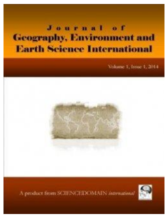

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Influence of Amenities in the Functioning of a Coastal Sediment Cell with a Moving Barrier: Case of Benin Coastal Segment between Hillacondji and Djondji in the Township of Grand Popo

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Authors' contributions

This article was written in the framework of the PhD thesis work currently led by author BDM the first author of the article. He mainly handled field work. The article drafted in close collaboration with author ALR specialist in coastal morphodynamics, particularly with regard to the analysis and interpretation and discussion of the results. Author KC, who supervised the work of author BDM, supervised all the stages of the writing of the article. All authors read and approved the final manuscript.

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ABSTRACT

The coast of Benin, 125 km long, is part of the overall west African coast, characterized by a narrow strip of coarse and medium sand and by an important coastal transit, which makes it an essentially fragile coastline. This coast also suffers from a strong anthropic pressure marked by the presence of port and hotel infrastructures as well as the administrative and private buildings wich disturb sedimentary dynamics of the coastline. The coastal sector between Hillacondji and Grand-Popo, which for a while, is confronted to erosional phenomena of sandy band, which was the subject of the present study.
Since 1980s, some short ears were erected on Togo coastline, 2 km far away from the border with

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Benin (Hillacondji). Since their erection, erosion has been observed on Benin Hillacondji – Djondji coastline, but without being too critical. Following the rehabilitation of these ears in 2012, the erosion phenomena were aggravated on the costal band of Hillacondji - Djondji causing important socio-economic consequences.
The purpose of this study was to assess the magnitude of the prevailing coastal erosion on the coastal band of Hillacondji – Djondji using data collected from field surveys and observation, as well as satellite images (Landsat).
This study indicated that this section of coast is under a generalized coastal erosion with a significant acceleration since 2012. The coastline retreat over the four last years (between 2012 and 2016) was estimated at 16.46 *m/year* at *Hillacondji* beach and at 5.13 *m/year* at *Agoue* beach. Only the coast segment between *Agoue* and *Avlo*, showssince 1982 a dynamic balance followed sometimes by exceptional episodes of erosion. The *Avlo-Djondji* is confronted to a disturbance related to the mobility of the Mono River (embouchure) which is accompanied of violent and very destructive erosion phenomena.

Keywords: Coastal erosion; sand cord; sedimentary dynamic; Hillacondji-Djondji; Grand-Popo.

1. INTRODUCTION

The coast of Benin is a geosystem inherited from the last marine oscillations occurred 6000 years BP, whose morphodynamical stability has been troubled in recent years by natural causes and as well by a series of developments on this coast and on the rivers flowing there.

The 125 km-long Benin coast is part of the West African coastal unit. It is characterized by a narrow strip made up of coarse and medium sands and by an important littoral transit, which makes it a fragile coast. This coast is also affected by intensive human activities [1-5]. Indeed, apart from the natural causes (swell and marine currents) of coastal erosion, those anthropic that constitute the construction of the ports (Ghana, Lome and Cotonou), the Akosombo dam on the Volta and the Nangbeto dam on the Mono river, the sea sand exploitation in Grand-Popo, the destruction of vegetation cover, the recharging and extension operations of the western of the estuary of the Mono river named “ Bouche du Roi ” of Aneho (Togo) carried out in 2012 have caused the systematic blocking of an important part of the sedimentary transit destined to feed the Benin beach, especially the 23 km-long strip of land between Hillacondji and Grand-Popo.

On the other hand, the estuary of the river Mono (la Bouche du Roi) in its mobility, has caused accumulation of sand at the east edge of the western cell following his displacement from West to East in the direction of littoral drift. Before the building of the Nangbeto dam, the estuary of the river Mono (la Bouche du Roi) was a temporary characterized by cycles of opening and closing which resulted in intense phenomena of beaches rearrangement limited to the front of the Koueta island [6-8], that confers a relative stability of position.

After the entry into service of the dam in 1987, the estuary (la Bouche du Roi) became a permanent outlet that migrates constantly in the direction of the littoral drift, at speeds up to 700 m / year [9]. This mobility of the embouchure is accompanied by violent erosion phenomena which destroys literally the beaches, the whole villages and the infrastructures (roads, schools, cemeteries, etc.) realized along the coast. The study area is a sand strip stuck between the Atlantic Ocean in the South and the coastal lagoon in the north in the district of Grand-Popo in the south-west of Benin (Fig. 1). It is characterized by a topography which consists of three (03) sets namely: the coast which corresponds to a sandy littoral strip (fluvial marine); wetland areas and flood-prone areas and the terminal continental shelf [10]. Three types of soil are notices such as littoral soils and sandy dune ridges, hydromorphic and fertile soils, and alluvial and hydromorphic soils.

The climate is sub-equatorial of Guinean type characterized by two dry seasons (mid-November to mid-March and mid-July to mid-September) and two rainy seasons (mid-March to mid-July and mid-September to mid - November) [11].

The local water system is composed of the Mono River, which has its source in Aledjo mountains at Atacora in northern Benin and its tributaries (the Sazue, Agogo, Adanwadonme) and the Grand-Popo lagoon which receives the sea waters, from the Mono river and communicates with that of Ouidah (Fig. 1).

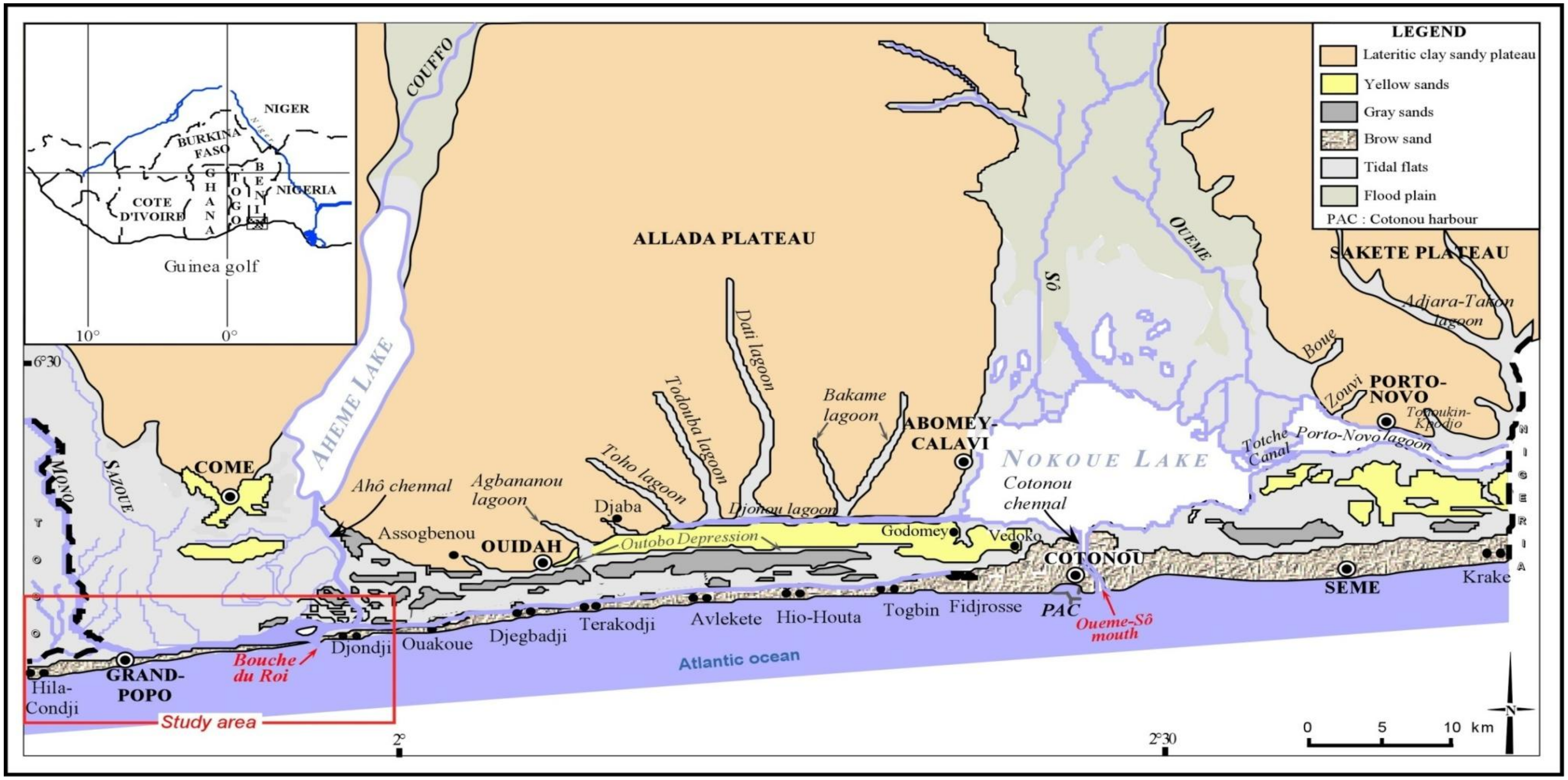

Fig. 1. Geomorphological map of South Benin showing the different segments of the Benin coast with in the box the west cell with a moving barrier

The local hydrographic system is composed of the Mono River, which in Aledjo Atacora Mountains in northern Benin and its tributaries (the Sazue, Agogo, Adanwadonme) and the lagoon of Grand-Popo receiving waters sea, river Mono and communicates with that of Ouidah (Fig. 1).

With regard to the marine hydrology, the tide is microtidal and semi-diurnal. It is characterized by generally low streams on the coast and extreme tides of +1.95 m and -0.20 m. The direction and regime of the surges are related to storms in the South Atlantic [6,12] and, to some extents to southwest winds, especially during the wet season (May to September). They show two seasons: one with low height surges (0.5 to 1 m) from October-November to May-June; the other from June to October with heights reaching and sometimes exceeding 2 m. Directions of the surges with height greater than one meter are between 160° and 230°. But, generally they are constant and show a predominance of the directions S at SSW for the first swells, and SSW at SW for the seconds [13]. Swell can thus be considered as an essential factor of sediment transport on the Benin coast, having between 10 s and 15 s period with a maximum frequency of 11 - 12 s. The obliqueness of the swell related to the shore vary between 4° and 9° with an average around 6° -7°. It causes longshore drift (between the bar and the foreshore) directed from west to east, responsible of the littoral transit along the coast and attracts 1.5 million m^3 of sand from Lome to Cotonou each year [14].

The present study aimed at revealing the sedimentary balance of the coast sector between Hillacondji and Djondji in the South-west of Benin based on data collected from field surveys, observations and measurements as well as analysis of satellite imagery.

2. MATERIALS AND METHODS

2.1 Material

The material used for this study was composed of measuring and observation tools, satellite images and data processing software. A GPS (GARMIN + 8S) and a camera (CANON IXUS 160) were used to locate the spot of observation and to take illustrative photographs of the beach phenomena during our fieldtrips. The analysis of the shoreline evolution and the morphology of beaches in the municipality of Grand Popo (Hillacondji-Djondji) were carried out using Landsat satellite imagery. The images used come from archive catalogs resulting from ETM + instruments (*Enhanced Thematic Mapper Plus*) and corresponded to the Landsat 7. They were downloaded via the website http://glovis.usgs.gov/. After a visual observation of the downloaded scenes, six (06) were selected for the analysis (Table 1). They were taken between 2011and2016. Each of the images used covers the littoral of the Gulf of Guinea, from the Volta delta (Ghana) to Lake Nokoue (Benin). The spatial extension was 185 X 183. All the scenes were directly ortho-rectified and projected in the UTM/WGS84 system and each was accompanied by metadata specifying the acquisition parameters, the type of sensor, the type of satellite, the date, etc.

The images derived from the raw data are delivered in a standard format with a spatial resolution of 30 m for the visible channels, near and middle infra red channels. For the panchromatic band, the pixel size is 15 m.

This method is used successfully in the framework of the study of the ministry in charge of coastal protection work of MEHU 2012 [15] by Laibi.

2.2 Methodology

The treatment of the six selected images (Table 1) allowed to appreciate the spatio-temporal kinematics of the coastal studied sector, according to the following methodological steps:

2.2.1 Image processing

Before exploiting the selected Landsat images, we evaluated their geometric quality by over lapping linear elements such as the river winding or meander for example. A good conformity was noted between scenes used. The study area was then delimited on the overall scenes according to the Erdas Imagine 8.5 software. To facilitate the photo-interpretation, false color composites were made by combinations of the views of channels 453 (RGB) which have a spatial resolution of 30 m. The multiband output images were then re sampled at 15 m by multi resolution fusion with the panchromatic band.

2.2.2 Choice of the reference line

The indicator chosen for referencing the coastline is the instantaneous line of the shoreline. It is the most easily identifiable

Table 1. Presentation of the variousLandsat images used

Scenes references used	Date of image capture	Designation of the shoreline extracted
LE71920562011314ASN00	10/11/2011	Shore2012 (R_{2012})
LE71920562013095ASN00	05/04/2013	Shore2013 (R_{2013})
LE71920562014050ASN00	19/02/2014	Shore2014 (R_{2014})
LE71920562015357ASN00	23/12/2015	--
LE71920562016056ASN00	25/02/2016	Shore2016 (R_{2016})
LE71920562016120EDC00	29/04/2016	--

indicator on the satellite images used [16] (Fig. 2). Moreover, this indicator is fairly well suited in our study area where the mean tidal range is only 1 m. For the various dates chosen, the digitization of the chosen reference entity is carried out by computer-assisted photo-interpretation. Thus, the instantaneous shore line is identified and digitized on the different image bottoms thanks to the ArcGis 9.3 software. It should be noted that the operation is relatively easy; so, we do not face major difficulties in identifying this instantaneous line represented by the transition between the pixels' populations of terrestrial and marine areas (Fig. 2). Also, the studied area was generally cloud-free and presented good color contrasts on all considered images.

2.2.3 Measuring of observed changes

The geomatic and statistical plug-in called DSAS (Digital Shoreline Analysis System) functions asa complementary module for ArcGIS. It measures the distances between the points of intersection of the transects and the coastlines and then calculates the evolution rates along each transect by by restoring the results in the form of attribute tables. The DSAS is reliable today in the majority of the use cases, because it allows to reproduce the past evolution of the littoral. It is quickly and easily operational, allowing, in addition, a great traceability of the different stages of evaluation of the erosion risk. The DSAS tool performs a statistical calculation of the rates of evolution from the coastlines of

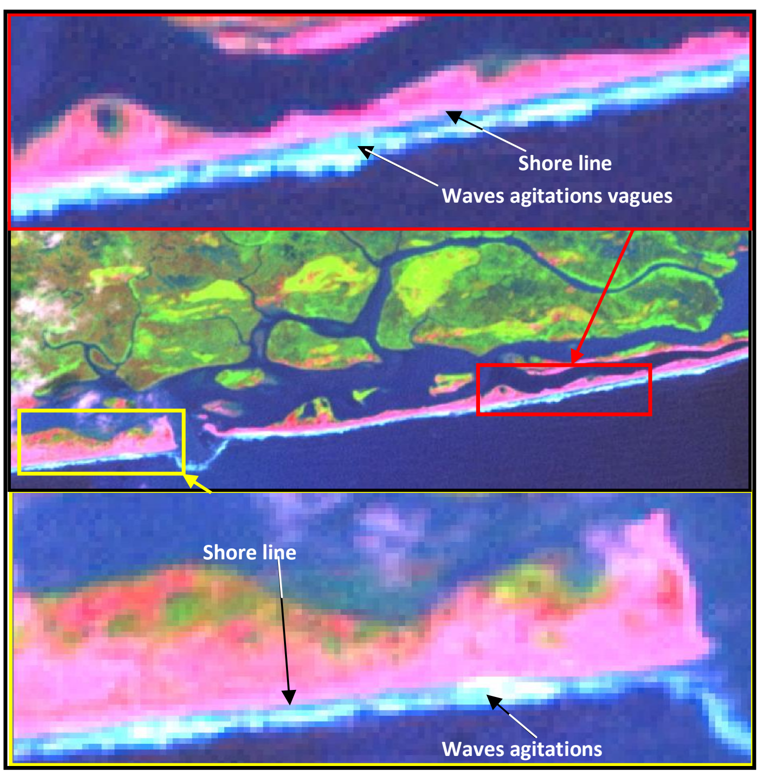

Fig. 2. Highlighting of the instantaneous shoreline on the Landsat image

several dates. The module integrates the evolution of different coastlines on the time interval considered; which makes it possible, intrinsically, to take into account the possible variations of the dynamic agents (wind, swell, storm, and rise in sea level).

From the statistical results of the DSAS tool, the knowledge of the land and from the bibliographic data of the sectors having a uniform speed of changes are defined. Thus, within each sector, the coastline is divided into sections each with an average rate of change.

For this analysis, the user guide supplied with the DSAS 3.0 [17] software was applied strictly to the study area, according to transects separated by 50 m, which are generated from a baseline (Fig. 3). The results obtained are translated into statistical graphical component (using the Excel spreadsheet) and compared to the cartographic part of the study area.

2.2.4 Estimates of the margin of error

We assessed errors that may affect shorelines identified from the satellite Landsat images. The main sources of estimable imprecision are those induced by the size of the pixel (Ep) and by the digitization of the reference line (Ed). In addition, the inequalities of the tidal levels and the intensity of the breaking surge in the swash area during the acquisition of the images generate additional errors (Em) on the instantaneous shoreline position.

The spatial resolution of the sampled Landsat images was 15 m. The error related to the pixel size (Ep) was therefore 15 m.

The precision of the digitization (Ed) of the coastline depends on several factors including the experience of the photo-interpreter and his appreciation of the shoreline considered, which is also conditioned by the resolution and the radiometric quality of the images [18]. Consequently, the line acquired by this method is approximate. Coyne and al. [19] suggested to repeat the digitization of the reference line several times. According to Moore and Griggs (2002), in [18], the error relating in this operation can be estimated by the sum of the average ($\overline{X}$) of the gap recorded during repetition of the digitization and 2 standard deviations (2σ):

$$E_d = \overline{X} + 2\sigma$$

Moreover, under the effect of the tide, the potential error being able to affect the accuracy of instantaneous shoreline corresponds to the horizontal deviation (Em) between the position of the low sea shoreline and that of the

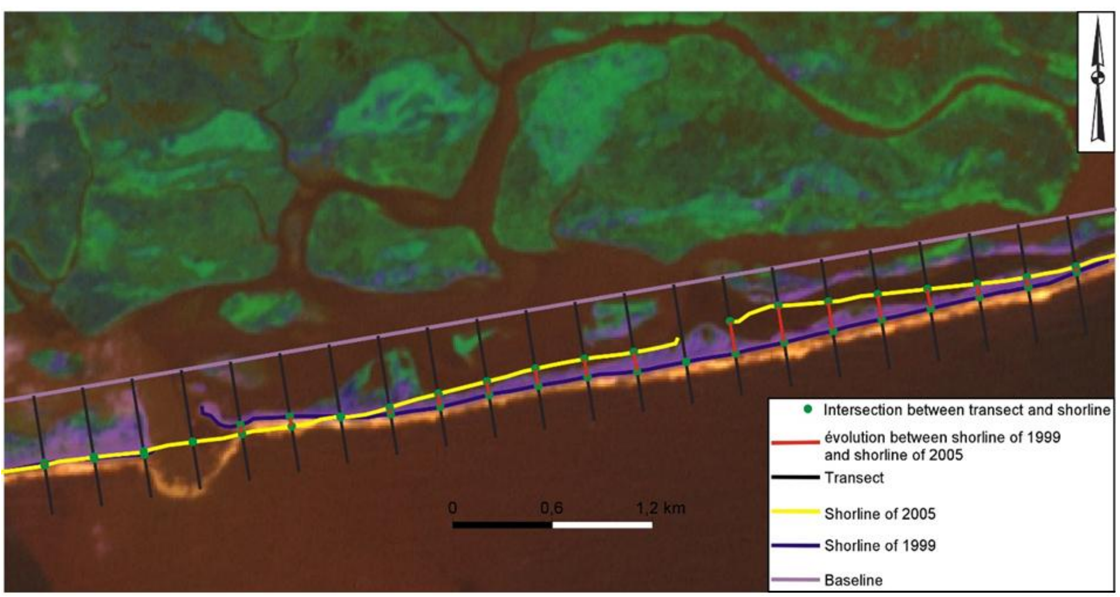

Fig. 3. Illustration of calculation principle of DSAS

high seas. This difference depends on the slope of the foreshore and the tidal range. It can be evaluated by the following geometric relation:

$$E_m = h/\tan(\theta)$$

E_m is the width of the foreshore covered or uncovered depending on the tide; h is the height of the tide at the time of satellite passage; θthe slope of the foreshore.

Since we have neither the value of the slope, nor that of the tide at the time of taking pictures, we considered:

- for the value of h, the average tidal range set at 1 m in the literature;
- for the value of θ, the average value of the slopes of foreshore measured by us between 2007 and 2009 in the study area (between Avlo and Djondji). This one is on average equal to 17%.

$E_m$is therefore about 6 m.

For each of the extracted shorelines, the error resulting from the photo-interpretation is lower than the size of the pixel (Table 2); it is the same for the potential error generated by the tide. On each of the extracted shorelines, the precision that we consider remains the resolution of the pixel (Table 2), because it covers both the error related to the tide that the one capable to be committed during the photo-interpretation.

3. RESULTS AND DISCUSSION

The study of the kinematics of the coastline over the period 2012 to 2016 allowed to identify three segments of coast between Hillacondji and Djondji: Hillacondji-Agoue; Agoue-Avlo and Avlo-Djondji.

3.1 The Coast between Hillacondji and Agoue

On this coast segment, the manifestation of the coastal erosion phenomena began in the 1980s, no doubt further to the construction of the groins of Aneho in Togo (Photo 1; Fig. 4). In 2012, the groins of Aneho were rehabilitated with UEMOA funding. The new functioning of these piece of work causes the systematic blocking of a large part of the sediment in transit to the Benin coast; which accentuates the phenomena of coastal erosion on the beaches of Hillacondji and Agoue.

It should be noted that currently erosion severely eroding the city of Hillacondji (Photo 2),the inter-state- highway or road is found in some places about 500 meters from the shore; the Benin-Togoles border which follows the Gbaga River is in some places, about 300 meters from the inter-state-highway or road Cotonou-Lome.

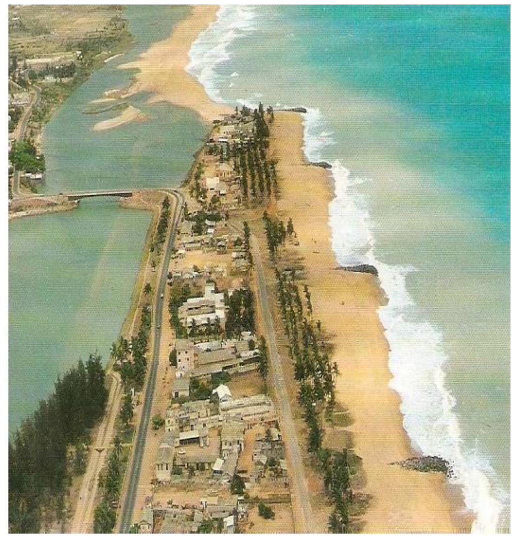

Photo 1. Rock wall protection of the coast; built in 1986 at Aneho in Togo and whose rehabilitation in 2012 (load of sediment and extension of the ears) accelerate erosion with adverse effects on the evolution of the coastline in Benin
(Photo, Mehu, 2012)

Photo 2. Illustration of the extent of erosion on the Hillacondji coast (a highly eroded beach profile showing the destruction of socio-economic settlements and settlements in the village of Hillacondji)
(Photo, Municipality of Grand-Popo, 2014)

The dynamics of this coastal sector is illustrated by Fig. 4, which shows a generalized erosion phenomenon, which increases every year since 2012 for about 5.65 m / year between 2012 and

Table 2. Details of shorelines extracted from satellite imagery

References of the exploited scenes	E_d (m)	E_m (m)	(E_p (m)
LE71920562011314ASN00	9,32	6	15
LE71920562013095ASN00	7,83	6	15
LE71920562014050ASN00	10,67	6	15
LE71920562015357ASN00	8,76	6	15
LE71920562016056ASN00	11,12	6	15
LE71920562016120EDC00	8,73	6	15

2013; 7.42 m / year between 2013 and 2014 and 12.49 m / year between 2014 and 2016. The average erosion progress calculated over the last four years (between 2012 and 2016) was16.46 m / year at Hillacondji beach and 5.13 m / year at Agoue beach (Fig. 5).

3.2 The Coast between Agoue and Avlo

The coastline between Agoue and Avlo evolves in the context of a dynamic balance with an accretion, at an average rate of 1.36 m / year (Fig. 5). In detail, this coastal segment faced significant erosion between 2012 and 2013, no doubt further to the disturbance introduced into the system by rehabilitation of groins of Aneho. From 2013 to 2016, the coast went through fattening and then erosion phases, which reflect the dynamic balance of the shoreline.

Moreover, in this sector, the case of the coast in front of the town of Grand-Popo appeared as a sensitive point with periodic fluctuations and the real identification of the root causes remains to be diagnosed. Since the great upset and successive episodes (1900 to 1905, 1922 and 1944) which the first destruction of the Grand-Popo city, the sea continued to advance until 1982. But from 1982 to date, there is a dynamic equilibrium sometimes interrupted by exceptional erosion episodes like the one in 1986 where the shoreline dropped 15 m in 18 months in front of the former Municipality of Grand-Popo. We estimate that the detailed bathymetric and hydrodynamic studies of the shore face of this sector will make it possible to better understand the interactions between forms and processes (it means between morphology and hydrosedimentary mechanisms).

3.3 The Coast between Avlo and Djondji

This is the sector of coast that appears to be a point of connection between Mono River and the sea, via the embouchure known as “la Bouche du Roi”. This coast segment has evolved over the recent years in a context of erosion and accumulation, due to the instability of the estuary, since Nangbeto dam was constructed on the Mono River. Before the building of this dam, the embouchure was temporary characterized by cycles of openings and closures; the openings were not always natural [6-8]. These cycles of opening and closing of the embouchure resulted in intense phenomena of rearrangement of beaches limited however to the front of the island of Koueta. This was considered as the relative stability of position.

After the launch of the dam in 1987, embouchure became a permanent mouth with a continual move in the direction of littoral drift, at a speed of up to 700 m / year ([9]; Figs. 6 and 7). This mobility of the embouchure is accompanied with violent erosion phenomena which literally destroyed the beaches, entire villages and infrastructures (roads, schools, cemeteries, etc.) along the coast (Photo 3).

The work of [9] showed that the change in the hydrological regime of the Mono River due to the dam of Nangbeto is the root cause of new functioning of the embouchure since 1987. Indeed, before launching the dam, the river Mono was subject toa single flood during the months of September-October with a flow which can reach 680 to 700 m³/s, and a low water level that lasts for nearly six months during which flow rates were almost zero (Fig. 8A). This natural hydrological regime of the Mono River did not allow a permanent opening of the embouchure. The mobility of the embouchure was therefore limited in space and time.

Since the launch of the Nangbeto dam in July 1987, the flow of the Mono River has become permanent followed with an increased in laminated floods and low-water flows (Fig 8B). With this regularization of the Mono flows by the dam, the opening of the embouchure became persistent. Ever since, the migration of the embouchure became permanent. This phenomenon occurred because of the construction of a sandy arrow at the upstreamdrift (well zone) and progressive destruction of beach at the downstream-drift (source zone). This mobility of the embouchure stopped periodically by openings of mechanical breaches first by the resident communities and todays by the Government.

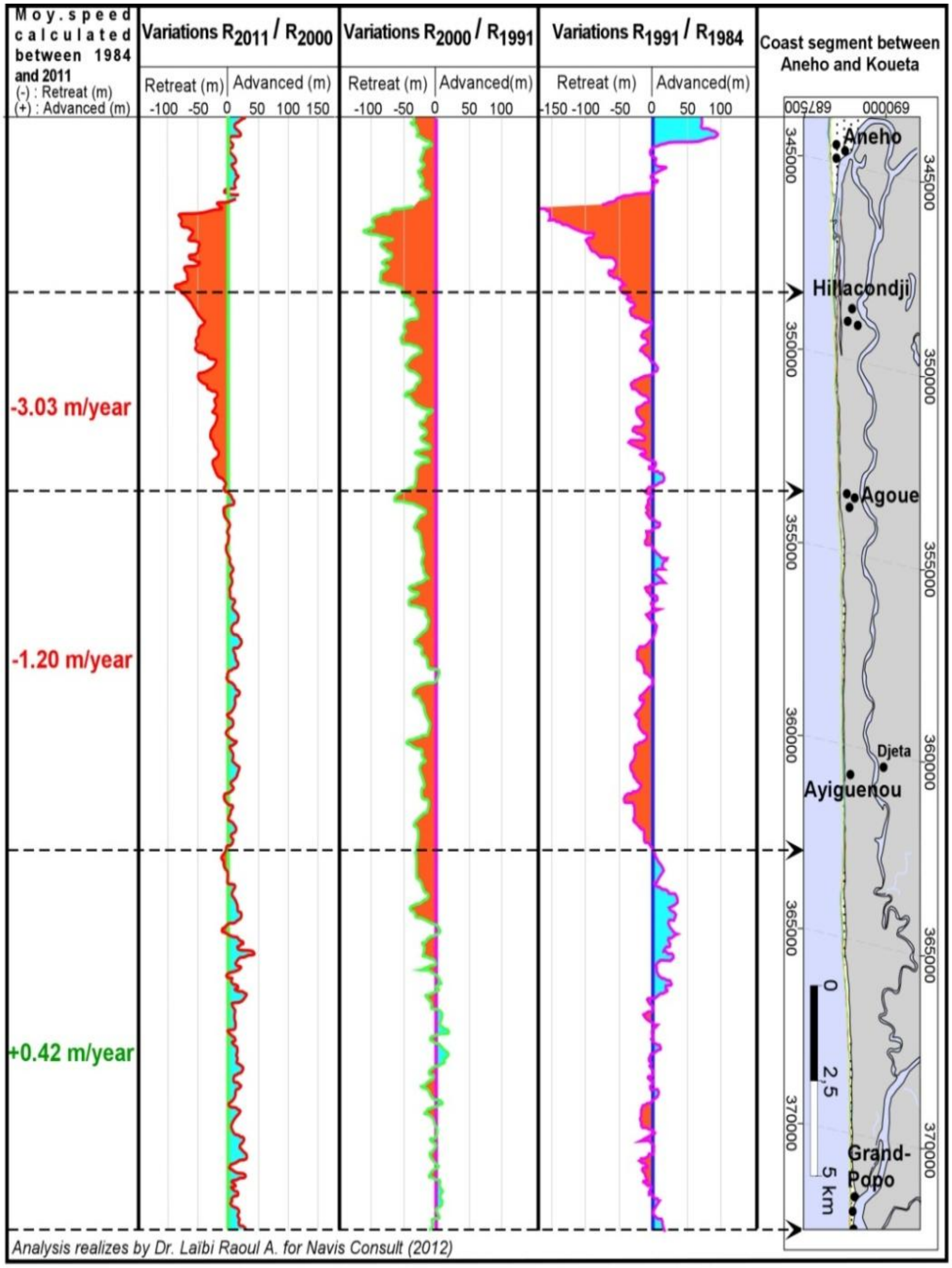

Fig. 4. Kinematics of the coastline and morphodynamics of the beaches of the municipality of Grand-Popo between 1984 and 2012

(Source Executed by Laibi in MEHU 2012 [15])

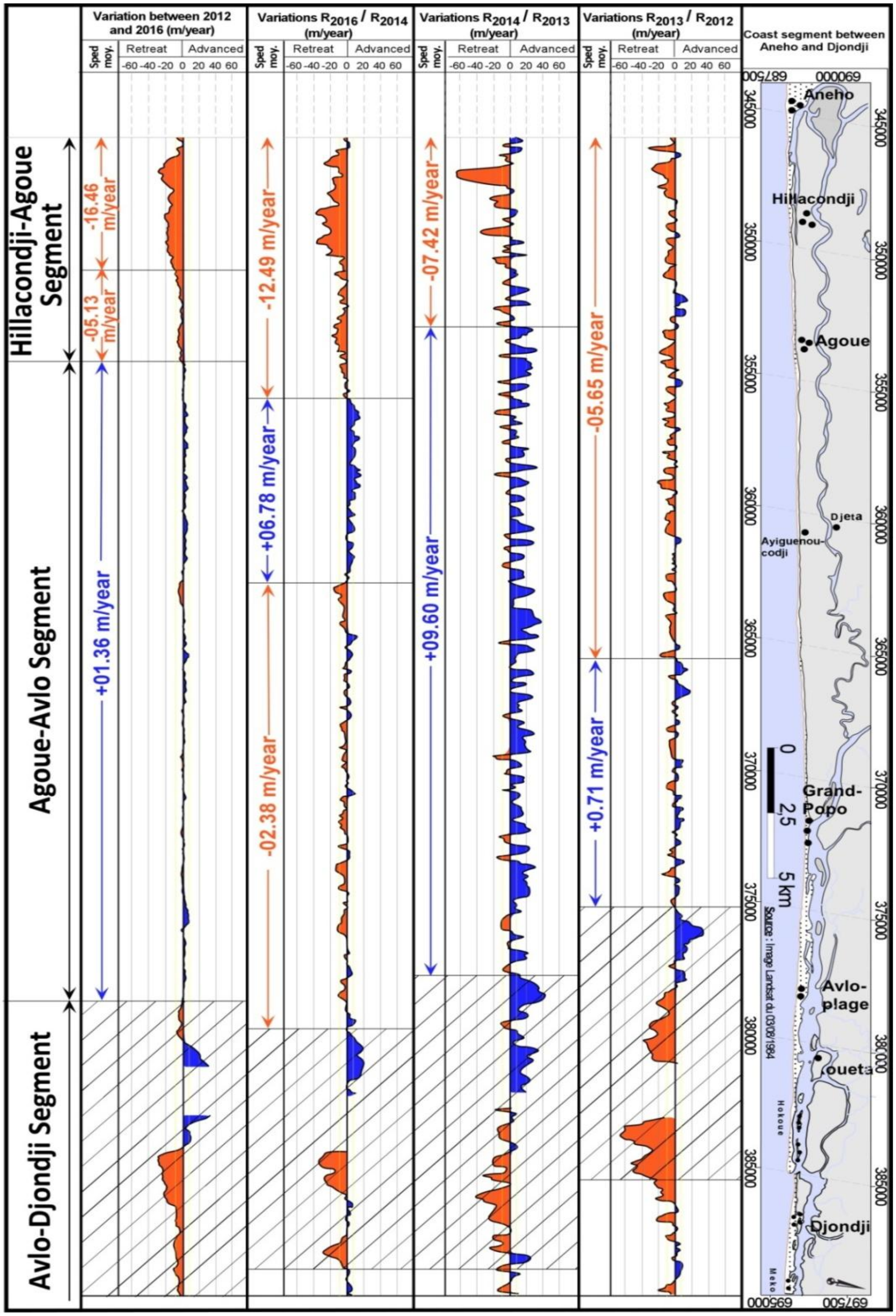

Fig. 5. Kinematics of the coastline and morphodynamics of the beaches of the municipality of Grand-Popo between 2012 and 2016

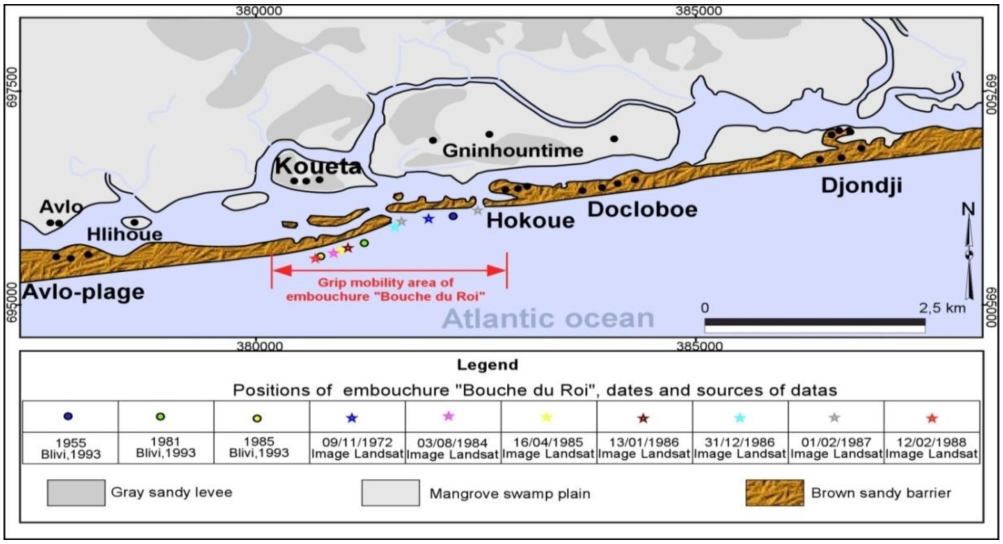

Fig. 6. The area concerned by the mobility of the embouchure (Bouche du Roi) before 1987

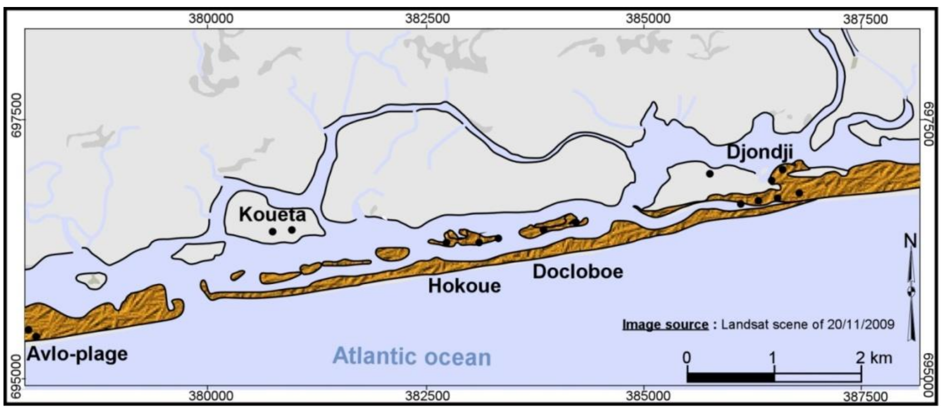

Fig. 7. Map showing the mobility of the embouchure (Bouche du Roi) and its consequences on the state of the beach, after starting up the dam of Nangbeto in 1987

Photo 3. Photographic images showing the devastation of erosion in front of the public primary school at Djondji

Image Laïbi Raoul, 09/10/2009, The damage is immeasurable: Disappearance of the coastal road, engulfment of countless coconut and threatening socio-economic infrastructures (school)

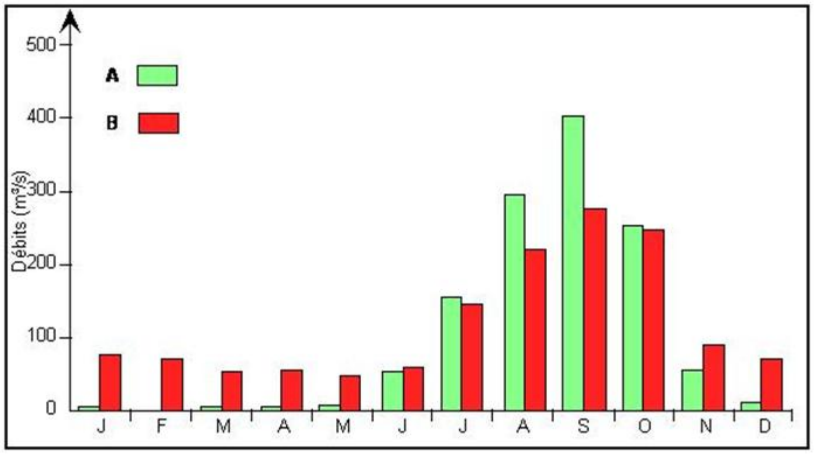

Fig. 8. Mean monthly flows of Mono at Athieme before and after the Nangbeto hydroelectric dam

A- Flow before the start-up of the dam; B- Flow after the start-up of the dam

Facing this permanent instability and especially with regard to the magnitude of damage it causes, it is necessary to research the types of arrangement that would serve as mitigation measures. In other words, it is imperative to think of solution approaches that will allow producing electricity essential for economic development while preserving as much as possible the heritage of landscapes and natural and touristic resources attached to this sector of coast.

As a result of our research work, it is recommended in the framework of the protection works to opt for more flexible, ecological, sustainable measures without downstream erosion impact. For example, it would be desirable for states to opt for coastal fattening by sand dredging and sand engine installation in eroded and fragile sectors.

4. CONCLUSION

Even if current considerations related to climate change (storms and violence of the swell, rising of relative sea level) are also to be taken into account in the evolution of the coasts Hillacondji-Djondji, the causes of erosion observed remain essentially anthropic. They are related on the one hand to the protection infrastructure of Aneho in Togo (sector Hillacondji-Agoue), and moreover (on the other hand), to the Nangbeto dam functioning (sector Avlo-Djondji). The dynamics of this coastal sector show a general erosive crisis, aggravated from year to year since 2012 with retreated for about5.65 m / year between 2012 and 2013; 7.42 m / year between 2013 and 2014 and 12.49 m / year between 2014 and 2016. The average calculated over the last four years (between 2012 and 2016) is 16.46 m / year on Hillacondji beach and 5.13 m / year on Agoue beach.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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