# CASE STUDY OF INTEGRATED COASTAL ZONE MANAGEMENT IN IVORY COAST: STABILIZATION OF A MIGRATING TIDAL INLET BY SOFT PROTECTION MEASURES

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The village of Lahou Kpanda (Grand Lahou, Côte d'Ivoire), located to the immediate west of the mouth of the Bandama River, on the barrier island of the Tagba lagoon, is highly vulnerable to coastal erosion. It is directly threatened by the migration of the river mouth, which has been occurring at an average speed of 160 m/year over the last 10 years, as well as by the risks of flooding and coastal flooding which the effects of climate change will exacerbate further. This article presents the study, beginning in 2019 and financed by the WACA programme, which contributed to the choice and dimensioning of a sustainable solution for stabilization of the Grand-Lahou sandy barrier island.

Keywords: ICZM, Updrift tidal inlet migration, Coastal Hazards and Coastal Erosion Vulnerability, Numerical and physical hydrosedimentary modelling, WACA Project

## INTRODUCTION

The village of Lahou Kpanda (Grand Lahou, Côte d'Ivoire), located 120 km from Abidjan, immediately west of the mouth of the Bandama River, on the barrier island of the Tagba Lagoon, is highly vulnerable to coastal erosion (Figure 1). This village is threatened by the migration of the mouth, which has been occurring at an average speed of 160 m/year over the last 10 years (Figure 2), as well as by the risks of flooding and coastal flooding, which will be further exacerbated by the effects of climate change.

The strategy followed so far has been based on adaptation and withdrawal, with the creation in 1973 of the new town of Grand Lahou, 18 km away, closer to higher ground. However, part of the fishing community has remained in place and its assets and economy are now directly at risk. Following a Multisectoral Investment Plan (PIMS) setting out the benefits of reconsidering the strategy adopted for sustainable economic and natural management of the lagoon, the WACA programme brought this opportunity to fruition by funding technical studies for the choice and design of a solution for stabilising the sandy barrier. The article presents the different components that made up this ambitious project and made it an example in terms of Integrated Coastal Zone Management (ICZM).

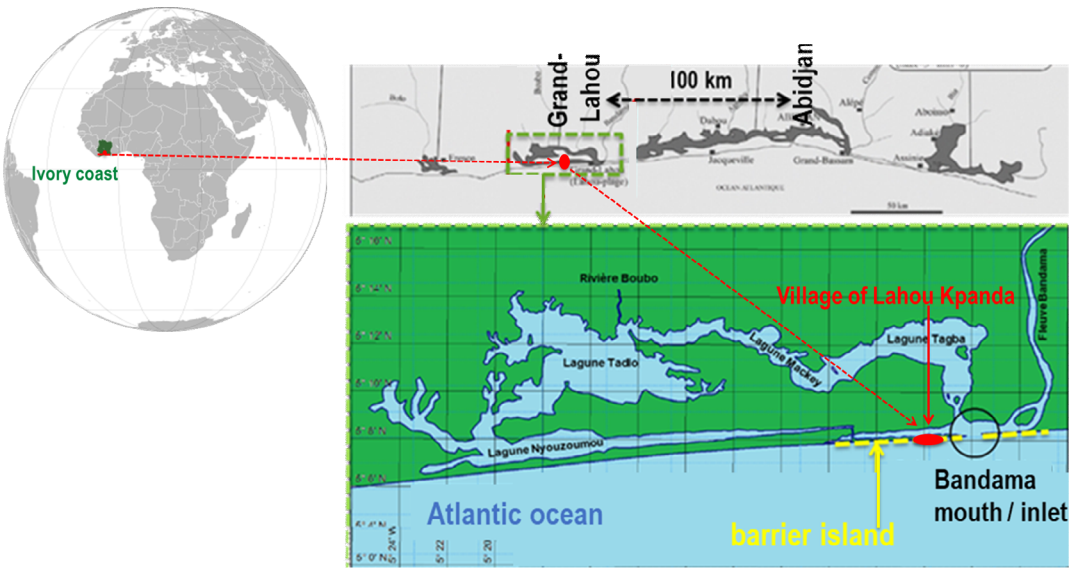


**Figure 1. Location and characterization of Ivorian lagoons and presentation of the Grand-Lahou lagoon system.**

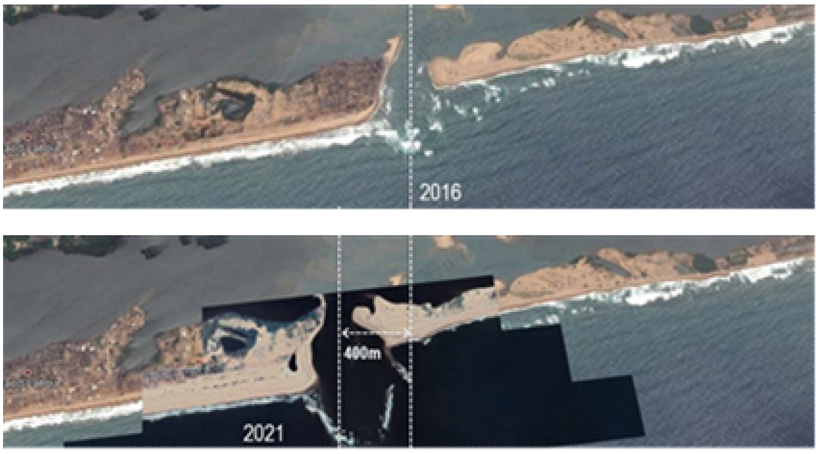


**Figure 1. Migration of the tidal inlet from 2016 to 2021.**

## UNDERSTANDING OF THE HYDRO-SEDIMENTARY PROBLEM

### State of knowledge at the start of the project

Over the course of 50 years, numerous scientific works and publications have been written about the system comprising the Bandama estuary, lagoons, barrier island and tidal inlet (BeDevelopment, 2017; DHI, 2015). Based on existing data found in the literature and collected from stakeholders (Figure 3), it appears that the stability of the inlet is conditioned by the joint, concomitant actions of the tidal currents (filling and emptying of the lagoon) and the river flow on the one hand, which keep the mouth open, and the littoral drift generated by the swell on the other hand, which has the effect of closing it (ARTELIA, 2019).


**Figure 2. Photographs of the meeting at the Lahou Kpanda chiefdom on 6/11/2029, and a visit of the barrier island showing the active erosion on the western bank of the channel.**

### Updating the system analysis

Additional field investigations (topo-bathymetric, currents and free surface level measurements, swell) and hydraulic and metocean studies leading to quantification of the monthly and annual longshore transport past records of the monthly flows of the Bandama, the migration speed of the inlet since 1957, demonstrate firstly the existence of a perennial inlet (Escoffier diagram) and secondly the presence of a marked ebb delta in front of it, providing a sedimentary bridge on either side of the inlet for the general East-West direction of drift.

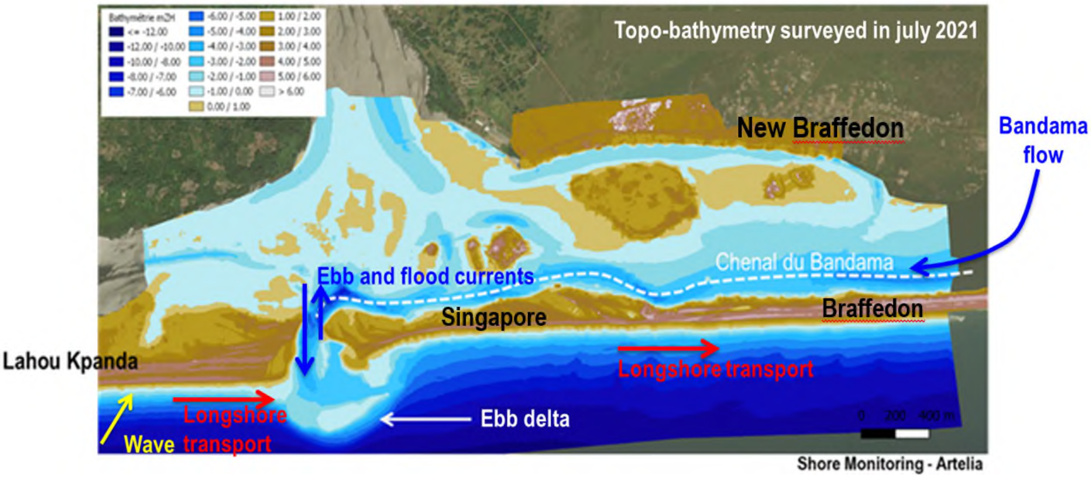


**Figure 4: Digital Terrain Model, resulting from the concatenation of the topographic and bathymetric surveys of July 2021.**

The diachronic analysis of the position of the inlet shows that it initially migrated weakly in the 1960s and has then migrated significantly since the 1990s from East to West, i.e. in the opposite direction to the net coastal sediment transport. This counter-intuitive direction of migration results from the progressive erosion of the western bank of the channel and the progressive accretion of the eastern bank. The inlet also shows strong seasonal variability in its aerial view form, with north-south oriented sand spits developing during periods of energetic waves and low water of the Bandama river.

Analysis of satellite images shows that the annual migration speed of the inlet is variable, from 0 to 350 m/year, and has been higher since 2010 (160 m/year on average over the period 2010-2019). However, there is no correlation between the annual migration speed and changes in the different environmental parameters (swell, Bandama flow), which, if found, would have explained this recent increase in migration speed that directly threatens the village of Lahou Kpanda with disappearance.

## NUMERICAL MODEL

### Development of an innovative numerical tool

In order to better understand and reproduce the complex short and medium term dynamics of the Grand-Lahou lagoon system, including the Bandama, the inlet and the sandy barrier island, an innovative numerical morphodynamic model has been developed. As a single tool, this model allows calculations to be made of changes in the seabed in response to forcing (tide, general current, emptying and filling tidal currents in the inlet, waves, flow of the Bandama River), and enables changes in the inlet (its migration) to be reproduced by pairing together two (2) main principles (figure 4). These are:

1. the TELEMAC-Mascaret modelling chain and its 3D hydrodynamic, wave and hydrosedimentary modules which calculate the sediment transport (including longshore transport) and seabed changes induced in the lagoon and the near-shore zone beyond the surf zone, but not the cross-shore processes at the coast which are causing unsustainable long-term erosion of the coastline;
2. a 1D coastline model to automatically reprofile the shallow water seabed of the coastal fringe (between the coastline and the closure depth) by reconstructing an equilibrium profile (Dean) by mass transfer along this profile.

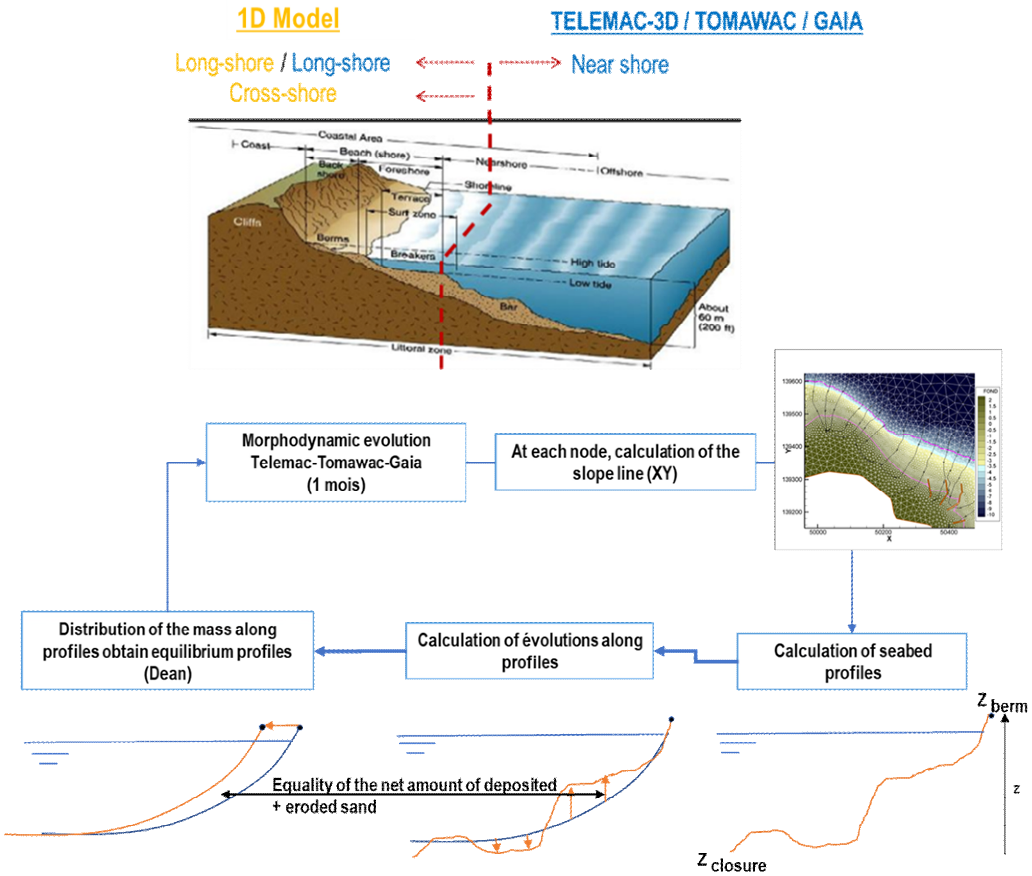


**Figure 5. Area of validity of the two coupled approaches and principles of the hybrid hydro-sedimentary model.**

Thus, the hybrid model, presented in detail in OUDART (2021), calculates at each time step and at each node of the mesh, the wave characteristics, the current, the sediment transport and the induced changes in the seabed and, at regular time intervals, the automatic reprofiling of the bottom of the surge zone by applying an equilibrium profile by mass transfer along this profile (see figure 5).

The model is hydraulically calibrated on a 2-month measurement campaign offering an optimal data set in terms of water level, current and waves, both in the Bandama channel and in the coastal area, during low water and flooding of the Bandama. The morphodynamic calibration consists in reproducing the seasonal evolution of the inlet plan form (short term) as well as the inlet migration (medium term - 3 years).

**Major contribution of the numerical model**

The innovative and operational model has enabled a significant step forward to be made in the understanding and reproduction of the mechanisms at play in the migration of the current channel. In particular, the numerical modelling has been instrumental in highlighting the role of the helical currents in the updrift migration (opposite direction to the littoral drift), with their three-dimensional effects developing at the foot of the western bank of the inlet in the presence of strong emptying flows contributing to the erosion of this bank, as described by AUBREY (1984):

1. these currents are generated by the sudden reorientation of the drainage flows (N-S or ENE - OSW) which in the coastal fringe are forced to align with the W-E wave current/littoral drift;
2. they develop on the upper side of the inlet’s curvature (western bank, where the free surface is locally higher) and participate in the erosion of the western bank, maintaining the inlet's curvature even when the inlet is moving in the opposite direction to the longshore transport.

On the lower side (western bank, where the free surface is locally lower), a hydraulic shadow zone develops which is conducive to sedimentation and the accretion of a sandy spit. This results in a migration in the opposite direction to the transit, which the model reproduces with the rates observed in nature, as shown by the evolution of the seabed calculated and illustrated in figure 6.

The model also clearly revealed the role of the ebb tide delta in the natural bypass of sediment transport on both sides of the inlet, and the influence of the position of the inlet along the sandy barrier on the migration mechanism. Simulation of the system's morphodynamics for three (3) different locations (West, Centre and East) within the inlet (figure 7.) showed that the direction and rate of migration of the inlet are strongly linked to the distribution of the East/West flows on either side of the inlet, coming in or out of the lagoon: if the East flow is greater than the West flow, the migration operates towards the East and vice-versa; and the greater the imbalance, the greater the annual migration rate. The central position, which is also the historical location of the inlet when the colonial trading post was in operation (before 1965), presents a relative equilibrium and better natural channel stability, which explains why the historical channel has existed for so long despite being reinforced only by a single deflector spur on its western bank.

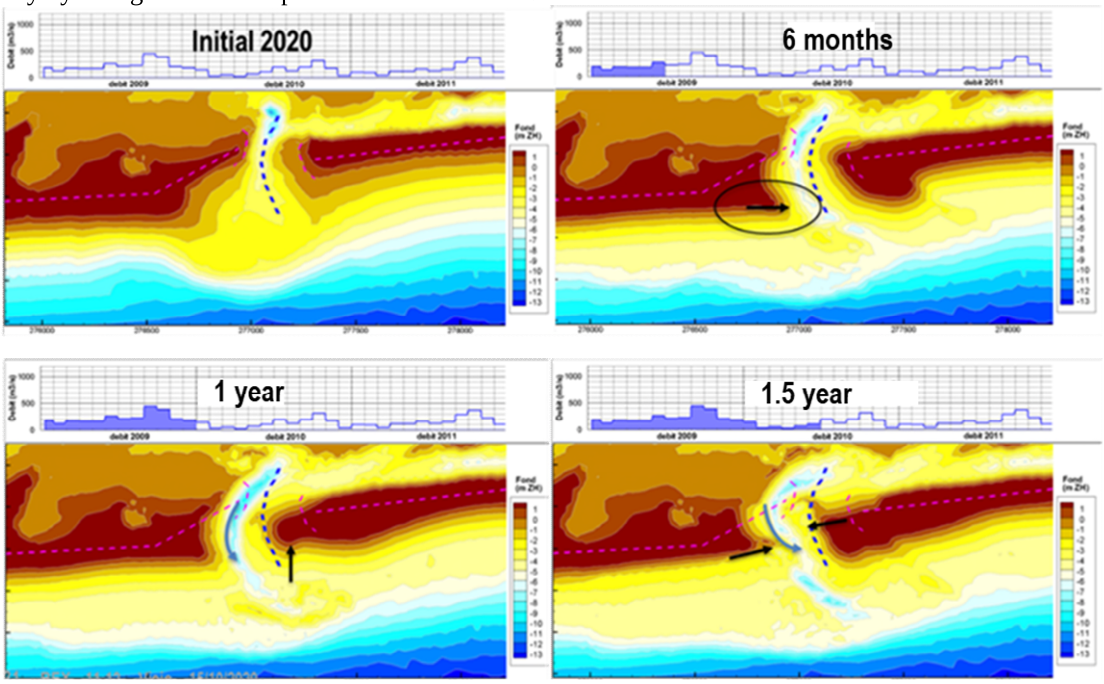


**Figure 6. Initial bathymetry (2020 state) and bathymetries from modelling: after 6 months - after 1 year - after 1 year and 6 months.**

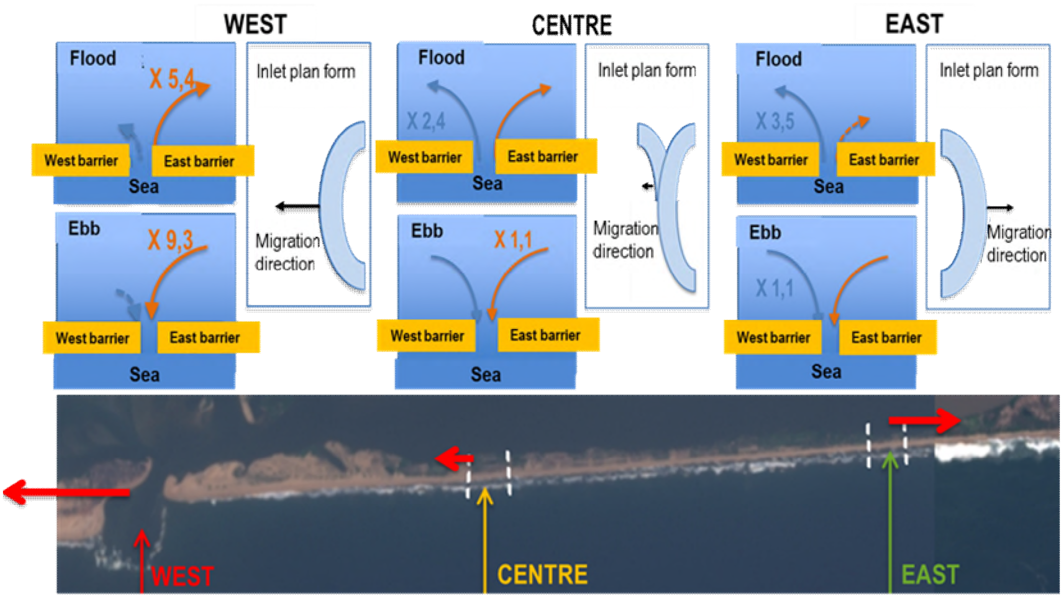


**Figure 7. Flow distribution on both sides of the fishway in different locations and with different induced migration directions.**

## INTEGRATED MANAGEMENT FOR PROJECT OWNERSHIP AND SUSTAINABILITY

The WACA Project Management Unit (Ministry in charge of the Environment) worked according to ICZM best practice to ensure the involvement of stakeholders in the different phases of the study, in order to guarantee acceptance and ownership of the future solution by the different local actors: organisation of workshops for the restitution and validation of the scientific and technical study with a Technical Committee, setting up of a Local Project Monitoring Committee (Figure 8) and organisation of field visits, surveys, consultations and validation workshops at the end of the key phases of the project. The PMU also ensured that the effects of climate change up to 2050 were taken into account and that sustainable management solutions for the site were promoted in a multi-criteria analysis that fed into the consultation for the choice of solution.

Finally, to accompany implementation of the solution, the PMU is coordinating the Environmental and Social Impact Studies, the study of an Early Warning System, a support programme for the populations through promotion of income generating activities, a capacity building programme for the conservation of mangroves as well as the implementation of a Resettlement Policy framework and a complaints management mechanism.

**Figure 8. First meeting of the Local Project Monitoring Committee (LPMC) held in Grand Lahou on 20 May 2021.**

## SELECTION AND SIZING OF THE CORDON STABILISATION SOLUTION

At the end of the pre-feasibility phase, the choice of the preferred development solution for the Grand Lahou sandbar was made in consultation with the project stakeholders in October 2020. This solution consists of five (05) components illustrated in figure 9: filling in the existing inlet, opening a new inlet 2.5 km to the east of the existing one, maintenance work on the western bank using soft engineering techniques (Réno anti-scouring mattress weighted with riprap in the area exposed to waves, figure 10), dredging of navigation channels in the lagoon, nourishment of the sandy barrier to limit coastal flooding in low-lying areas, all of which are supported by a maintenance station that is crucial to the sustainability of the solution. A clear choice was made not to interfere with the longshore sediment transport or the eastern bank of the future inlet in order to preserve the natural character of the barrier island as much as possible, at the expense of operational and perennial nautical access to the sea for larger ships than at present. For these, the possibility of passing through the Azagny canal (with dredging), the Ebrié lagoon and the Vridi canal is advocated.

Dimensioning of the solution and its components required geotechnical and geophysical measurement campaigns, including a search for obstacles in the seabed likely to be dredged. A study of phasing of the opening of the new inlet and the closing of the current one, a crucial point for the success of the works, was carried out, based on the numerical model presented above. In addition, in order to remove the design uncertainties relating to the maintenance works on the western bank of the new inlet, a 3D physical sedimentological model (with movable floors) was implemented (figure 11).

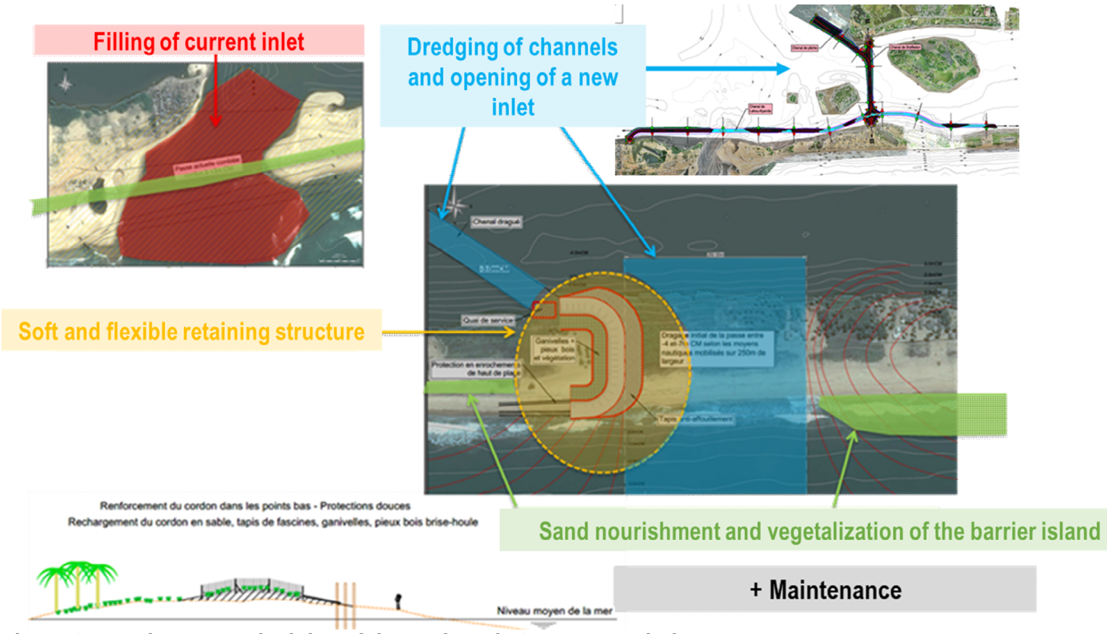


**Figure 9. Development principles of the preferred "CENTRE" solution.**

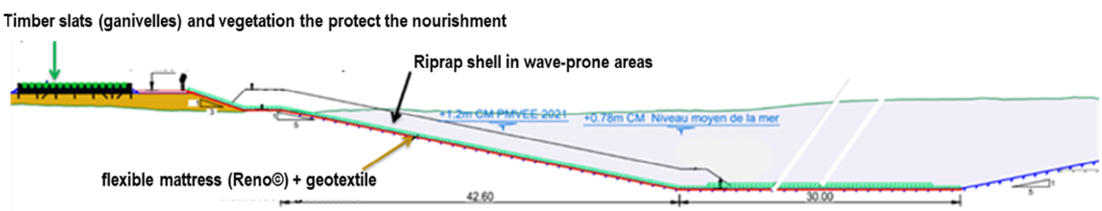


**Figure 10. Mixed gabion/rock armouring of the western bank - representative cross-section.**

This model, at a reduction scale of 1:250, encompasses a model area of 20 m along the west-east axis and 5 m along the south-north axis, to reproduce a natural line of 7,000 m of shoreline down to depths of -12 m BSL Using the model, verification was made of the maximum scouring depth, the erosion phenomena at the edge of the structure, the behaviour of the anti-scouring mat in the context of erosion of the surrounding area, and the feasibility of phased closure of the current inlet as arising from the digital model. In addition to the interest it presents for the dimensioning of the maintenance structure, the physical model is also a didactic tool that offers effective visualization of the phenomena and forcing at work in this complex system.

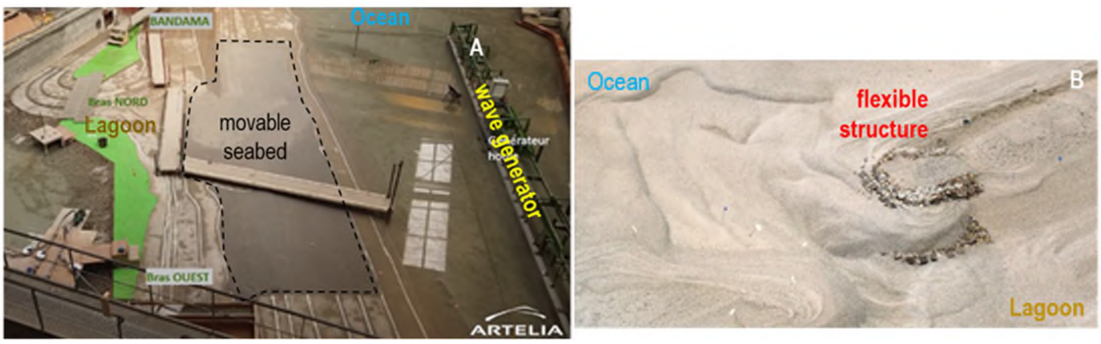


**Figure 11. View of the physical model (A) - View of the bottom of the future fishway and the bank retaining structure after 3 annual cycles.**

Regarding the impact of the planned works on changes to the coastline, the study identified three main issues concerning:

1. realignment of the coastline in the vicinity of the current channel following its closure, which will eventually result in erosion near Lahou Kpanda and accretion in front of Singapore and Braffedon. The models (physical and numerical) show that this phenomenon is partially compensated for by migration towards the coast of the undredged volume of the ebb tide delta created by the current channel following its closure. An assessment of the evolution of the coastline in the short, medium and long term, taking into account the effects of climate change (see figure 12), predicts a retreat of the coastline at Lahou Kpanda of 15 m in 15 years and 35 m in 10 years, and concludes that regular monitoring of the coastline is recommended, with no initial nourishment but a provision for risk of 20,000 $m^3$/year of sand for maintaining the barrier beach and protecting dwellings if necessary, making use of the sand from the maintenance dredging planned in the management method study for maintenance work;
2. trapping of the longshore transport in the formation of the ebb tidal delta created by the new channel, and the associated temporary erosion downstream. Changes in the sediment bypass near the ebb delta and retreat of the coastline on the eastern bank were quantified using the physical model, corroborating the estimates obtained by the numerical model, and thus defining the preventive beach nourishment downstream of the new channel;
3. the presence of low-lying areas of the barrier beach exposed to the risk of coastal flooding and breach creation. Nourishment at the top of the barrier beach to raise the level of any areas below 4.8m ASL was recommended.

Lastly, a study dedicated to the management of maintenance work was carried out to propose a framework ensuring the success and sustainability of the solution in the medium and long term.

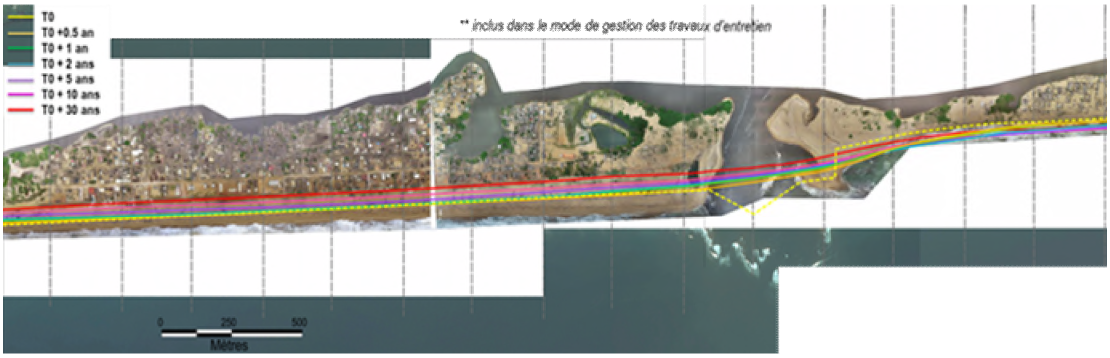


**Figure 12. Expertise on changes to the coastline over 30 years, in the vicinity of the current channel after filling.**

## CONCLUSION

The method implemented during the pre-feasibility study in order to find a stabilization solution for the sandy barrier of the Grand-Lahou lagoon complex, where three (3) aquatic ecosystems meet (Bandama river, Tagba lagoon and Atlantic Ocean), is innovative. It required scientific and technical studies supported by innovative and ambitious tools, from the risk assessment through to selection of the "Centre" position, which offers a relative balance and better natural stability for the new inlet.

These same tools were then used for detailed design and phasing of the solution, taking into account the strong environmental constraints: phasing of the inlet dredging and filling operations, optimisation of the structure to maintain the western bank of the new inlet and the route taken by the channels in the lagoon, etc.

Lastly, following consultations and the distribution of convincing results to all stakeholders in order to achieve concerted validation and convergence towards the preferred solution, an Integrated Coastal Zone Management (ICZM) framework was set up to ensure perpetuation of the achievements of this project involving the adaptation and resilience of local populations and the environment of the Grand-Lahou lagoon complex in the context of climate change.

## ACKNOWLEDGMENTS

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