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Analyses of Short- and Long-Term Shoreline Trends of the Southwest Benin Coast

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ABSTRACT

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Coastal zones are the economic heart of coastal countries and are therefore densely populated. In recent times, coastal zones are found to be globally eroding at variable spatiotemporal scales, leading to loss of business activities, ecosystems, economic lands, and infrastructures. Similar to elsewhere in the world, in West Africa and particularly the Benin Republic, the problem of the eroding shoreline is on the increase. Currently, the Grand-Popo section (the western part of the Benin coast) is experiencing serious shoreline change, which is causing the destruction of physical infrastructure and ecosystems. This study aims to determine the shoreline change trends in the study area over approximately a 10-year period from 1988 to 2018. To attend this objective, the SPOT and Sentinel-2 remotely sensed data of 10-m resolution were used, and the shoreline feature was extracted using the high-water line as an indicator. The shoreline feature dynamics were analysed using the Digital Shoreline Analysis System extension in ArcGIS, where the shoreline change statistics were computed and analysed. The results indicate that from 1988 to 2001, a high net shoreline accretion occurred, representing 80.39% of the entire study area at an average rate of 3.46 m/y. From 2001 to 2012, the Grand-Popo shoreline was affected by erosion representing approximately 85.17% of the study area at an average erosion rate of –4.54 m/y. Net shoreline accretion corresponding to 76.08% of the entire study coast at an average rate of 7.98 m/y also occurred between 2001 and 2012. Considering the entire study period (1988 to 2018), 68.51% of the shoreline accreted at an average rate of 0.79 m/y whereas 31.49% of the entire coast eroded at an average rate of –0.75 m/y. Major erosion was observed near the mouth of the Bouche du Roy estuary.

ADDITIONAL INDEX WORDS: *Grand-Popo coast, shoreline change, DSAS, satellite imagery, Bouche du Roy.*

INTRODUCTION

In many parts of the world, coastal zones developed into great business hubs and are therefore densely populated. Thus, they play key roles in the economies of the coastal countries. Coastal zones represent the home of more than 60% of the world's population (Boye *et al*., 2018). Coastal areas comprising mainly beaches, estuaries, and special ecosystems provide diverse ecosystem services to the riparian communities. However, in recent years the most common environmental issues observed in the coastal zones worldwide are the shoreline change and floods. More than 70% of the world's coast is undergoing coastline retreat (Makota, Sallema, and Mahika, 2004). This coastline retreat is inevitably related to loss of business activities, economic lands, and properties and also the destruction of natural ecosystem and services. This loss of natural ecosystem and the change of the estuaries are likely to increase flood damages to the riparian communities (Alexandrakis *et al*., 2010).

The West African coastline, comprising mainly estuaries, beaches, economic lands, and properties, is not immune to this degradation. The coastal section of the Benin Republic in the Gulf of Guinea (121 km) occupies about 0.5% of the country's total surface area. This coastal section, which houses about 1.8 million people (about 18% of the country's total population), represents the economic heart of the country (ABE, 2016; MEHU, GEMGG, and CEDA, 1998). Similar to other coastal countries, the coastal fringe of the Benin Republic is facing shoreline changes. Several studies indicated that the occurrence of coastal erosion could be detected through analyses of shoreline change over a period. Shoreline change is caused by various factors; however, three key factors are sea-level rise (Boye *et al*., 2018; IPCC, 2007; Kumar *et al*., 2003), change in storm climate (Vassie, Woodworth, and Holt, 2004), and human interference with coastal processes (Appeaning Addo, Walkden, and Mills, 2008; Zhang, Douglas, and Leatherman, 2004). The Grand Popo Township, which is part of the Benin Republic coastal fringe, is subjected to strong coastal erosion that presents an environmental imbalance, in particularly around the Bouche du Roy estuary (Gnélé, 2010). This phenomenon is expected to increase in the coming decades in response to sea-level rise as a result of global warming (Dégbé, 2009; IPCC, 2014). According to Boudjerda (2010), coastal erosion in this area is a natural phenomenon caused by a shortage of sediment supply to the coast. This is further accentuated by human activities such as the construction of the Nangbéto Dam, coastal defence infrastructures, deforestation, *etc*. (Toffi, 2008).

According to Boye *et al*. (2018), the process through which coastal landforms occur is the shoreline change. The better way

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to understand this process is to analyse the shoreline dynamics through a comparison analysis of several scenes of satellite imageries captured over a considerable period. The trend analysis of shoreline change conveys information about the causative factors; thus, mitigation efforts could be suggested from such studies. For instance, in Massachusetts, USA, this analysis showed that the shoreline was receding at the rates ranging between 0.18 m/y and 4 m/y (Ruggiero *et al*., 2013). In another previous study conducted in Texas, USA, the shoreline change was analysed based on 125 years of dataset. This study indicated that both accretion and erosion occurred at different sections along the shores (Morton, 1997). Also, this study revealed that the short-term change is caused by a complex interaction of climate change, whereas the long-term change showed that most parts of the coast still experience erosion provoking the landward retreat. Furthermore, a study conducted in France using data from 1992 to 2000 revealed that the shoreline of West Brittany was affected by the alternation of eroding phases at rates between 0.2 m/y and 2 m/y and accretion phases (Dehouck, 2006). In South Africa, a study along the Eastern coast using 37 years of dataset indicated that the coast was receding (Corbella and Stretch, 2012).

In West Africa, however, few shoreline-change studies have been performed over a long-term period that would allow researchers to understand the behaviour of the shoreline. Limited short-term analyses of shoreline-change studies of some small sections of the coast of Ghana were undertaken (Appeaning Addo *et al.,* 2011; Boye *et al*., 2018). These studies analysed the shoreline dynamics in different locations to determine the behaviour of the shoreline. In the Benin Republic, the shoreline dynamic is observed along the entire coast, but the western zone of the coast is very worrisome. This section of the coast is highly unstable with fluvio-marine activities. At the mouth of the river Mono (western zone) called Bouche du Roy, where the river flows into the sea, complex morphological changes have taken place and the outlet is shifting along a stretch of about 10 km between Avlo and Djondji. The situation has greatly deteriorated since 1990 with the implementation of the Nangbéto dam, and a great deal of erosion has occurred over the period. Several coastal settlements and installations have been washed away. For instance, in August 1999, the Djondji village was lost to erosion following the submerging of Docloboé village in previous years. This deterioration has continued since 2000 (WACA, 2017).

Moreover, the loss of natural habitat of the coast land engendered loss of biodiversity and natural services, such as wetlands for flood control, areas for recreation and tourism, and bank protection by mangroves (WACA, 2017). Some simulations performed in 1992 had suggested a relative stability/accretion of the Bouche du Roy estuary area for 25 years (*i.e*. until 2012) after the construction of Nagbeto' dam. The amount of sediment provided by the Mono River to the coast decreased from 100,000 m^3/y to 25,000 m^3/y (Blivi, 2000; Rossi and Blivi, 1995). In 1998, a study revealed that the estuary of Bouche du Roy and its adjacent beaches were experiencing sand loss of about 600,000 m^3/y because of the construction of the Nagbeto dam and sand mining (Adam, 1998). Considering the foregoing narratives, it is imperative that the shoreline change along the Coast of Grand-Popo Township be investigated at different time scales to understand the cyclical nature of the shoreline and the morphodynamic processes of the coast. The study describes the shoreline change trends over the last 30 years (covering the period between 1988 and 2018) and identified locations with greater shoreline changes and/or progressive shoreline retreat within the western zone of the Benin Coast.

METHODS

Studying the short- and long-term shoreline trends requires different periods of satellite imageries and an appropriate image processing technique. This section presents the study area, the data with the processing methods, and the results accuracy assessment techniques.

Study Area

Benin Republic has about 121 km of shoreline from east to west. The coastal area is habited by about 1.9 million people representing approximately 17% of the total population. The urban coastal population is about 1.8 million (97% of the total coastal population). The coastal area of the Benin Republic is divided into four zones, namely the East zone, Central East zone, Central West zone, and West zone (Antea Belgium, 2017). This study was performed in the West zone, which lies within latitudes 6.27° and 6.29° N and longitudes 1.83° and 1.93° E (Figure 1). The shoreline of the West zone stretches to about 23 km, constituting about 19% of the Benin Republic coastline. The ocean tide affecting this coast is semidiurnal and microtidal, with extreme tidal ranges between 1.95 m and –0.20 m, with an amplitude of 1 m. The direction and regime of swells are related to storms in the South Atlantic, especially those generated by the Saint Helena High and incidentally local winds (Anthony and Blivi, 1999; Sitarz, 1960).

The study area experiences a subequatorial climate, Guinean type with a bimodal rainfall. The annual rainfall is about 900 mm. Because of the maritime influence, temperatures are characterized by small variations. The annual average temperature is about 27°C. The highest maximum temperatures are recorded in March (34°C), whereas the lowest temperatures are observed in August (23°C). The relative humidity is high and varies between 70% and 90% because of the proximity of the sea.

Oceanographic climate in this area shows an average significant wave height ranges between 0.4 and 2 m and a significant wave period between 10 and 15 seconds, with average frequency from 11 to 12 seconds. These high waves are considered as the swell, which is an essential factor controlling sediment transport along the Benin coast. In breaking waves, the skew of the swell in relation to the shore varies between 4° and 9°, with an average ranging between 6° and 7° (Rossi, 1989). This causes a longshore drift directed from west to east, and the longshore drift measured in Cotonou ranges between 0.3 and 1 m/s (Sitarz, 1960). This current is responsible for the annual sediment transport of 1.2 to 1.5 million m^3 of sands along the coast of the Gulf of Guinea (Laïbi, 2012; LCHF, 1984; NEDECO, 1975; Sitarz, 1960). Prevailing waves approach the coastline from the S to SSW directions for the first wave, and SSW to SW for the second (Rossi, 1989; Sitarz, 1960). The study area comprised homogeneous coastal material characterised by

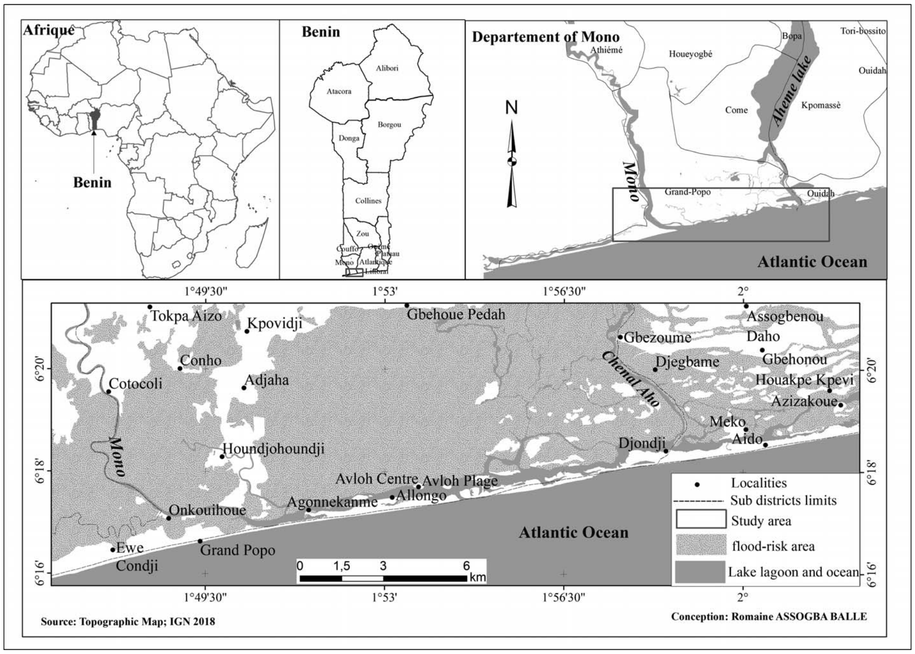

Figure 1. Study site highlighted at south western Benin, West Africa. It is showing the part of Benin coast that was considered in this study with the location of some villages that are vulnerable to coastal erosion.

sandy beaches, intersected by some lagoons and estuary, and stretches to about 20 km (Onkihoué–Méko). The Mono and Couffo rivers supply sediment materials to nourish the build-up of the shores. The two rivers entered the sea through two lagoons that interact with each other via the Aho channel and the Bouche du Roy estuary. The depths of these lagoons are quite low (1 to 3 m), with the bottoms characteristically muddy to sandy-muddy (Ago, 2005; Blivi, 2000; Bokonon-Ganta, 1987; Toffi, 1991).

Data Acquisition and Processing

Shoreline position was determined using satellite images with 10-m pixel resolution. The historical images were SPOT images (1988, 2001, and 2012) obtained from the OSFACO Project (Observation Spatiale des Forêts d'Afrique Centrale et de l'Ouest) performed by DGEFC (Direction Générale des Eaux, Forêts et Chasses) in the Benin Republic. A recent additional satellite Sentinel-2 image (2018) was downloaded for free from Copernicus (2020) (Table 1). The four images were already georeferenced and orthorectified from the source and projected using the UTM/WGS84 projection system.

The shoreline features were extracted by digitizing and then being integrated in an ArcGIS 10.4 environment. A GPS (Garmin 64S) was used in the field collection of more than 12 well-separated ground control points. This helped in the accuracy assessment after the image processing. A combination of image processing and interpretation techniques were applied for this study following Dehouck (2006), Durand (2002), Moore (2000), and Shoshany and Degani (1992). The shoreline positions within the study area were extracted from the images using the instantaneous high-water line as shoreline proxy on the images because it is the most easily identifiable indicator on the images used (Thieler *et al*., 2013). Moreover, it is quite suitable for a study area where the average tidal range is only 1 m. Approximately 20-km multidate shorelines from Onkihoué to Méko (Figure 1) were digitized, and the change rates were analyzed. The total root mean squared error for the rectification process was maintained below 1 pixel. The shorelines were therefore compatible for the change detection and comparison. A geodatabase was created where all the shoreline features were stored after keying in specific attributes as prescribed by the Digital Shoreline Analysis System extension before appending all the shorelines (Thieler *et al*., 2009). A baseline feature was created, and perpendicular transects were cast at an interval of 10 m to cross the merged shoreline positions (Figure 2). The shoreline change statistics were computed using the end point rates and the linear regression rates (LRR) methods, respectively, for the delta between 1988 and 2018. Detailed discussion on these methods can be found in Boye *et al*. (2018) and Frazer, Genz, and Fletcher (2009). These methods were used because of their accuracy because aberrations in the shoreline datasets can be excluded by use of the line of best fit (Boye *et al*., 2018).

Table 1. *Dates and resolution of satellite images.*

Satellite Images	Acquisition Date	Resolution (m)
SPOT1-HRV2-XS	12/01/1988	10
SPOT4_HRVIR2_XS	30/11/2001	
SPOT5_HRG2_XS	19/12/2012	
Sentinel 2	23/12/2018	

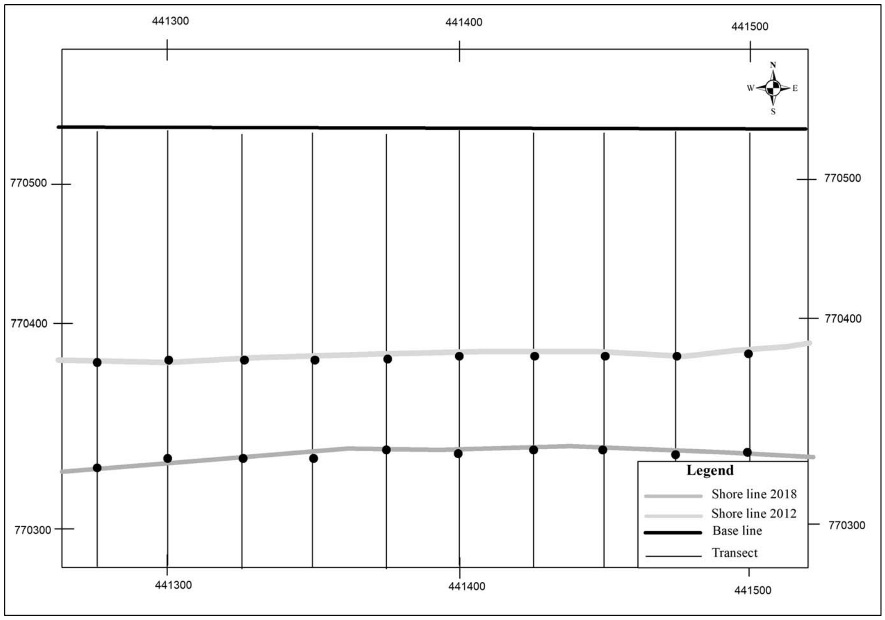

Figure 2. Transect and baseline approach used by the Digital Shoreline Analysis System to create and to measure the evolution of the coastline between different periods (*e.g.,* between 2012 and 2018). The baseline feature was created, and perpendicular transects were cast at an interval of 10 m to cross the merged shoreline positions.

Estimation of Associated Uncertainties

Uncertainty statistics can be computed either from a built-in error margin table or from a default value (Himmelstoss, 2009). The main sources of inaccuracy that can be estimated are those induced by the pixel size (Ep), the digitization (Ed) of the reference line, and the position of the reference line (Em). According to Hapke *et al*. (2006), Himmelstoss (2009), and Moore (2000), the digitization error (Ed) can be estimated as the sum of the average of the recorded offsets ($\bar{X}$) during the repetition of the digitization and two standard deviations:

$$\mathrm{Ed} = \bar{X} \cdot 2\sigma \quad (1)$$

In addition, under the tide effect, the potential error that can influence the accuracy of the instantaneous shoreline corresponds to the horizontal distance (Em) between the position of the low-tide and high-tide shorelines. The difference therefore depends on the slope of the foreshore and the tidal ranges. It can be evaluated by the following geometric relation (Laïbi *et al*., 2012):

$$\mathrm{Em} = \frac{h}{\tan(\theta)} \quad (2)$$

where, Em is the width of the foreshore covered or discovered depending on the tide; h is the height of the tide at the time of passage of the satellite; and θ is the slope of the foreshore in the study area between 2001 and 2018, averaging 17%. Because the value of the slope and of the tide did not exist at the time of taking the images, the value of h has been considered as the average tidal range, set at 1 m according to the literature. Mean values for each uncertainty term were calculated for each shoreline (Table 2).

Table 2. *Precision of shorelines extracted from satellite images.*

Satellite Images	$E_{d\ (m)}$	$E_{m\ (m)}$	$E_{p\ (m)}$
SPOT1-HRV2-XS	8.16	6	10
SPOT4_HRVIR2_XS	9.8	6	10
SPOT5_HRG2_XS	7.68	6	10
Sentinel 2	6.72	6	10

RESULTS

The shoreline change rates were computed at 10-m transect intervals across the 20 km stretch of the shoreline from 1998 to 2018. This period was divided into three subperiods: 1988 to 2001, 2001 to 2012, and 2012 to 2018. For the entire period and the three subperiods, the spatiotemporal trends of the shoreline around the Bouche du Roy estuary were analyzed.

Shoreline Dynamic from 1988 to 2001

The shoreline change rates computed for the study area from 1988 to 2001 showed a general trend of advancing seaward in 80.39% of the study area, with an average and maximum rate of 3.46 and 24.03 m/y, respectively. However, shoreline recession was observed in 19.61% of the coastline at maximum and average rates of –18.75 and –5.48 m/y (Figure 3). The coastline recession mostly occurred around the Kouéta, Hakoué, Gonko, and Hounkounou villages. Furthermore, a migration of the mouth of the Bouche du Roy estuary was observed during this period. In 1988, the estuary's mouth was located at Hlihoué, whereas in 2001 two openings occurred: an artificial one not far from Hèvè and a natural one toward Djondji. The artificial opening was undertaken to ease the flood menace affecting the area at that period. This migration

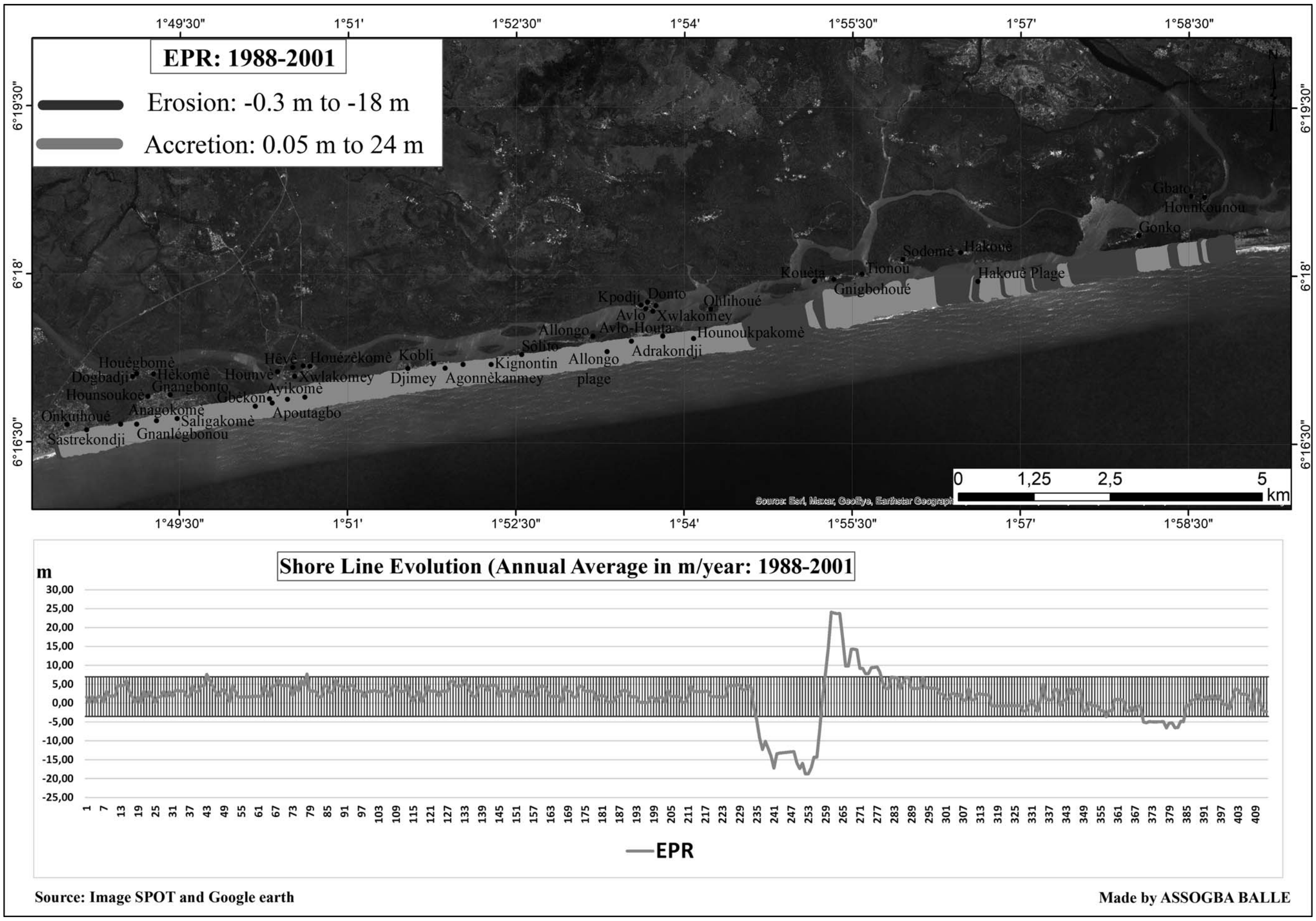

Figure 3. Shoreline dynamic highlighting the accretion (light gray) and erosion (dark gray) phenomena observed from 1988 to 2001. The map of the magnitude of shoreline change rate at 10-m transects intervals by computing the statistics of change using the end point rates method is shown through the graphic directly below. The names and location of the affected villages are indicated on the map.

occurred over a period of 13 years at an average migration rate of ≈360 m/y.

Shoreline Dynamic from 2001 to 2012

The shoreline change rates computed across the shoreline in the study area (20 km stretch of shoreline) from 2001 to 2012 showed a general trend of recession over most portions (85.17% of the study area). A mean change rate value of –4.54 m/y was recorded for the entire study area, with a maximum recession rate of –20.1 m/y (Figure 4). During this period of 11 years, the maximum landward net shoreline movement was –221.08 m. The accreting zone recorded maximum and average accretion rates of 12.22 and 5.25 m/y, corresponding to seaward advancement of 134.43 m. During this period, as the initial opening of the Bouche du Roy estuary mouth migrated from Djondi to Koua at a migration rate of ≈300 m/y, the second opening completely disappeared.

Shoreline Dynamic from 2012 to 2018

Figure 5 shows the shoreline dynamic around the Bouche du Roy estuary from 2012 to 2018. From this figure, it was observed that the 20 km stretch of shoreline were most dominated by accretion of the coastline, where 76.08% of the entire study coast advanced seaward at maximum and average rates of 49.91 and 7.98 m/y, corresponding to a coastline advance of 299.50 m. During this six-year period, shoreline erosion occurred in 23.92% of the study coast at a maximum and average rate of –20.25 and –5.05 m/y, corresponding to a coastline retreat of 121.52 m. In addition, the estuary mouth migrated from Kouéta to Hlihoué at an average speed of 205 m/y.

Shoreline Dynamic from 1988 to 2018

In Figure 6, showing the trend of erosion and accretion rates based on the LRR for the past 30 years (1988 to 2018), the balance of the 30-year period was 68.51% accretion compared to 31.49% erosion. The eroded coast stretched from Alongo beach to Gnigbohoué and from Gonko to Hounkounou, with an average erosion rate of –0.75 m/y. It should be noted that the high rate of erosion was observed at the estuary mouth, whereas accretion areas stretched from Onkihoué to Sôlito and

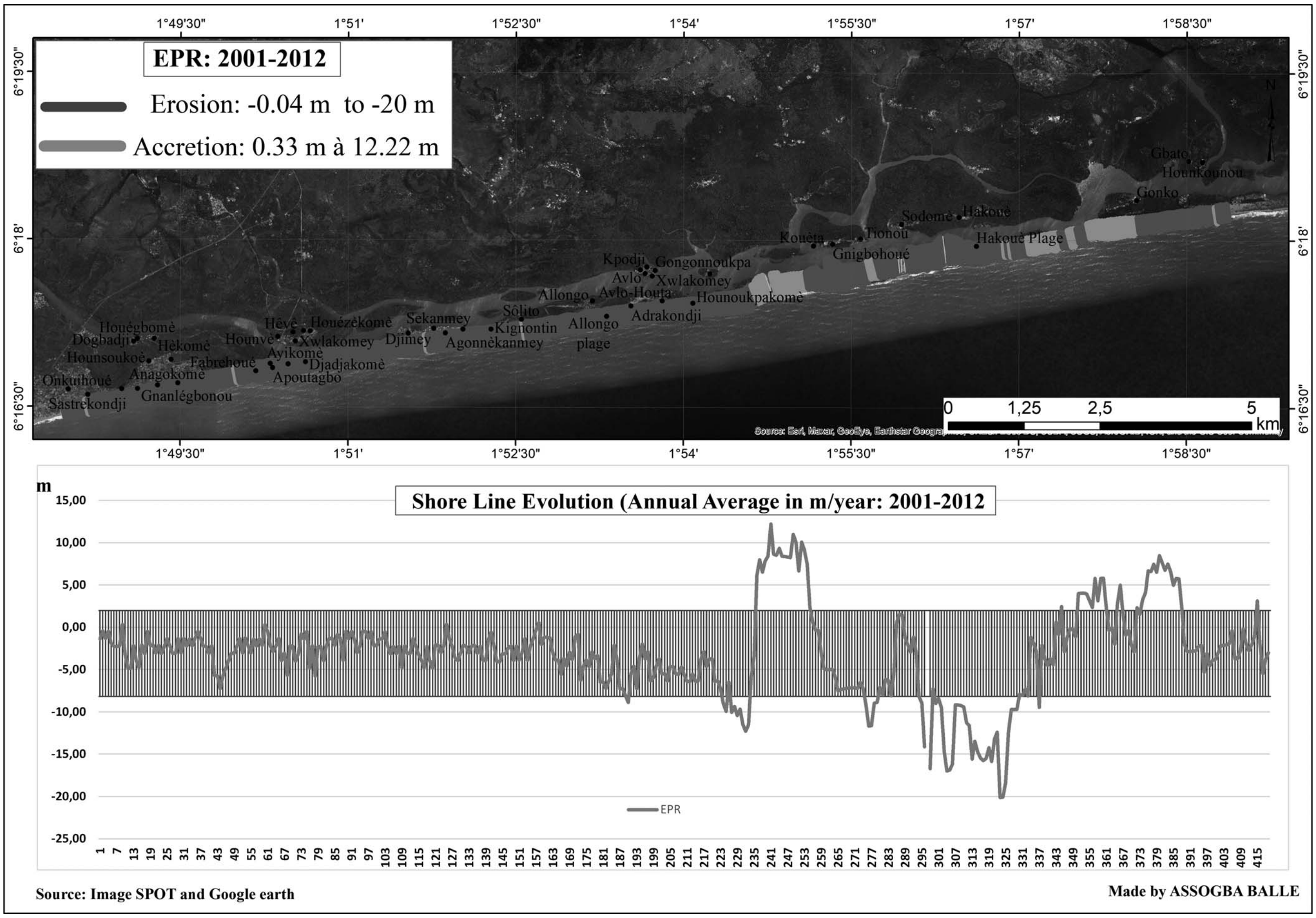

Figure 4. Shoreline dynamic indicating the accretion (light gray) and erosion (dark gray) phenomena observed from 2001 to 2012, with the locations of the affected villages. The graphic directly below the map shows the magnitude of shoreline change rate at 10-m transects intervals by computing the statistics of change using the end point rates method.

from Kouéta to Tionou and Hakoue beach with an average accretion rate of 0.79 m/y.

DISCUSSION

From this study, the spatiotemporal dynamic of the shoreline around the Bouche du Roy estuary was dominated by seaward migration (accretion) with small portions of migration landwards (erosion) from 1998 to 2001. The graph (Figure 3) shows the magnitude of shoreline change rate at 10-m transects intervals. It portrays an up and down movement with a slight positive magnitude from the starting transect point at Onkuihoué to Ohlihoué, where little accretion occurred. Around Kouéta, Hakoué, and Hounkounou, it was observed that shoreline erosion occurred with a maximum amplitude of –18.75 m/y at Kouéta. However, at a nearby location (neighboring Gnigbohouéit village), a maximum accretion of +24.03 m/y was observed. From 2001 to 2012, the spatiotemporal dynamic of the shoreline was mostly characterized by migration landwards, accompanied by slight migration seawards (Figure 4).

Along the coastline and during the period from 2001 to 2012, significant accretion of about 240 m occurred between Xwlakomey and Kouéta and also about 180 m of accretion around Hakoué Plage and Gonko villages. In the same period, the shoreline erosion increased at a rate of –20 m/y around Kouéta, Hakoué, and Hounkounou compared with the previous period (1988–2001). The shoreline erosion extended during the period (2001 to 2012) to the immediate neighboring Kouéta (Gnigbohoué) village, which was accreting at a rate of +24.03 m/y in the previous period (1988–2001).

In summary, it was observed that from 2001 to 2012 the rate of migration landward ranged between –0.04 and –20 m/y, whereas the rate of migration seaward ranged from +0.33 to +12.22 m/y. Further, the spatiotemporal dynamic of the shoreline from 2012 to 2018 indicated mostly migration seawards at a rate ranging between +0.22 and +49.91 m/y, whereas migration landward occurred at specific locations at a rate between –0.08 and –20.25 m/y (Figure 5). During this period, the most significant build-up of coastline (accretion) occurred on a section between Tionou and Hakoué Plage,

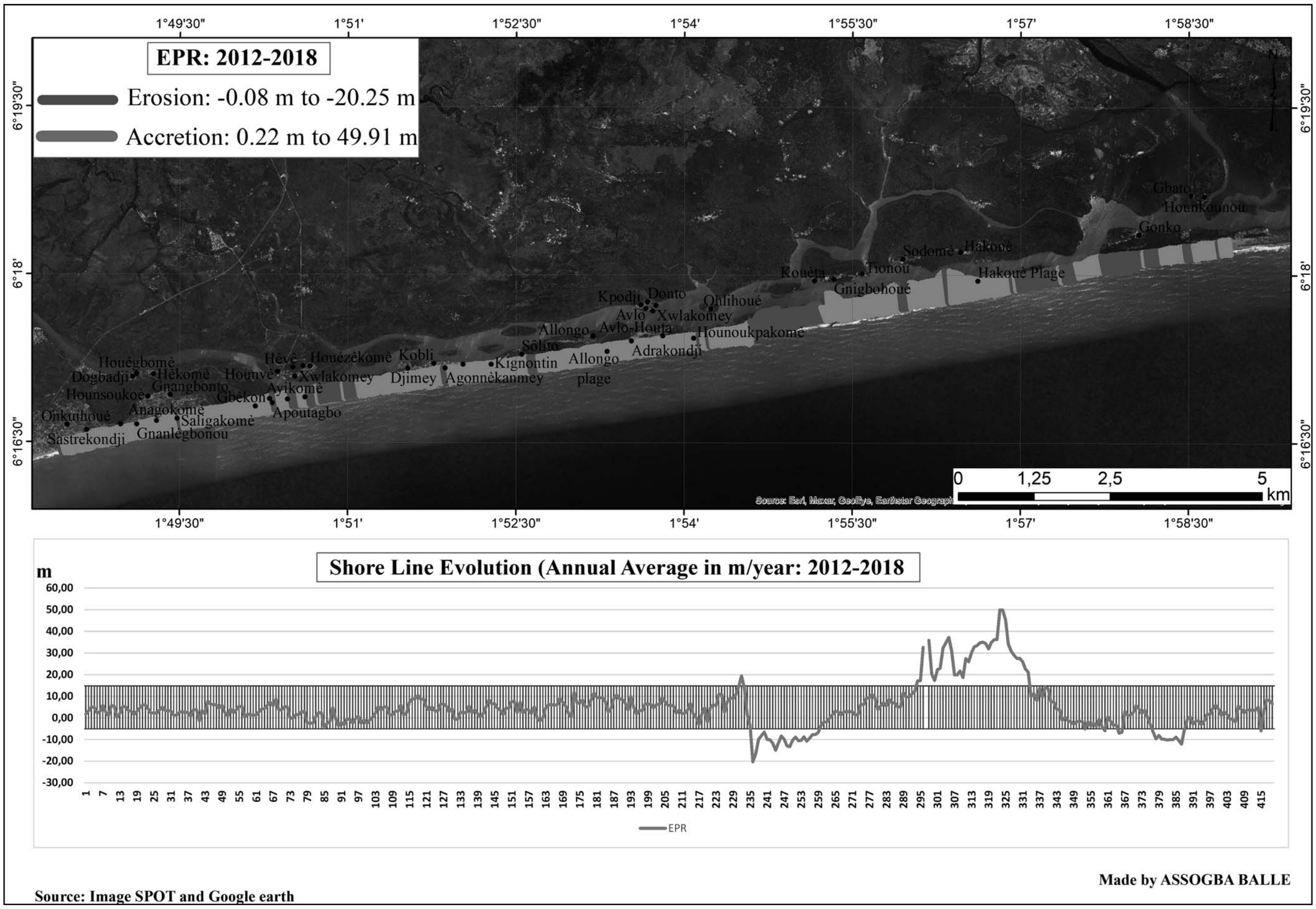

Figure 5. Change in shoreline highlighting the accretion (light gray) and erosion (dark gray) phenomena observed from 2012 to 2018. The placements of the villages around the coast are indicated to show how they are affected or not by these phenomena. The graphic below the map shows the magnitude of shoreline change rate at 10-m transects intervals, computed from the statistics of change using the end point rates method.

whereas the most significant coastline erosion was observed on a section between Ohlihouéet and Kouéta. Comparing the three short-term shoreline change trends, it shows that the western section (from Onkuihoué to Hounkpakomé) tends to change at a lower rate compared with the eastern section (from Hounkpakomé to Hounkounou) of the study area. During these three short-term periods, the migration of the Bouche du Roy estuary mouth was accompanied by localized coastline erosion, which literally destroyed the beaches. These findings are in line with the shoreline evolutionary trends previously highlighted by Dégbe *et al*. (2017), Laïbi *et al*. (2012), and Ozer, Hountondji, and De Longueville (2017). According to Boye *et al*. (2018), the variability in the shoreline change rates in the study area gave an indication that the causative factors and the corresponding response factors (*i.e*. mostly the erodibility of the coastal materials) vary in magnitude in the study area. However, the short-term changes in the shoreline range varied considerably in the section around the Bouche du Roy estuary mouth between Avlo and Hakoué villages, where significant magnitudes of erosion and accretion phenomena was observed. This observation suggests that the site-specific characteristics play a crucial role in modeling of the study area (Boye *et al.,* 2018).

The graph in Figure 6 shows a relative long-term shoreline change trend (30 years, *i.e*. 1988–2018) in the study area, which reflects similar changes in comparison with the short-term trends. The entire shoreline in the study area is characterized by alternative movements of erosion and accretion. The dynamics of the western section generally tends to be at a slower rate of erosion and accretion compared with the eastern section. The portion around Bouche du Roy estuary mouth is characterized by high magnitudes of erosion and accretion.

The comparison of the short- and long-term shoreline change trends showed an almost equal variability at the western part of the mouth of the estuary, indicating that in the western section, both erosive and resistive forces are in a state of dynamic equilibrium. In this case, the shoreline change driving and response factors could be considered at a regional scale (Boye *et al.,* 2018). Around the mouth of the estuary, especially toward the eastern parts, the rate of change is observed to vary more significantly for the short-term than the long-term category. This indicates that the factors driving the short-term

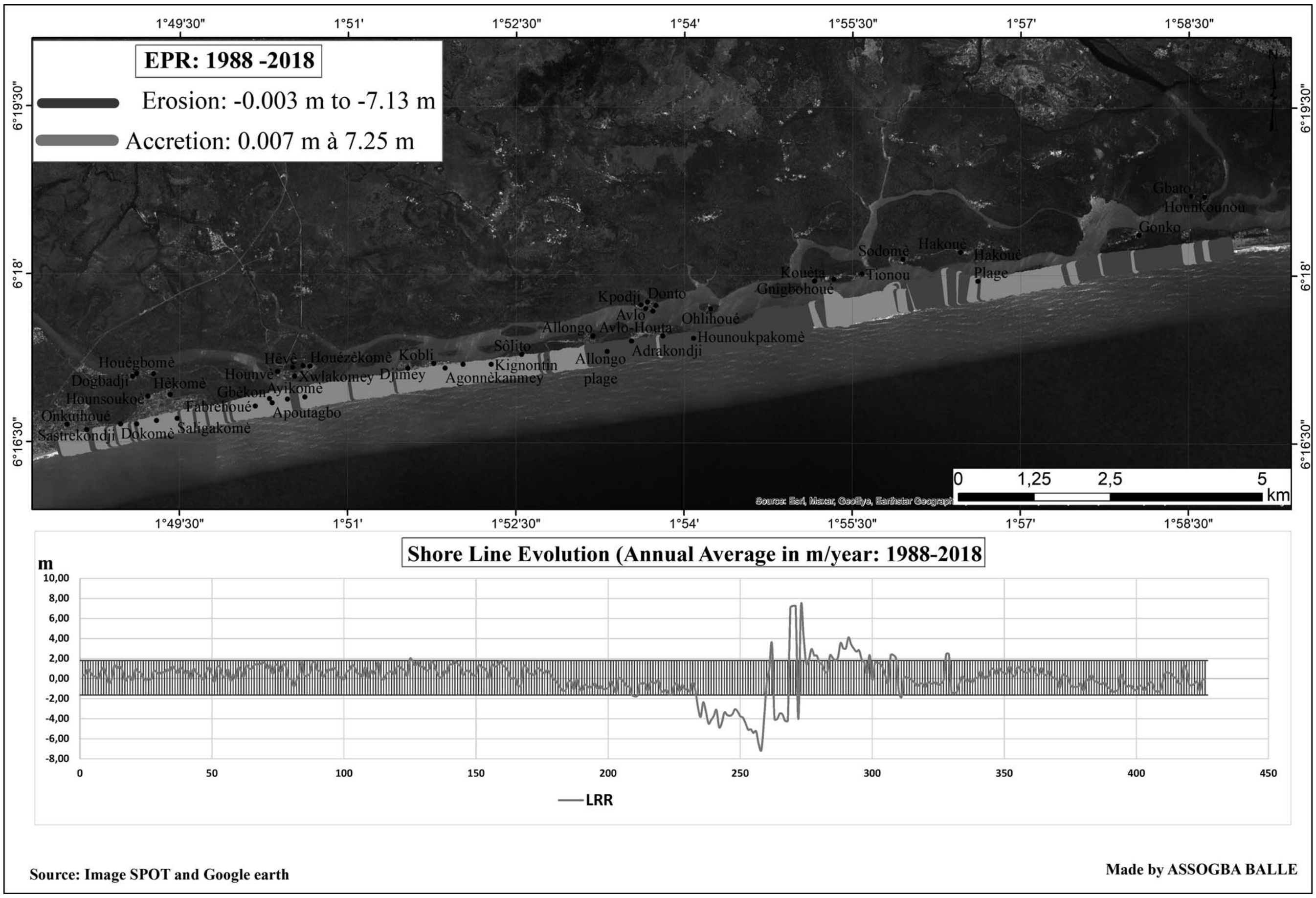

Figure 6. Coastline dynamic highlighting the accretion (light gray) and erosion (dark gray) phenomena observed for the entire period considered for this study (1988 to 2018). The location of the villages affected by the two phenomena are shown. The graphic below the map presents the magnitude of shoreline change rate at 10-m transects intervals by computing the statistics of change using the linear regression rates method.

change vary in greater magnitude compared with the long-term rates of change. Also, the short-term change trends generally recorded higher values relative to the long-term change rates, except for some isolated sites. Finally, in the study area, a sharp contrast was observed between the short- and long-term change rates. The short-term analysis recorded an average accretion rate ranging from 3.46 m/y to 7.98 m/y, whereas the average erosion rate was between –4.54 m/y and –5.58 m/y along that stretch of the coastline. On the other hand, the long-term analysis registered about 0.79 m/y average accretion rate and –0.75 m/y average erosion rate. The long-term change rates therefore reflect a dynamic equilibrium of the shoreline change from 1988 to 2018.

The high values logged for long and short terms along the stretch of the coastline around the mouth of the Bouche du Roy estuary could be attributed to the construction of the Nangbéto Dam in 1987. Indeed, prior to the construction of this dam, the mouth of Bouche du Roy estuary was characterized by cycles of openings and closings (Guilcher, 1959; Laïbi *et al*., 2012; Oyédé, 1991; Pliya, 1976). These cycles of opening and closing result in a phenomenal reworking of beaches within the limits of the Kouéta island (Dégbe *et al*., 2017; Laïbi *et al*., 2012). The construction of the Nangbeto Dam created a fluviatile influx deficit on the coast (Kaki, Oyédé, and Yessoufou, 2001). Following the completion of the dam in 1987, therefore, the mouth of the Bouche du Roy estuary began to migrate in the direction of the littoral drift. The observed migration of the mouth was accompanied by intense erosion that destroyed the beaches in the area (Laïbi *et al*., 2012; Ozer, Hountondji, and De Longueville, 2017). In addition, the Lomé deep-water port infrastructures and the coastal protection works undertaken along the Togolese coast further led to the decrease in sediment input from the west-east littoral drift (Dégbe, 2009). This dynamic evolution was reported in Kirk (1992); according to Kirk, the interruption of the longitudinal sediment transport caused by the presence of coastal infrastructures led to accretion of beaches in the updrift (west side of the protection infrastructures), whereas erosion affects the beaches down drift (east side of the protection infrastructures). Paskoff (2004) also noted that the port facilities that advance into the open sea critically disrupt the transit of materials carried by coastal drifts because they modify the behavior of the adjacent coastlines. Other factors such as the coastal sand mining and the destruction of mangroves also contribute to the high rates of change observed at the section of the coastline around the estuary (Lévêque, 2001). For instance, the low percentage (23.92%) of erosion reported in this study during the third period (2012–18) compared with the higher percentage (85.17%) of erosion during the second period (2001–12) could be explained by the stoppage of coastal sand-mining activities since June 2009. In addition, Benin's coastline is characterized by loose sediments (coarse to fine particles) and active coastal littoral movements created by the obliquity of the wave crests. The foregoing factors could explain the changes observed along the stretch of the coastline from 1988 to 2018 in this study.

CONCLUSION

This paper shows a detailed analysis of shoreline changes along the stretch of the coastline of Grand Popo section in Benin for 30 years (1988–2018), using SPOT and Sentinel-2 satellite images. Three short-term trends and one long-term trend were investigated. The analyses revealed that the shoreline is changing at a slower rate in the long term compared with the short term. The first short-term trend (between 1988 and 2001) was characterized by a net shoreline accretion (80.39%) of the entire study area at an average rate of 3.46 m/y. The second short-term trend (2001 to 2012) was characterized by high net shoreline erosion (85.17%) of the study area at an average erosion rate of –4.54 m/y. The third short-term trend (2001 to 2012) was dominated by net shoreline accretion (76.08%) of the entire study coast at an average rate of 7.98 m/y. Finally, the long-term trend (1988–2018) indicated that 68.51% of the shoreline accreted at an average rate of 0.79 m/y, whereas 31.49% of the entire coast eroded at an average rate of –0.75 m/y. In addition, major erosion was observed near the estuary mouth, eroding at –7.13 m/y. The foregoing analysis indicates that both erosive and resistive forces of the stretch of Grand-Popo coastline are in a state of dynamic equilibrium. This means that an alternation occurs between erosion and accretion to rebalance the beach as much as possible. However, with the dramatic erosion at the estuary mouth, continuous monitoring and periodic assessment of small-scale shoreline developments in this area is needed, while taking into consideration all aspects related to the dynamics of the littoral area, including the anthropogenic pressure on the littoral. Shoreline change information plays a vital role in understanding future shoreline evolution trends and in formulating coastal management policies.

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