-4}	9.4×10^{-4}
06/12/2009 13:07	2.7×10^{-3}	3.9×10^{-3}

The difference between the first and second numerical approach is the way of taking into account the boundary conditions in term of velocity in the telemac2d code and using wave simulation result directly into some sediment transport formulae in Sisyphe code.

For the Hardelot and Wissant data, the comparison between measured and simulated sediment fluxes show that the first approach gives better results, but for Zuydcoote it seems that the second approach is more appropriate (see Table I and Fig. 8).

The results obtained with the other formulas show that there is often an order of magnitude between in-situ and computed data which demonstrate that although these early tests are interesting further work is still needed to improve sediment transport modeling in these macrotidal environments (see Figs. 9 and 10).

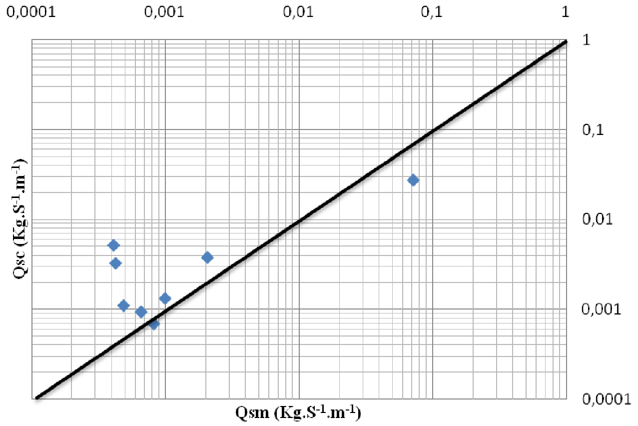

Figure 8. In-situ data Qsm (Zuydcoote) and simulated Qsc (second approach) longshore sediment fluxes (data from Table I).

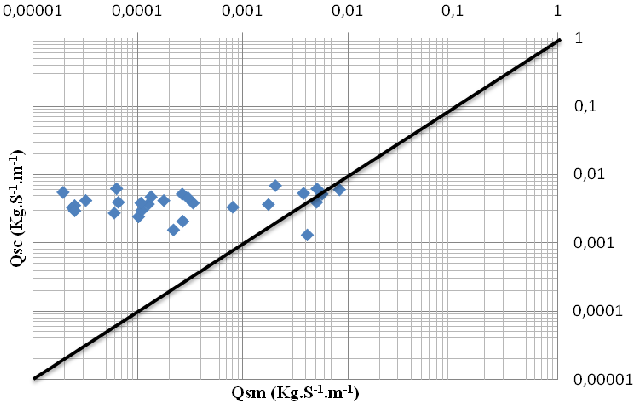

Figure 9. In -situ data Qsm (Hardelot) and simulated Qsc (first approach, with Bijker) longshore sediment fluxes (depth = 1m).

All the numerical results are taken in the middle of the simulation domain between the beach and the offshore boundary. But we can see that there is no variation in the calculated flux with Bijker or Van Rijn on respectively Hardelot and Wissant while the sediment flux measured vary greatly (see Figs. 9 and 10). To avoid this problem, our numerical results were extracted at the same location in which the water depth over the measurements is (for all case test on a site) in the same order of the average water depth of the simulated data (see Figs. 12 and 14, respectively for Hardelot and Wissant site). In these figures, the value noted case-figure 11 and case-figure 13 correspond to those measured during data collection in-situ.

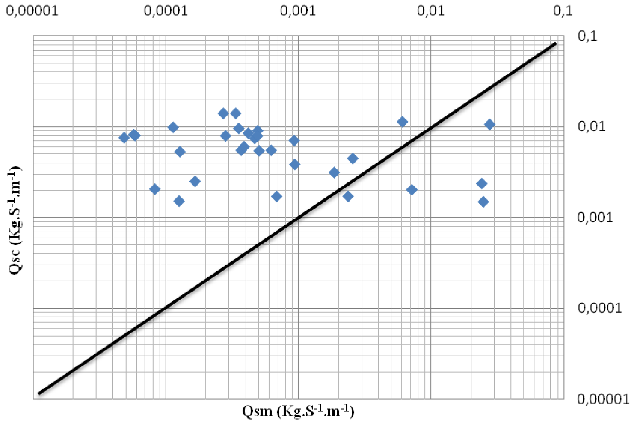

Figure 10. In-situ data Qsm (Wissant) and simulated Qsc (first approach, with Van Rijn) longshore sediment fluxes.

We can see on Figs. 11 and 13 a better consistency between the predicted and the measured transport rate. The next step of our study will be to calibrate correctly the way of extracting the numerical fluxes and compare the results with the all formulas tested against the in-situ data.

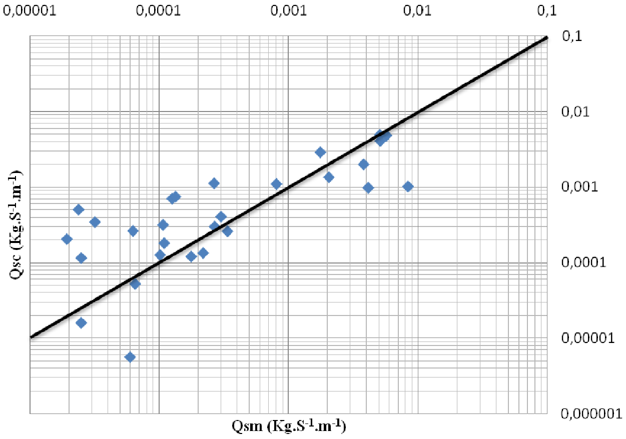

Figure 11. In -situ data Qsm (Hardelot) and simulated Qsc (first approach, with Bijker) longshore sediment fluxes (depth average around 1m).

The sediment traps mainly collecting sediments transported in suspension, the next step of this study will be to de-couple-the suspended and bed load transport calculation in the different sediments transport formulas to compare only the suspended fluxes in the North sea and English Channel

Beaches data. The second improvement will be to reach a better precision on the velocity field.

V. CONCLUSIONS

We used a 2DH morphodynamic model to simulate the evolution of linear sandy beaches , these investigations being aimed to better define the vulnerability of these coastal landforms to storm event. We have calibrated our numerical methodology of simulation against in situ measurements. The first results are good in terms of comparison with in-situ data regarding the hydrodynamic and morphodynamic parameters. This work was based on different scenarios of wave classes, storm occurrence frequency, etc… We have had to simulate all these configurations to identify the sensitivity of rising-apex-waning of the storm. Our methodology of simulation and the complementarily of both models allowed us to test the various configuration of storms to understand the results derived from the in-situ data.

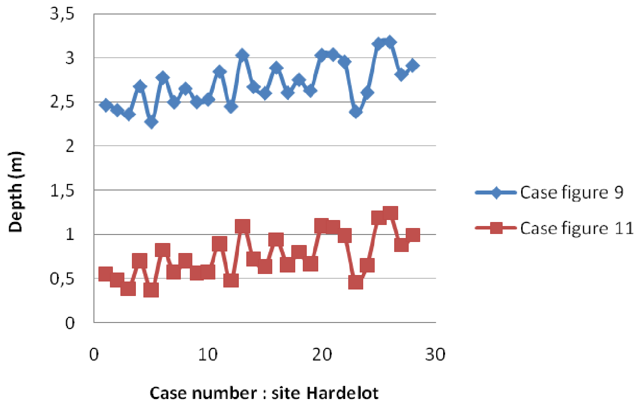

Figure 12. Water depth for all the run and data on Hardelot used in Figs. 9 and 11.

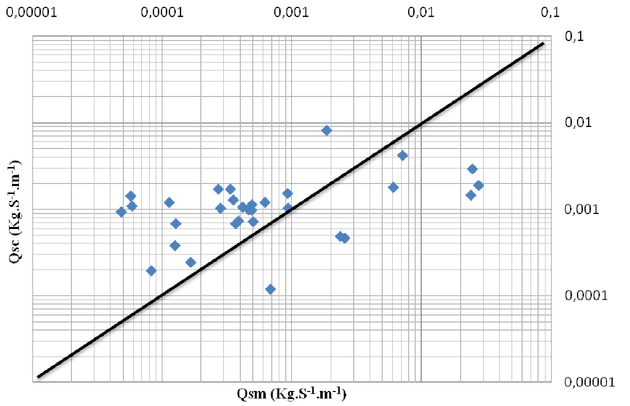

Figure 13. In-situ data Qsm (Wissant) and simulated Qsc (first approach, with Van Rijn) longshore sediment fluxes (depth average around 1m).

ACKNOWLEDGEMENT

This work has been supported by French Research National Agency (ANR) through the Vulnerability Milieu and Climate program (project VULSACO, n° ANR-06-VMC-009), RELIEF MICROLIT and the CNRS PLAMAR project. We highly appreciate the constructive discussions with D. Idier, (BRGM, Orléans, France), Raphaël Certain and Nicolas Robin from the University of Perpignan.

Figure 14. Water depth for all the run and data on Wissant used in Figs. 10 and 13.

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