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Innovative 3D hydrosedimentary modelling of migrating inlets

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Abstract—**At its downstream part, the Bandama river flows into Tagba lagoon, located 150 km west of Abidjan on the Ivoirian coast. The large lagoon system is separated from the Atlantic Ocean by a 15 km-long and 200 m-wide ridge of sand interrupted by a 300 m wide inlet that allows hydraulic exchanges between fresh water and ocean due to tidal oscillations of sea level and hydraulic regime of Bandama river (flood and low water periods). Settled on this sandy ridge, the fishing village of Lahou Kpanda is the remains of the ancient wealthy colonial city of Grand-Lahou, and is highly vulnerable to coastal erosion, East-West migration of the mouth of the Bandama river with a speed of 160 m/year over the past 10 years, as well as coastal and river flooding.**

The TELEMAC-MASCARET modelling system, coupling TELEMAC-3D (3D hydrodynamic module) – TOMAWAC (wave propagation module) and GAIA (hydro-sedimentary module), calculates the 3D hydrodynamics and resulting sediment transport. This complex model succeeds in correctly simulating longshore coastal transport and seasonal inlet morphodynamics. The main significant result is the modelling of the mean annual migration rate of the inlet in the opposite direction of the littoral drift. This phenomenon is mainly due to the secondary currents generated at the extrados of the Bandama channel during lagoon drainage (Aubrey and Speer, 1984). However, the good results obtained for short-term morphodynamics get worse for mid and long terms: satisfying at the beginning of the simulation, the simulated erosion affecting the West side of the inlet and consecutive East-West inlet migration is stopped due to the non-inclusion of the cross-shore processes that are responsible for accretion of the sandy eastern ridge (for its emerged part). The correction of the cross-shore profile requires the development of a unique numerical tool able to re-profiling automatically the bathymetry between the coastline and the closing depth.

A preliminary review of the state of the art has shown that one-line models (based on equilibrium beach profile concept and bypassing cross-shore processes resolution) are perfectly suited for long-term shoreline evolution modelling. However, their validity domain is limited to simple shoreline shapes under quite simple hydrodynamic conditions. For complex configurations, 1D modelling has to be supported by a cross-shore calculation module in a so-called “hybrid modelling” (Kristensen et al, 2016). The main difficulty of this coupling is how to generate automatically a 1D mesh from any 2D mesh considering a time varying bathymetry. For that reason, since 2016, ARTELIA has been developing a hybrid model based on the unstructured triangular mesh used by TELEMAC-MASCARET. Automatic re-profiling of the seabeds located between the coastline and the closing depth is carried out considering principles of equilibrium profile and cross-shore mass transfer by ensuring mass conservation. This new hybrid model has been first validated on simple theoretical cases such as a growing sand spit and is applied for the first time to a complex concrete case: the Grand-Lahou site.

I. INTRODUCTION

The village of Lahou Kpanda (Ivory Coast), located immediately to the west of the Bandama river mouth, on the barrier island of Tagba lagoon (Fig 1 and 2), is subject to intense coastal erosion, threatened by the migration of the tidal inlet at an average speed of 160 m/year over the last decade with an acceleration of the migration observed during this period [1, 2 and 3].,

Since the 1960s it has migrated about 1.5 km. The entire colonial city is already destroyed and the remaining fishing village has been subjected to a significant shoreline retreat. As the sandy ridge is very low, the village is regularly flooded, as a proven consequence of climate change.

Despite the decision in 1973 to adopt a strategy of relocating the stakes to the site of N'Zida, located 18 kilometres to the north on a high plateau, some inhabitants of the fishing village reluctant to leave the lagoon, stayed in Lahou Kpanda objected to the risks of migration of the inlet, shoreline retreat, and coastal and river flooding. Their assets are threatened with programmed disappearance if no human intervention is undertaken. The call for help from the local population and the opportunity of economical development of the lagoon - make however question this passive strategy.

Thus, the WACA program has funded in 2017 a Multisectoral Investment Program (MIP) to study different scenarios for sustainable management of the inlet. This plan has notably concluded to the need for a more detailed study of the hydro-sedimentary dynamics of the system composed of Bandama outlet- lagoon - inlet - sandy ridge, a proper understanding of the system being an essential prerequisite for the choice and sizing of solutions of development and maintenance for a sustainable stabilization of the inlet.

Artelia was therefore commissioned to carry out a technical, environmental and social feasibility study for a sustainable management of Grand Lahou inlet. This study is based on a scientific investigation of the system, relying on a

Figure 1. Location of the studied system, Grand Lahou, Ivory Coast

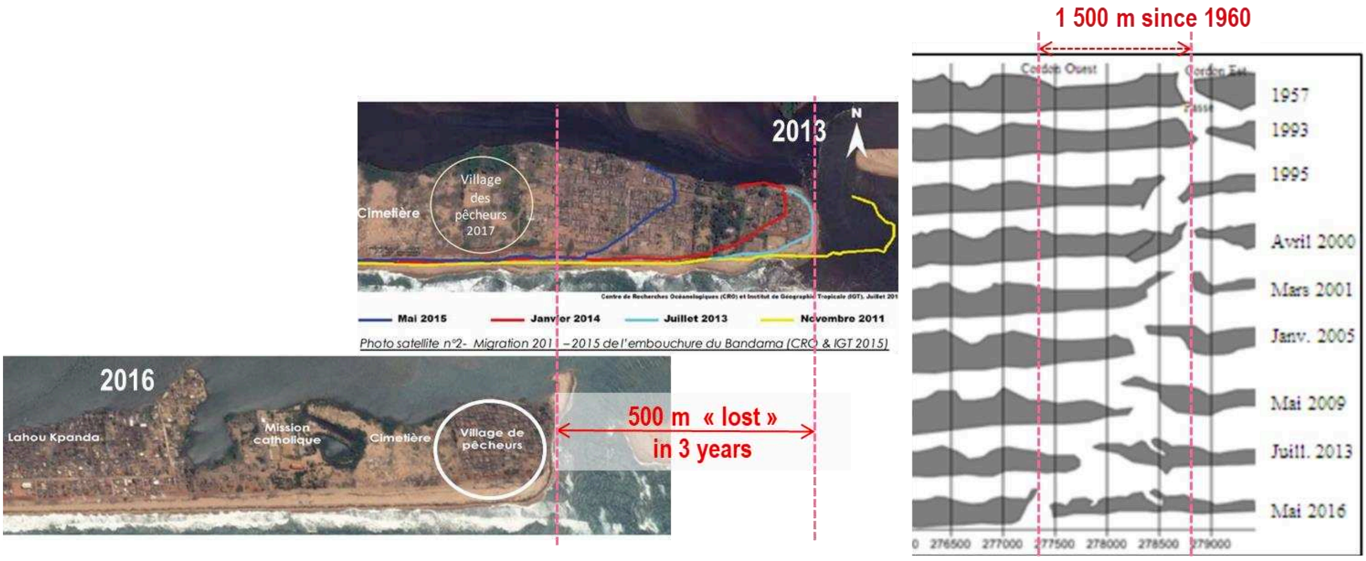

Figure 2. System evolution since 1960

numerical hydro-sedimentary modelling which aims at reproducing the observed morphodynamic evolutions of the system, in order to deduce future trends, with and without development, in order to compare the benefits of the different tested solutions for sustainable management of the mouth and to identify the better scenario.

The first goal of this feasibility study is to validate the model by reproducing past event, in particular the inlet migration opposite to the littoral drift **Error! Reference source not found.**. Adaptive solutions were then proposed and tested with the model.

II. Hydrodynamic Model

All the software used for this regional coastal numerical modelling comes from the TELEMAC-MASCARET software chain except the re-profiling tool. TELEMAC-3D (hydrodynamic), TOMAWAC (wave propagation) and GAIA (sediment transport) are all coupled together.

A. TELEMAC-3D

Telemac-3D allows simulating the dynamics of three-dimensional free surface flows. The software calculates, at all points of the mesh, the velocity fields in the 3 directions and the value of the scalar quantities possibly transported (temperature, salinity, suspended sediment...); on the surface mesh, we obtain the spatial and temporal evolution of the marine water layout.

The model is forced at its lateral boundaries by the astronomical tide (evolution of water levels and currents).

In addition, the model is forced in its momentum equations by the wave driving forces from the wave propagation model to reproduce the nearshore currents.

B. TOMAWAC

The TOMAWAC software, a 3rd generation/propagation model, allows studying the spectral propagation of sea states by using the main physical processes affecting the waves (refraction, shoaling, friction on the bottom, breaking waves, wind contributions, interaction with currents, diffraction ...). It calculates the evolution in space and time of the directional wave energy spectrum and can handle varied and complex sea conditions: ocean swells, splashes, sea states with several peaks in direction and/or frequency. From the directional wave energy spectrum, the software calculates, at all points of the mesh, the characteristics of the sea state: spectral significant wave height, mean wave direction, mean and peak frequencies, mean directional spread, radiation stresses, etc...

The TOMAWAC wave propagation code is coupled with the TELEMAC-3D calculation code and the GAIA sediment transport code.

It should be specified that a particular development was carried out in Telemac-3D to take into account the radiation constraints (2D) in 3D, as well as the energy induced by the surge, which makes it possible to better approximate the return currents [7].

The nesting of these models allows taking into account the consideration of wave currents due to surges in hydrodynamics as well as for sediment transport.

C. GAIA

The GAIA code coupled with TELEMAC-3D and TOMAWAC allows studying sediment transport under the combined action of currents and swell. The software calculates, at all points of the mesh, the evolution of the bottom and the solid flow at each time step. The local sediment sizes have been taken into account.

III. Model setup

A. Bathymetry

Different bathymetric sources (Fig. 3) have been used. SRTM data to compute the main slope of the Bandama river, PAA map in the lagoon, Shom map offshore, and more recent bathymetric survey near the inlet.

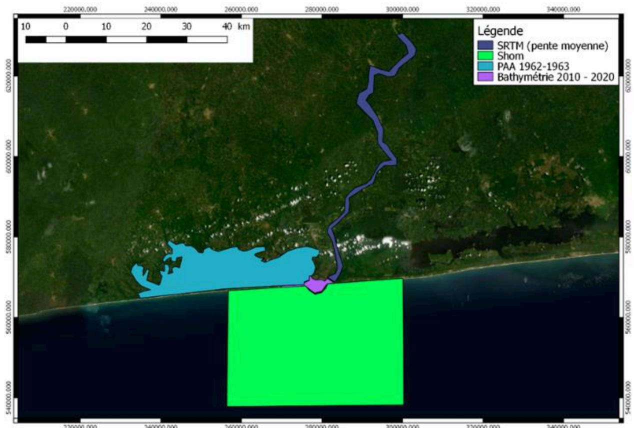

Figure 3. bathymetric data

B. Mesh

The horizontal mesh consists of triangular elements varying in size throughout the model from 1000 m offshore to about 30 m in the channel and at the dune cord, for a total of 48 342 knots and 90 044 elements (Fig. 4). The mesh size in the Bandama river is about 150 meters given the limited bathymetric data available in this area. For the same reason, the mesh size varies from 500 meters at the lagoon center, to about ten meters to ensure hydraulic connections in narrow areas. For the pass, as well as the dune cord, 30 metres mesh size were used in the dynamic zone (Fig. 5). This allows a free movement of the pass over a large area and does not constrain the morphodynamic calculation.

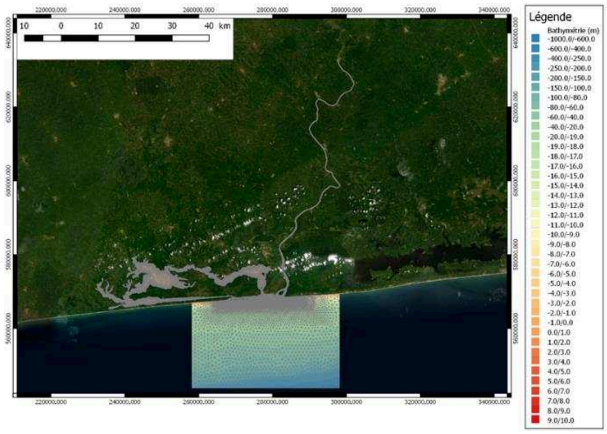

Figure 4. global mesh

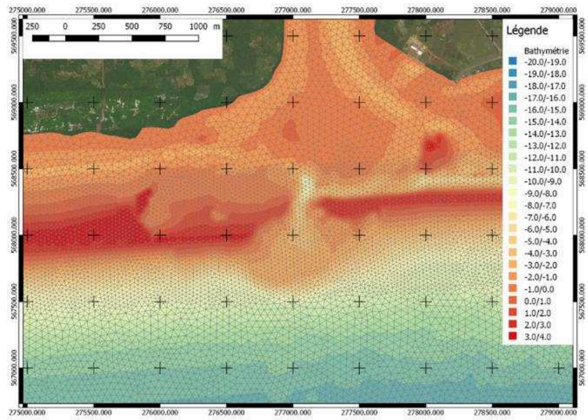

Figure 5. Mesh at the inlet localisation

IV. Hydrodynamic Validation

The hydrodynamic model is forced by taking into account the Bandama river flow rate, waves, tide, and general currents [6]. The model is then validated in three steps.

A. Water level

Water levels and currents are validated with two ADCP measurements (Fig. 6). One ADCP is located offshore of the inlet, the other one is located "inside" in the lagoon.

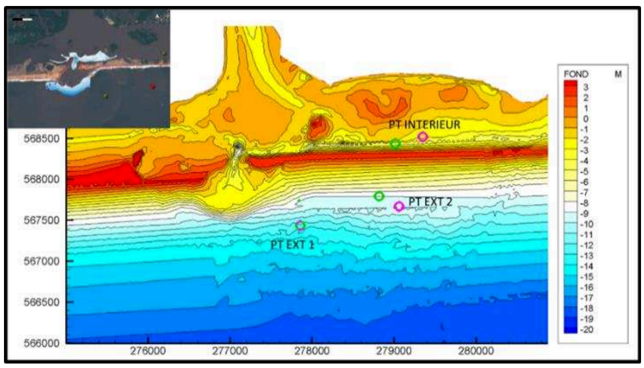

Figure 6. ADCP location inside and outside

The model is able to reproduce the water level at the two locations (Fig. 7), in particular the variation of the mean water level due to the variation of the Bandama river flow rate.

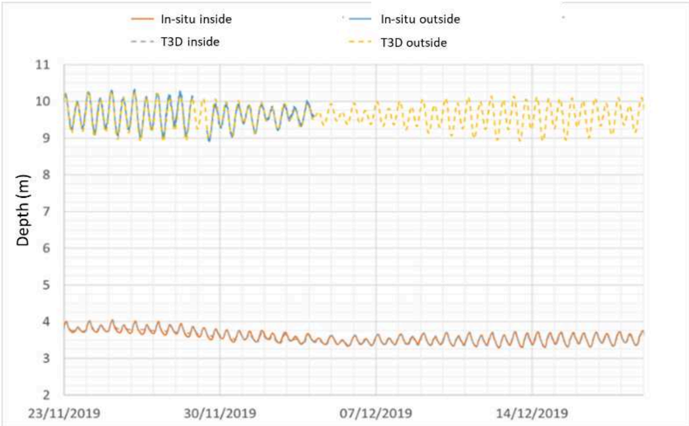

Figure 7. Water depth comparison at ADCP location

B. *Current validation*

River flow rate variations induce changes in velocity intensity and direction inside the lagoon which is well reproduced by the model (Fig. 8).

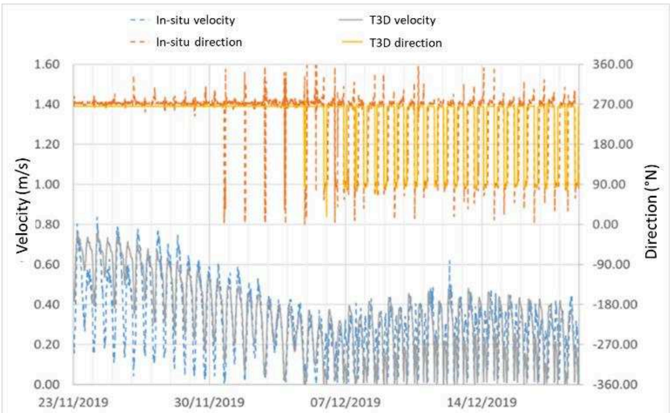

Figure 8. Velocity comparison at ADCP location

C. *Morphodynamic*

The morphodynamics is validated through three criteria: first through the global total sediment transport due to the littoral drift going east (while the inlet is migration westward, meaning updrift) with the CERC formula (Fig 9), secondly by mid term bathymetric evolution of the inlet observed between December 2019 and March 2020 (Fig 10 and 11); thirdly by the reproduction of seasonal inlet variations depending on the flowrate of the Bandama river.

The littoral drift is well reproduce, with 5 to 25% of difference with the CERC formula, but the system evolution has notable differences. The inlet start to move west, and sandy rerash east and west appear at expected localisation. The simulation was continued, but the model no longer evolves significantly following the expansion of the inlet.

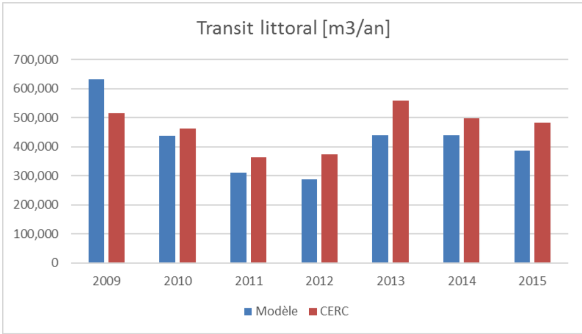

Figure 9. East littoral drift

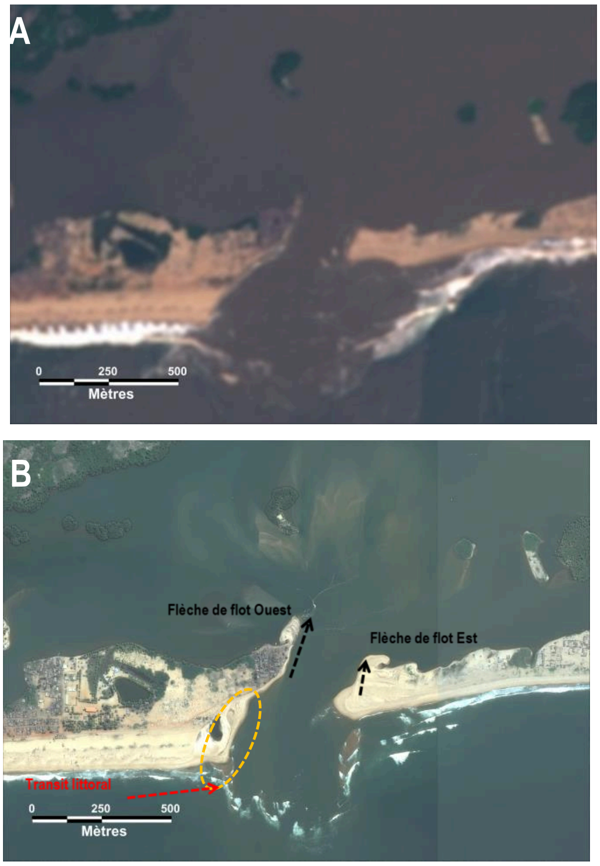

Figure 10. System evolution between December 2019 and March 2020

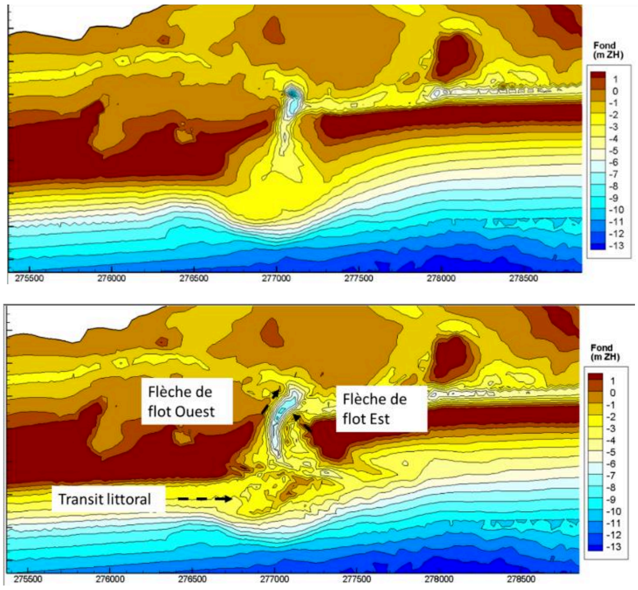

Figure 11. System evolutions modelled between December 2019 and March 2020

V. HYBRID ALGORITHM

The beach re-profiling tool (Fig 12, 13 and 14) is based on the equilibrium beach profile concept with a particular care for mass conservation. The tool is used every simulated month and any error in mass can lead to an overestimation or underestimation of beach nourishment and may lead to important errors in the global evolution of the system. To avoid mass errors, the tool is used directly on the mesh points, without intermediat grids.

The tools can be decomposed in four main steps:

- Determination of the profile for every point of the mesh
- Compute the theoretical profile
- Calculate the mass distribution over all the profile
- Apply the massProfile determination

In this step, the algorithm tries to define for every mesh point the profile from a top of the sand ridge to a bottom closure value. The profile path is determined from the slope of the bathymetry. For point where no profile can be found, especially peaks or troughs, their profiles are found by interpolating neighbour profiles. Many data are stored for every profile, like the main point associated, every neighbour to this profile, and the distance between the profile and the neighbours (Fig 12).

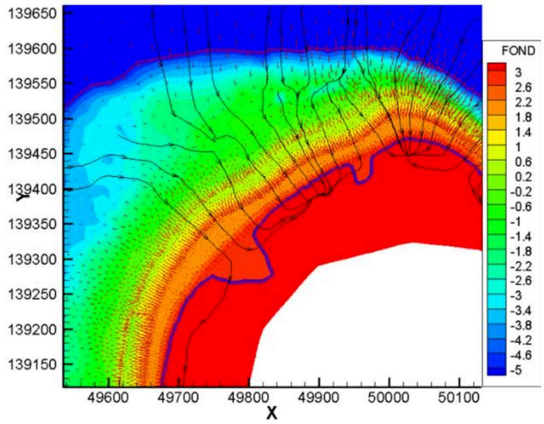

Figure 12. Profil determination

A. Calculate the theoretical elevation

For every mesh point where a profile has been found, the elevation from equilibrium profile is then calculated and an associated mass (to be added or removed) is computed (Fig 14, step 1 to 3). This theoretical elevation (1) takes only into account the curvilinear distance to the sand ridges, the closure altitude Z_0 and a coefficient A determined from the initial bathymetry slope.

$$Z(s)=Z_0-(A.s^{2/3}) \quad (1)$$

B. Calculate the mass repartition

For each profile, the mass added or removed is then distributed iteratively over all the points of the profile, ensuring mass conservation and weighting due to the distance to the profile (Fig 14, step 4). If a point exceeds the closing altitude (top and down), only the part of mass to reach the closure is applied, and the rest is redistribute iteratively along the profile.

C. Apply the mass distribution

For every mesh point, the sum of the mass from the previous step is calculated coming from all profiles. A coefficient common to all points is computed to avoid local exceeding of the closing altitude. Finally, it is only the mass sum weighting by this coefficient that is really applied to modify the bathymetry. Because no real modification is applied before this step, this is like applying the coefficient at the second step and correcting only partially the profile (Fig 14, step 5 and 6).

These last three steps are then repeated to slowly correct the bathymetry (Fig 14, step 7).

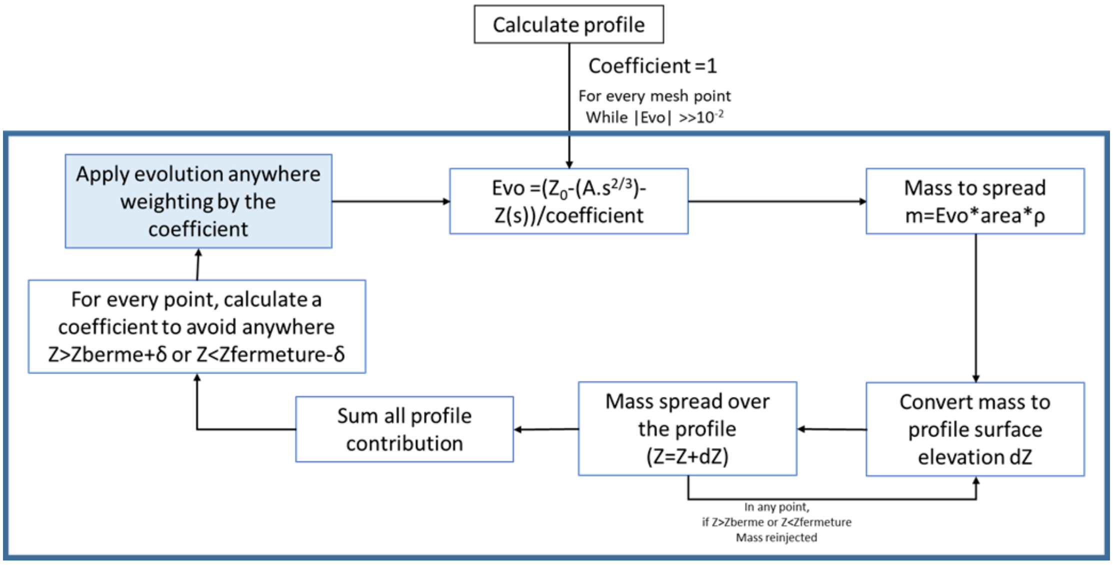

Figure 13. Re-profiling tool diagram

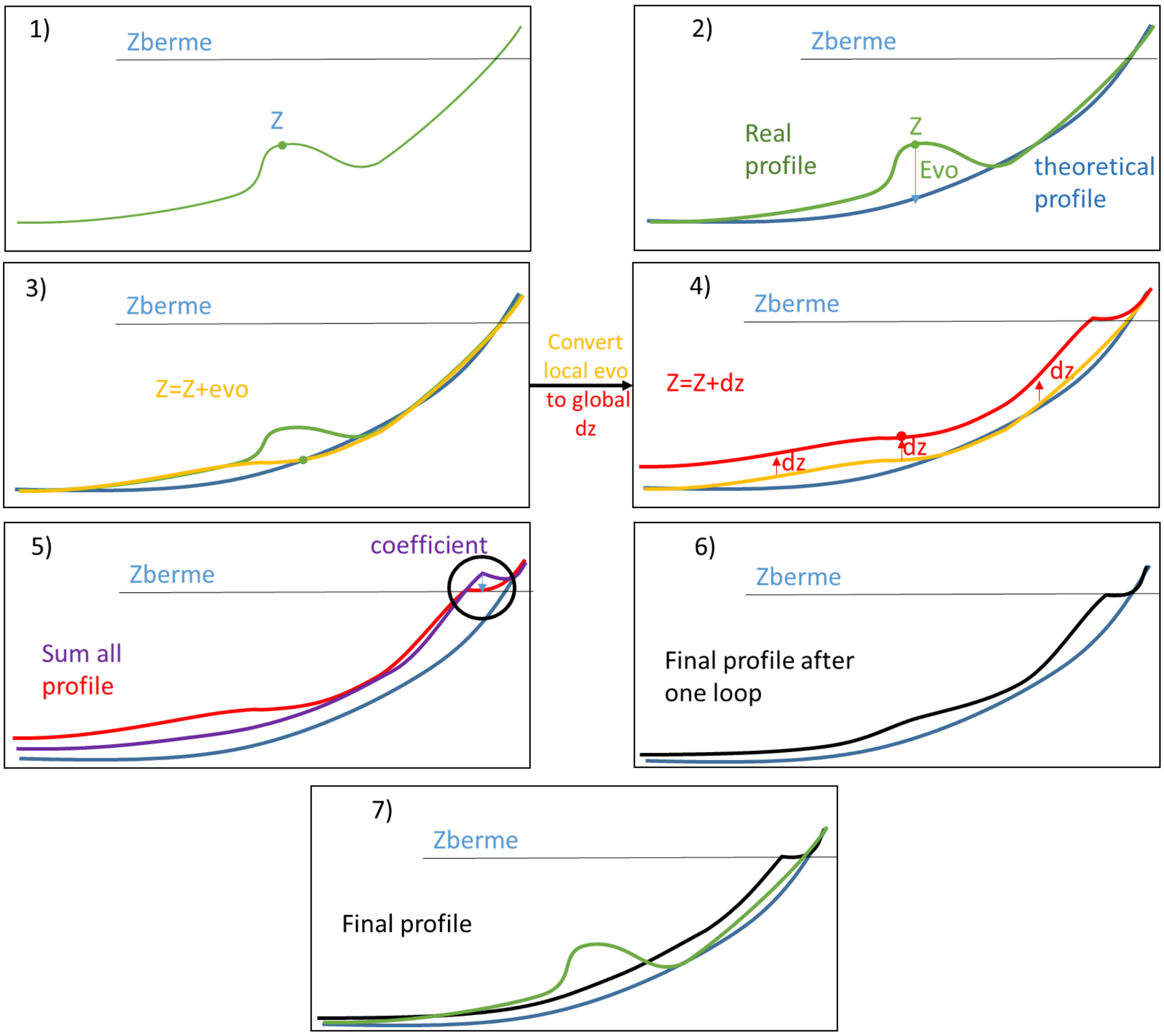

Figure 14. Re-profiling tool on one profile

VI. Results

First, the hybrid model is tested over two inlet states, one representing the 2009 configuration (not presented here) to compare the velocity of translation of the inlet, the second representing the actual configuration (2020) but with 2009 Bandama flow rate (no data are available). The following figures (Fig 15) shows the improvements provided by the hybrid approach.

Without the tool, the inlet is widening and moving slowly westward (fig 11), while with the hybrid tool, the east sand bar is reconstructed and progresses westward allowing a faster westward migration of the inlet, as observed in nature. With the tool, the beach profile is maintained during the entire simulation at east and west of the inlet.

The model correctly reproduces the erosions due to the helical currents that allow the movement of the inlet eastward with an average rate of migration of 155 m/year. This average rate is correctly maintained for 2 consecutive years, what can be seen on the following figures: the dashed lines make it possible to materialize: the axis of the initial pass and the initial East and West dune. In the third year, the migration rate has slowed, due in particular to the increase in the width of the Western Cordon.

Other scenarios have been tested, like closing the actual inlet and opening the lagoon at different east location or also by adding structure to protect the west sand bar (Fig 16).

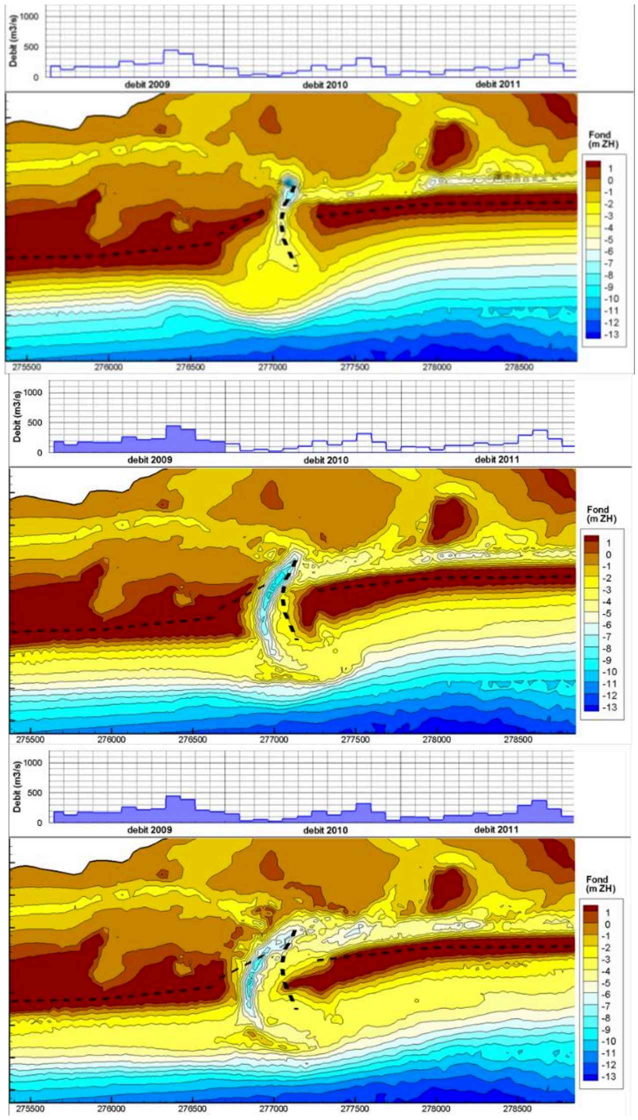

Figure 15. Initial bathymetry (top) and model result after one year and after 3 year (bottom) with reprofiling tool applied once a month

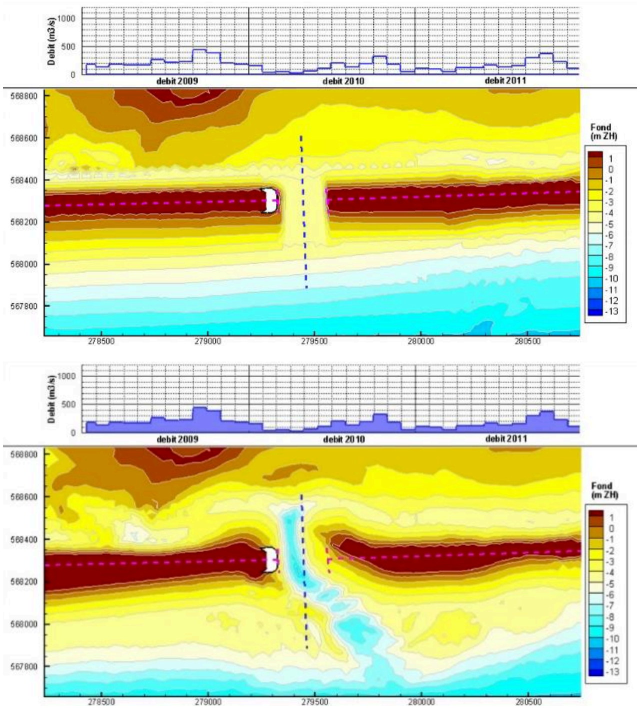

Figure 16. Scenario with one opening as in 1960 with structures to protect west sand bar, at initial state (top) and after three years (bottom).

VII. Conclusion

The hybrid model have been test and validated on the Grand Lahou system. It allows maintaining the beach profile and reconstructing sand bar. This tool can be used for long-term modelling.

Acknowledgement

ARTELIA wants to thank the cooperation and efforts of WACA executive team led by Pr A.D. Ochou, Pr E.V. Djagoua and H. Ouattara, as well as the World Bank for its confidence.

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