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Multi-decadal shoreline changes in Eastern Ghana—natural dynamics versus human interventions

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Abstract
Human infrastructures, such as dams, seawalls, and ports, can affect both the sedimentary budget and nearshore hydrodynamics, enhancing and accelerating the loss or gain of coastal sediments. Understanding the processes and factors controlling beach morphodynamics is essential for implementing adequate adaptation strategies in coastal areas, particularly in those regions where coastal protection measures are scarce. This study analyzes shoreline changes in the Keta Municipal District, located in southeastern Ghana (West Africa). This area is characterized by the sedimentary input of the Volta River, forming a river delta situated to the west, i.e., updrift, of our study site. Following the construction of two dams (Akosombo and Kpong) on the Volta River in 1965 and 1982, groins and revetments have been built along the coast between 2005 and 2015 to reduce the high rates of coastal erosion in this area. Here, we explore the influence of these dams and the hard protection constructions on beach morphodynamics using historical maps and satellite images complemented by a shoreline survey undertaken with a differential GNSS in 2015. The multi-decadal evolution between 1913 and 2015 reconstructed for 90 km of shoreline suggests that local erosion rates in the region predate the construction of the two dams on the Volta River, indicating that these structures might not be the primary driver of coastal erosion in this area, as previously suggested. We emphasize that delta dynamics under conditions of high-energy longshore drift, modified by anthropogenic drivers such as sand mining, play a key role in the long-term evolution of this coast. Our results also show that the infrastructures built to halt coastal erosion result in localized erosion and accretion down-current along the coastline towards the border with Togo, highlighting the need for a transnational perspective in addressing the problems caused by coastal erosion.

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Introduction

Coastal erosion is one of the most significant threats to coastal populations and infrastructures on unconsolidated sedimentary coasts, particularly in deltaic areas. These coasts, when undisturbed, are in dynamic equilibrium as they are open systems constantly nourished by sediment from rivers, that is then transported towards deeper waters by coastal currents (Masselink et al. 2011). An imbalance between sediment supply and sediment loss leads to erosion or accretion of coastlines and can be driven by either natural or human causes (e.g., Camfield and Morang 1996; Nicholls and Cazenave 2010; Masselink et al. 2011). Dams in tributary rivers are among the anthropic interventions that may cause coastal erosion, as they diminish the fluvial sediment load transported, thus causing sediment deficits on the coast. Damming-induced coastal erosion has been reported from several deltas affected by human activities worldwide, e.g., the Nile (Stanley 1996), Mississippi and Rhone (Day et al. 1995), Ebro (Sanchez-Arcilla et al. 1998), Skokomish (Jay and Simenstad 1994), and Trinity (Phillips et al. 2004). Moreover, case studies show that removing dams is effective in reversing coastal erosion patterns (Warrick et al. 2019).

In this study, we focus on the wave-dominated Atlantic coast of Eastern Ghana, from where rapid coastal erosion has been reported (e.g., Anthony 2015). At the same time, coastal infrastructures in this area are highly vulnerable, as they are located very close to the shoreline (Appeaning Addo et al. 2018). The causal connection between erosion and various potential driving factors is still not fully understood, while it is highly relevant for designing and managing coastal protection measures. During the twentieth century, the Keta area experienced a severe shoreline retreat (Ly 1980; Appeaning Addo et al. 2011; Boateng 2012), threatening coastal communities along this stretch of the coast. It has been reported that by 1996, more than half of the area of Keta and its surrounding rural communities was lost to erosion and inundation, leaving more than 10,000 people homeless and causing significant economic losses (Ile et al. 2014; Oteng-Ababio et al. 2011; Danquah et al. 2014). To mitigate the coastal erosion problems, the Ghanian government invested US$ 83 million to build the groins and seawall of the Keta Sea Defence Project (KSDP) in 2001–2004, with the aim of protecting 1.6 km of shoreline (Boateng 2009).

Here, we analyze the historical shoreline evolution in the Keta Municipal District to understand the causes and dynamics of the massive coastal erosion reported throughout the twentieth century and the effect of the coastal protection engineering. We focus on the river delta sediment dynamics in the context of natural processes and human interventions. We therefore reconstruct the evolution of 90 km of coastline across one century based on historical maps, satellite images, and a shoreline survey done with a differential global navigation satellite system (GNSS) in 2015.

Study area

This study focuses on the easternmost coastline of Ghana, which largely falls under the administrative boundaries of the Keta Municipal District (between 5°45′N and 0°40′E to 5°55′N and 1°5′E, Fig. 1). The town of Keta and several other settlements are located on a sand barrier system that stretches for 75 km between the Volta Delta in the west and the City of Denu in the east (Fig. 1b). Some 50 km of this sand barrier form a sand spit separating the Keta Lagoon from the Bight of Benin (Awadzi et al. 2008).

The coast of the Bight of Benin (Fig. 1a), spanning across 300 km along Eastern Ghana to western Nigeria, is thought to be the longest beach-ridge barrier-lagoon system worldwide (Boateng 2012). In Eastern Ghana, the generally narrow shelf of West Africa reaches 15–33 km in width (Anthony 2015). With its exposure to high wave energy from SSW, combined with its lack of natural offshore breakwaters such as coral or oyster reefs, the West African coast is subjected to intense coastal dynamics. Consequently, the coastline of Eastern Ghana is characterized by steep, medium to coarse sandy beaches. The wave-dominated regime causes strong longshore drift driving the widespread formation of sand barriers and spits in the region (Anthony 2015) separating lagoons from the ocean (Angnuureng et al. 2013; Wiafe et al. 2013). This longshore drift towards the east has one of the highest transport rates in the world (max. 1.2–1.5 million m^3 between Lomé in Togo and Cotonou in Benin; Blivi et al. 2002). The main sediment source of the Bight of Benin is the fluvial input from the Volta (Ghana) and Mono rivers (Togo) that is transported eastward by drift currents (Rossi 1989; Goussard and Ducrocq 2014). Sandy sediment from the Volta Delta can be traced eastward along a coastal stretch roughly 300–500 km long, reaching the Niger River Delta (Blivi et al. 2002; Anthony 2015). Typical for this setting, the Keta area is characterized by a sand barrier complex that stretches for about 30 km from Anloga to Kedzi and has an average width of about 2 km and an elevation of 3–6 m above mean sea level (Anthony and Blivi 1999).

The Volta River is a confluence of five tributaries draining a catchment consisting mainly of sandstone, with an extension of about 400,000 km^2 (Anthony 2015). Before the construction of two large dams (Akosombo in 1965 and Kpong in 1982, see Fig. 1a for location), the sand load carried by the river to the delta was estimated at 1 million
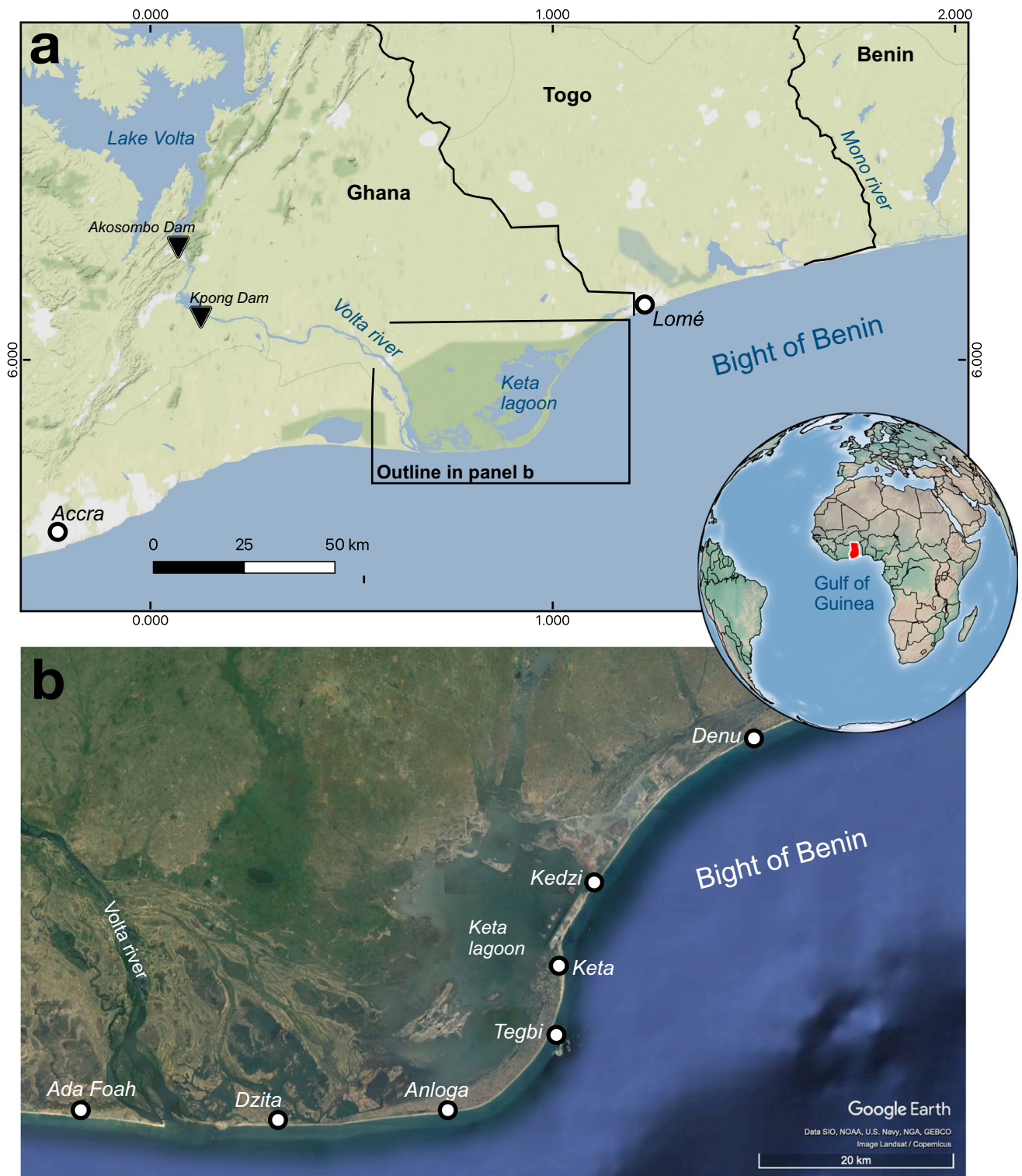
Fig. 1 **a** General geographic setting along the Bight of Benin, including the countries of Ghana, Togo, and Benin, main rivers, and capital cities. Background map tiles by Stamen Design (https://stamen.com), under a CC BY 3.0 license (http://creativecommons.org/licenses/ by/3.0). **b** Satellite image of the inset shown in **a** with location and geographic names used in the text. Background image from Google Earth, with data from SIO, NOAA, U.S. Navy, NGA, GEBCO, Landsat/Copernicus

m³/y (Delft Hydraulics 1990), Where it reaches the Bight of Benin, the Volta River forms a delta of about 4562 km² with an elevation of less than 5 m (Appeaning Addo et al. 2018). The river is connected to the ocean by a single outlet channel from which the large sand spit extends in the east of the Volta Delta (Appeaning Addo et al. 2018).

The study area has a dynamic history with respect to coastal erosion and accretion as reported in numerous studies (e.g. Anthony et al. 2016). A net accretion of at least 180 m of the Keta shore (specifically in its eastern part) occurred between 1784 and 1907 (Akyeampong 2001). Rapid shoreline accretion would explain the position of the Danish Fort Prindsensten in Keta, built in 1784 at the shoreline, but which later, by the beginning of the twentieth century, was located several hundred meters inland (Akyeampong 2001). However, other studies report widespread coastal retreat (up to 1 km, Kumapley 1989) between the mid-1880s and mid-1980s. During the time between 1907 and 1932, the coastline at Keta moved back to its 1784 position because of erosion. This erosion was perceived as such a severe threat that the colonial government started to measure high-water marks to monitor the shoreline evolution (Akyeampong 2001).

An attempt to stop erosion with a targeted engineering intervention was undertaken in 1923 when wooden groins were placed to break incoming waves and facilitate sedimentation. While this defense system seemed to be successful at first, in 1926, the groins were destroyed by the sea, and erosion set in again (Akyeampong 2001; van der Linden et al. 2013). In 1929, the first engineering study undertaken on this coastal area concluded that coastal erosion had taken place since 1870–1880 as a natural process (Coode 1929). Similarly, Batley (1950) concluded that erosion is part of the dynamics of the delta and is related to long-term changes in the position of the river mouth. As a new attempt for intervention, a steel wall made of sheet piles was built in 1955–1956 but broke down in the 1960s. A further effort to protect Keta by revetments was attempted in 1976–1978. This was reported to also have failed, as the rocks of the revetments sank into the sandy sediment (Alves et al. 2020). A comparison between the shorelines of 1895 and 2002 shows a calculated net erosion rate of 5.5 m/y eastwards of the city of Keta, while some accretion is recorded at the sand spit west of Keta, but on average, erosion prevails at a rate of 0.5 m/y, with the western side of the Volta Delta showing erosion rates of up to 8.7 m/y (+/−0.4 m/y) (Boateng 2012).

Until the 1960s, the Volta River sand drift formed a single sedimentary entity along the Bight of Benin coast (Anthony 2015). The construction of two dams along the Volta River in the 1960s and 1980s has reduced its sediment input towards the coasts (Anthony 2015). From 1961 to 1965, the Akosombo dam was built 100 km upstream of the Volta River, resulting in the world's largest artificial lake

with a capacity of 148 km³ (Wiafe et al. 2013). From 1977 until 1982, a second dam, the Kpong dam, was constructed some 20 km downstream of the Akosombo dam on the Volta River. A pre-construction study by Halcrow (1954) in the context of building the Akosombo dam predicted that the dam would reduce the sediment deposition at Cape St. Paul but would result in less erosion at Keta. In contrast, Freedman (1955) correctly predicted that erosion will continue at Keta, as indeed after the construction of the Akosombo dam, erosion amounted to 8–10 m/y in Keta (Ly 1980). In addition, the construction of ports in Lomé (Togo; 1965–1968) and Cotonou (Benin; 1964) further disrupted the sediment dynamic balance in the broader coastal region. In these areas, local erosion rates exceed 10 m/y (Ozer et al. 2017).

In response to the coastal erosion of the study area, the "Keta Sea Defence Project" (KSDP) was implemented between 2002 and 2005 between the cities of Keta and Kedzi (Fig. 2). The sea defense consists of an 8.3 km long roadway with six groins with a spacing of 800 m and a length of about 200 m. To quantify the coastline dynamics following the construction of the KSDP, Appeaning Addo et al. (2011) reconstructed the shoreline positions from satellite images taken in 1986, 1991, 2001, 2007, and 2011. They conclude that before the construction of the KSDP, the erosion rate was about −3.1 m/y, while after the construction, erosion rates were higher at the east of the KSDP, and accretion occurred at its western side (Appeaning Addo et al. 2011). Similarly, Angnuureng et al. (2013) showed that east of the groins, erosion dramatically increased from about 3.2 m/y (pre-construction period) to about 17 m/y (post-construction).

Another set of infrastructures designed to counter coastal retreat, the "Atorkor-Dzita-Anyanui Sea Defence Project" (ASDP), was constructed between 2012 and 2014. Fourteen groins were built about 15 km east of the Volta River over a length of about 2.5 km with a spacing of 150–200 m and a length of about 80 m.

Material and methods

To reconstruct shoreline changes in the study area between 1913 and 2016, historical survey maps from the Ordnance Survey of Great Britain and various Landsat, QuickBird2, and RapidEye satellite images were georeferenced. These data were complemented by a shoreline survey done with a differential GNSS (see below). Not all data sets analyzed here cover the entire study area. Therefore, the area is subdivided into 12 sections (S1–S12, Table 1, Fig. 3). Each shoreline section is 8 km long, comprising in total 1836 transects perpendicular to the shoreline with a spacing of 50 m between each transect. Accordingly, the entire analyzed shoreline stretch covers a length of 91.8 km. The analysis
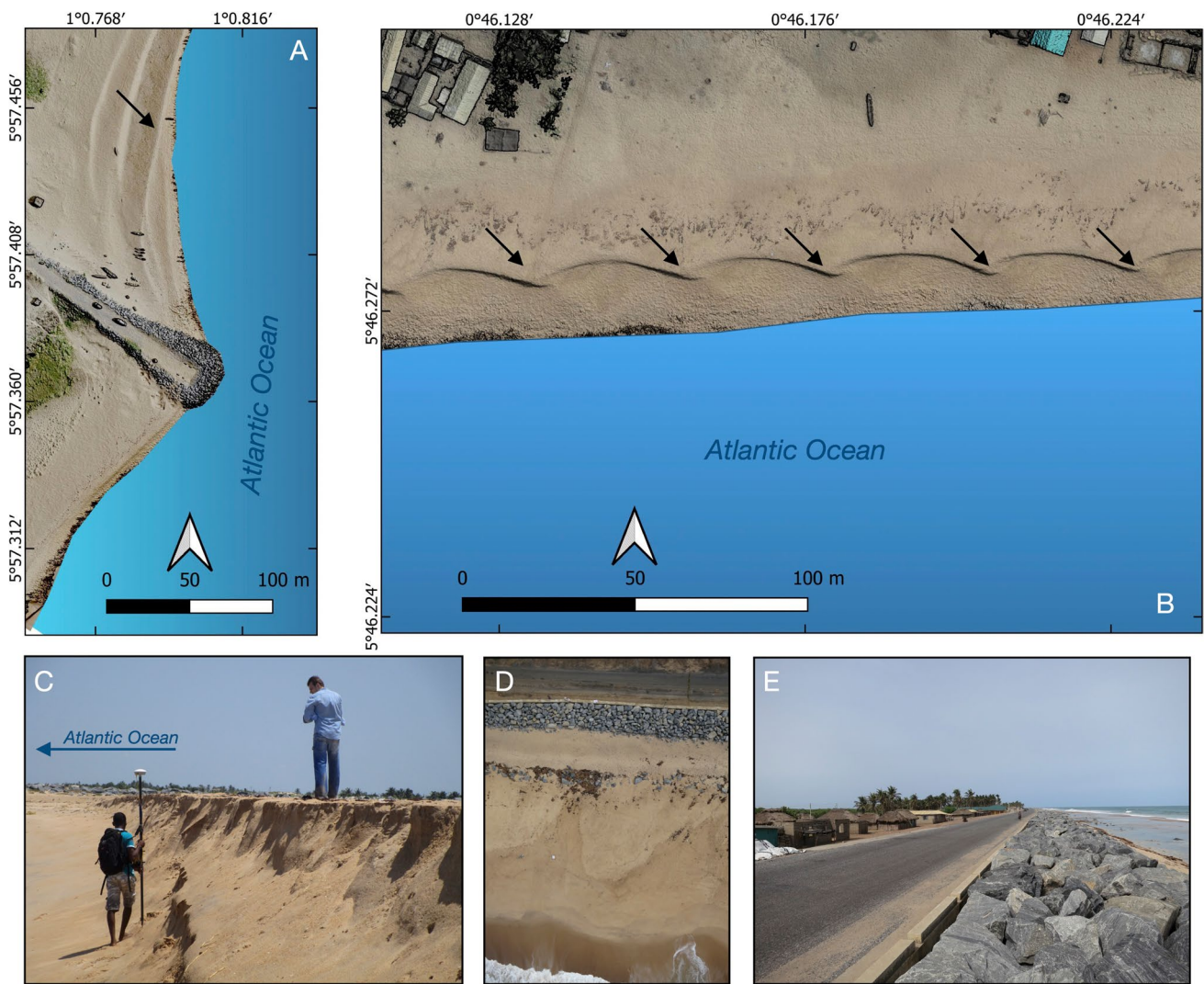
Fig. 2 Aerial and ground images from the Keta region, Ghana. **A** Aerial image (with DEM hillshade, from SfM-MVS from drones) produced by Structure-from-Motion and Multi-View Stereo techniques applied to drone imagery of one of the groins of the "Keta Sea Defence Project" located in proximity of the town of Kedzi. The arrow indicates a beach erosional scarp close to the modern shoreline. **B** Aerial image (with DEM hillshade) of an unprotected beach in proximity of the town of Dzita, with houses located less than 50 m from the shoreline. The arrows indicate beach cusps forming on the shore. **C** Beach erosional scarp in proximity of the town of Kedzi. **D** and **E** Respectively aerial image and terrain view of the parallel coastal defence east of Dzita, along the Anloga-Anyanui road

focuses on different periods and shoreline sections based on the available data to better understand spatio-temporal shoreline dynamics over the study period.

Comparable proxies for shoreline positions have been used to reconstruct shoreline changes from the different data sources. The shoreline on the historical maps corresponds to the Mean High Water Line (MHW), which is the average of all high-water lines observed over several months or years. In May 2015, we undertook a shoreline survey with a differential GNSS receiver. The system was composed of a Trimble ProXRT receiver and a Trimble Tornado antenna, equipped to receive OmniSTAR G2 real-time corrections. These corrections allow for measuring the elevation of a point with an absolute accuracy of ~ 0.1–0.2 m, depending on the survey conditions (e.g., the presence of trees or buildings affecting the GPS signal reception). The GNSS survey covers S4 to S6. The recent shoreline survey was undertaken by walking along the high-water line with the GNSS mounted on a pole of known height, thus tracking the high-water line (HWL) as a shoreline proxy. Similarly, on the satellite images (except for the Landsat data), the HWL was identified as the highest wet-dry line on the beach (Ruggiero et al. 2013).

The HWL and MHW used here as shoreline proxies have been digitized manually by a single operator using ArcGIS 10.3. Prior to shoreline digitization, all remote sensing data

Table 1 Remote sensing and survey data used to reconstruct shoreline changes for the present study

Image type	Date	Resolution	Scale	Shoreline sections covered	Uncertainty in shoreline position
Historical map	7 October 1913	-	1:1250	1–6	419.3
Historical map	1926	-	1:62,500	1–6	90.5
Historical map	1947	-	1:5000	1	1.2
Satellite image	13 January 1986	30	-	1–11	30.7
Satellite image	10 October 1991	30	-	1–12	30.1
Satellite image	1 April 2000	30	-	1–12	30.1
Satellite image	17 January 2002	30	-	1–12	32.6
Satellite image	2005	0.5	-	1–7	1.1
Satellite image	30 November 2009	5	-	3–9	5.4
Satellite image	2010*	5	-	1–2, 8–9	5.4
Satellite image	7 December 2011	5	-	1–5, 8–9	5.4
Satellite image	17 August 2013	0.6	-	4–7	1.3
Satellite image	2014**	5	-	1–2, 5–7	5.4
Satellite image	2 January 2015	5	-	3–9	5.4
Survey	12 May 2015	-	-	1–2	0.1
Satellite image	23 March 2016	5	-	4–6	5.4

*Merged mosaic from images taken on 23 October and 12 December 2010

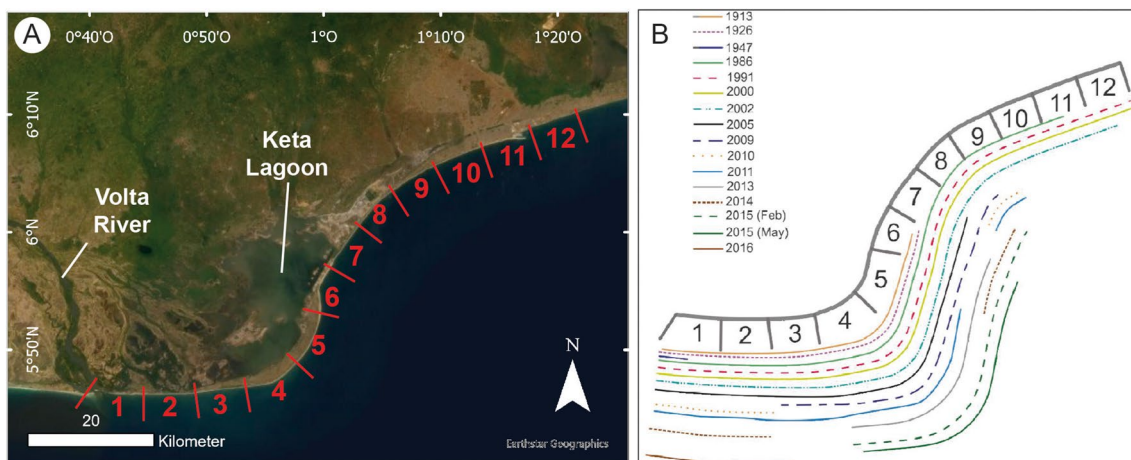**Merged mosaic from images taken on 19 January and 3 February 2014

Fig. 3 A Location of the 12 shoreline sections along the analyzed coast. **B** Spatial coverage of the remote sensing data used to reconstruct shoreline changes between 1913 and 2016. Background image sources: Esri, Maxar, Earthstar Geographics, and the GIS User Community

used have been transformed to the same coordinate system (UTM WGS84, Zone 31) and rectified based on evenly distributed ground control points (GCPs; ranging from 4 to 11 GCPs) such as intersection points of the coordinate grid of the historical maps, positions of road crossings, and corners of buildings. In the present study, the shoreline survey of 2015 was used as a reference map because it is the one with the highest resolution.

Shorelines from the Landsat satellite images were extracted automatically on a pixel-based method using the histogram threshold technique within the Integrated Land and Water Information System (ILWIS; Frazier and Page 2000; Fletcher et al. 2003). The software separates land and water bodies observable on remote sensing data by the differences in energy absorption in the near-infrared band 5. Threshold values in the resultant histograms were set between the two peaks for land and sea to account for the fact that the histogram is characterized by a transition zone resulting from mixed pixels and moisture rather than a sharp boundary between water and land (Alesheikh et al. 2007).

The Digital Shoreline Analyses System (DSAS) software has been used to analyze absolute shoreline changes and rate-of-change statistics. DSAS is a software extension within ArcGIS and is among the predominant analytical tools used to analyze planform changes of shoreline position from time series (Thieler and Danforth 1994). In order to determine changes in shoreline positions, an on-shore baseline running parallel to the shoreline was constructed manually. Subsequently, DSAS generates transects perpendicular to the baseline intersecting all extracted and digitized shorelines. Based on the intersection points between the transects and the shorelines, DSAS calculates the Net Shoreline Movement (NSM), End Point Rates (EPR), and Weighted Linear Regression (WLR), which are all proxies for shoreline change through time.

To relate the observed long-term WLR rates and trends of shoreline change to the construction of hard engineering structures along the study area, we have calculated EPR for particular time intervals for shoreline sections S1–S9 (see location in Fig. 3A). EPR have been determined for the years 1913, 1926, and 1947, to represent the time before the construction of the Akosombo and Kpong dams, and for 1986, 1991, 2000, and 2002, to represent the time after the dam construction. Similarly, EPR calculations representing the time before the construction of the Keta Sea Defence Project (KSDP) comprise imagery from 1986, 1991, 2000, and 2002; while the time after KSDP construction is represented by data from 2005, 2009, and 2011. This post-KSDP construction data set represents shoreline dynamics before the construction of the Atokora Sea Defence Project (ASDP), while the shoreline changes after ASDP construction were extracted from images from 2013, 2014, 2015, and 2016.

All digitized shorelines include data acquisition and processing uncertainties (Moore 2000). For example, the MHW shoreline proxy from the historical maps largely excludes uncertainties resulting from natural fluctuations due to wind, waves, tides, storms, and seasons. However, the line thickness of the shoreline on the rectified maps accounts for a positional uncertainty of ± 20 m. In contrast, the digitized HWL has a considerably lower positional uncertainty, but it might have been affected by storms or other high-magnitude events if such events occurred immediately before the satellite images were captured.

To quantify the horizontal uncertainties for each dataset as accurately as possible, we followed the methods suggested by Ford (2011) for the manually digitized shorelines and Marfai et al. (2008) for those shorelines that were extracted within ILWIS. Accordingly, we have attributed pixel size, image rectification, and shoreline digitization errors to the manually extracted shorelines, where the total error is calculated as the root sum square of each source of uncertainty. The resultant uncertainty is expressed as the End Point Rate Confidence Interval (ECI). For the automated shoreline extraction from Landsat images, the mean distance between two possible shorelines (highest and lowest digital number in the histograms) accounts for the digitization error. Total positional uncertainties were implemented during the calculation of rate-of-change statistics using 2σ confidence intervals and are shown for each shoreline in Table 1.

Results

Weighted linear regression (WLR)

For the shoreline sections S1–S9, the WLR indicates that numerous parts of the analyzed shoreline have been subjected to significant erosion and accretion, respectively, over the time covered by our data set (Fig. 3B). From W to E, the rates of shoreline erosion decrease from -9.2 ± 0.8 m/y for the section S1 on the east side of the mouth of the Volta River to -2 ± 0.6 m/y at the shoreline section S4. At the boundary between S5 and S6, the WLR detects a significant shoreline accretion accounting for 10.6 ± 2 m/y. Further towards the E, in S6 and S7, a stagger pattern with overall positive rates of shoreline change occurs, followed by another section (S7) with reconstructed WLR rates of -4.2 ± 2.5 m/y.

WLR analyses based on the entire data set indicate that the uncertainty of the results prevents the detection of statistically significant shoreline trends and rates of change at the scale of the entire study area. From transect 1360 onwards (S9–S12), the observed uncertainty of 300 m/y is likely related to the fact that the shoreline sections S9–S12 are merely covered by Landsat data with a relatively low spatial resolution of 30 m (Fig. 3B; Table 1).

End point rates of change (EPR)

The EPR of the transects in shoreline sections S1–S9 before Akosombo and Kpong dam constructions ranges between -63.85 and 15.44 m/y (mean EPR of -16.57 m/y, and the average ECI of 2σ (95.5%) is 31.55 m/y), indicating an overall recessive trend of the shoreline between 1913 and 1947 and a relatively large uncertainty, except for the western half of shoreline section S1 between 1913 and 1926 (Table 1, Fig. 5A). After dam constructions, a mean EPR of -0.22 m/y is calculated, indicating significantly less erosion than before dam constructions. The minimum and maximum EPR values after dam constructions range between -18.19 and 25.24 m/y, pointing to more shoreline stability in many sections. The average ECI is 3.1 m/y, pointing to a lower uncertainty for the analyzed period after dam constructions.

After the construction of the KSDP, i.e., shorelines from 2005, 2009, and 2011, the mean EPR is -0.73 m/y and the

Fig. 4 Results of the weighted linear regression (WLR) for the entire analyzed shoreline showing shoreline sections S1 (western end of the study site) to S9 (eastern end of the study site). Indicated with black bars are also the location of the Atokora Sea Defence Project (ASDP) and Keta Sea Defence Project (KSDP)
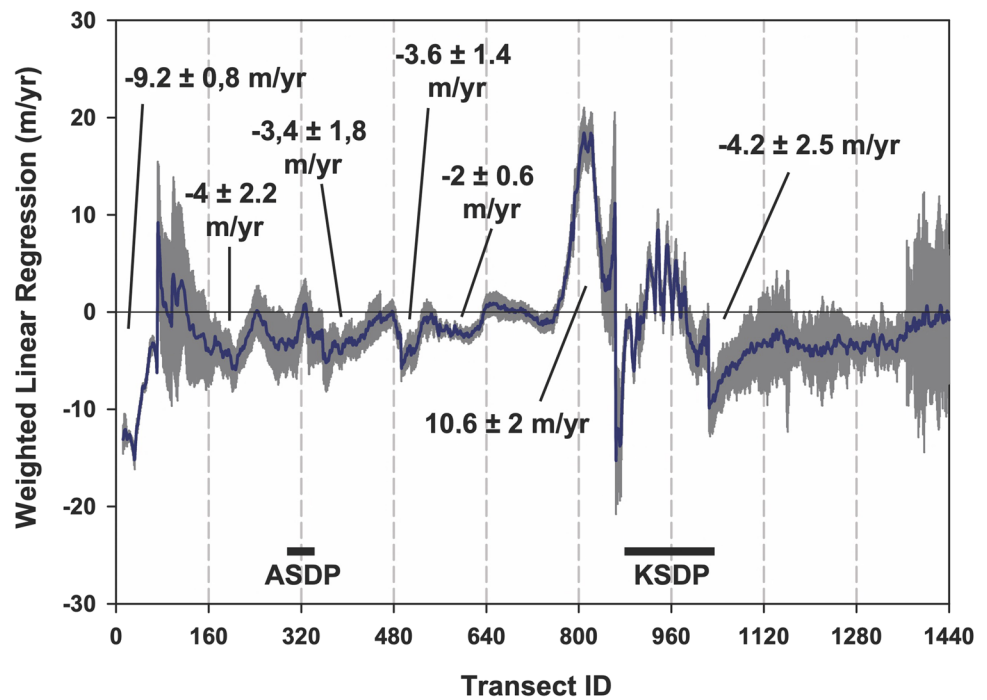
values range between -31.89 and 31.69 m/y. The ECI is, on average, 1.57 m/y (Fig. 4b). The mean EPR for the time after construction of the ASDP, i.e., 2013, 2014, 2015, and 2016, is -0.24 m/y, with values ranging between -102.57 and 53.65 m/y. The ECI is, on average, 3.54 m/y (Fig. 4c).

Discussion

After the construction of the Akosombo dam, which blocked the transport of large amounts of sediment to the coastal area studied here, erosion has been reported to have increased from -4 up to -10 m/y in Keta (Ly 1980). However, when comparing the EPR data in S1–S3 and in S4–S5 from the time before and after the construction of the Akosombo (1965) and Kpong (1982) dams (Fig. 4a), it becomes clear that erosion had been severe already before. This indicates that the erosion is not causally linked to the dams. In S1 and S2, less erosion and even accretion are observed after the dams were built (Fig. 4a). One major problem in assessing the changes caused by the construction of the dams is that the baseline sediment influx to the study area is not well documented. There is a considerable range in the estimate of sediment discharge from the Volta River before the dam was constructed. Besides the construction of the dams, the discharge of the Volta River has been strongly reduced by the decreasing rainfall in the catchment in the Sahel since 1975, potentially causing a sediment deficit at the coast (Oguntunde et al. 2006), but it is not possible to disentangle the causes here. However,

the literature consistently states that after a dam construction, only a small fraction of the previous sediment load is discharged by the river (e.g., Boateng et al. 2012; Bollen et al. 2011). The substantial reduction in sediment load is reflected by sedimentation rates in the Volta estuary that have decreased from 1.08 g*cm^{-2}/y before the construction of the dam to 0.50 g*cm^{-2}/y after construction (Jayson-Quashigah et al. 2019).

The high WLR rate of -9.2 ± 0.8 m/y calculated for S1 and S2 reflects the delta's inherent dynamics and the development and migration of the sand spits. Our WLR analyses indicate long-term accretion in S5–S6 to the west of the KSDP (10.6 ± 2 m/y) and long-term erosion in S7 to its east (-4.2 ± 2.5 m/y). In S6–S7, the KSDP groins baffle a considerable amounts of beach sediment on their windward side while they increase erosion on their leeward side. Immediately to the west of the groins, significant erosion is observed after KSDP construction, as seen in both, the long-term WLR data (S6 in Fig. 4) and in the EPR data (S6 in Fig. 5b). In contrast, no or minor erosion is detected at the same shoreline section in the EPR prior to KSDP construction. The significant erosion observable after the KSDP's construction could be caused by strong wave reflection along the massive seawall and alongshore or offshore sediment transport that leads to pronounced shoreline retreat (Kraus 1988; Tait and Griggs 1990; Plant and Griggs 1992; Kraus and McDougal 1996). Similarly, the erosion observed in S7 to the east of the KSDP is likely the result of pronounced sediment accumulation at the groins, reducing the sediment available for longshore transport, thus creating a sediment

Fig. 5 **a** EPR before (red line) and after (blue line) the constructions of the Akosombo and Kpong dams. **b** EPR before (red line) and after (blue line) the construction of the Keta Sea Defense Project (KSDP). **c** EPR before (red line) and after (blue line) the construction of the Atokora Sea Defence Project (ASDP)
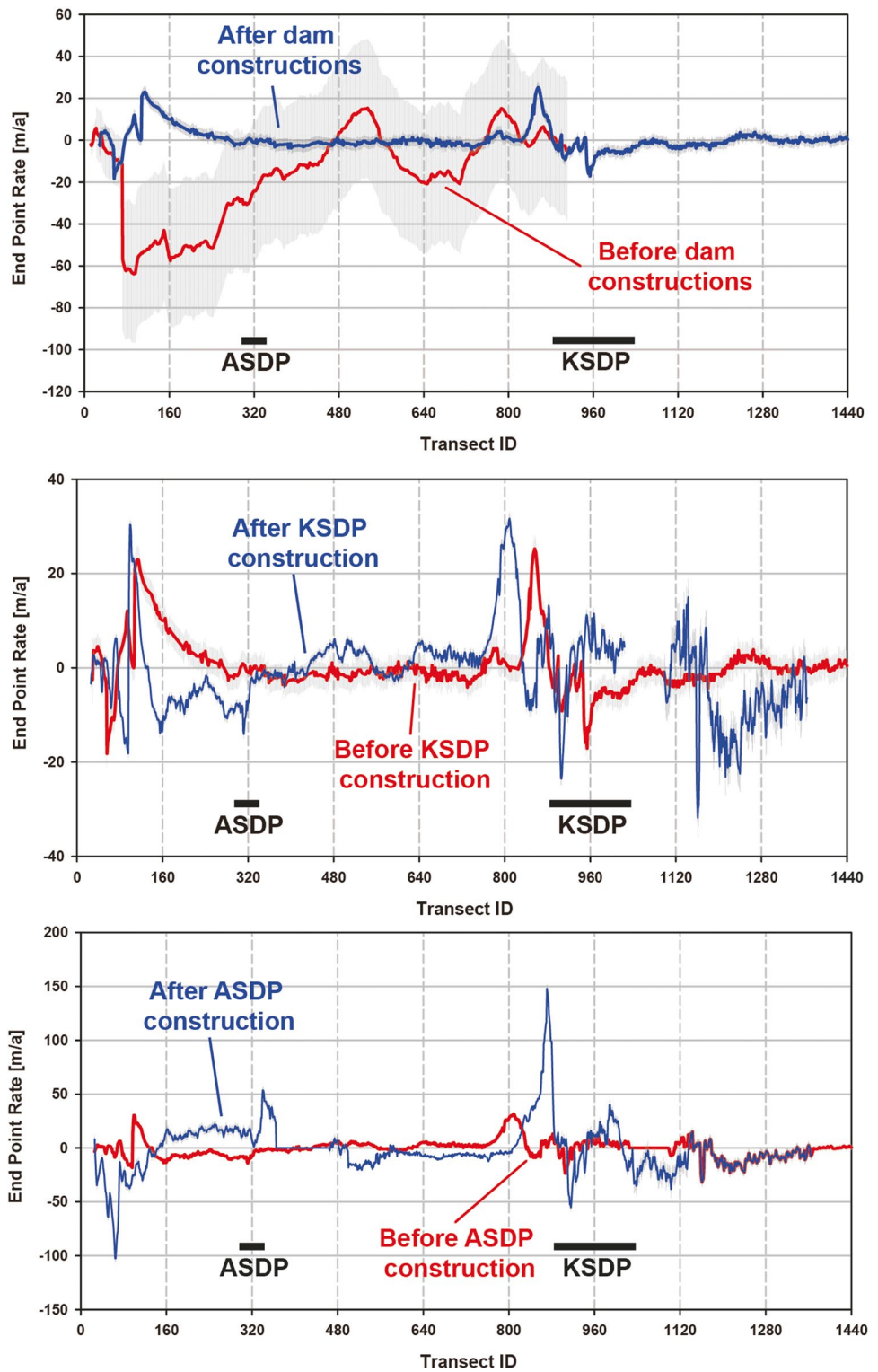
deficit downstream towards the east (Appeaning Addo et al. 2011; Angnuureng et al. 2013).

The long-term significant shoreline accretion in S5–S6 before and after KSDP construction is observed in both, WLR data and EPR data. Interestingly, this accretionary

section appears to have shifted westward after the construction of the KSDP. It is therefore possible that the position of this accretionary hotspot has been affected by the construction of the KSDP, but that this accretion is naturally induced, e.g., through the convex-shaped coastline in this area, where

the littoral transport velocity is reduced and deposition occurs (cf. Anthony and Blivi 1999; Anthony et al. 2016).

To the west (S2; −4 ± 2.2 m/y) and to the east (−3.4 ± 1.8 m/y) of the ASDP, WLR analysis indicates long-term erosion for the period between 1913 and 2016 (Fig. 4). EPR analyses, however, indicate that before the construction of the ASDP, the shoreline was eroding in S2 and largely stable in S3. After the construction of ASDP, the shoreline sections around the ASDP showed mainly accretion with a considerable positive peak in S3, following transect #320 onwards. The strongly positive EPR after the construction of the ASDP surprisingly might be related to a storm that affected the study site on the 7th of August 2013, i.e., 10 days before the Quickbird 2 satellite image analyzed here was taken. Storms are well known to cause severe erosion across beach profiles, usually followed by a beach recovery phase (Morton et al. 1994; Woodroffe 2002). The comparison of EPR shows a higher erosion rate between 2011 and 2013 (ca. −18 m/y in S3) than in the years before and after this storm event. Accordingly, the positive peak in S3 might reflect beach recovery rather than sustained accretion resulting from the ASDP, as in the long-term perspective, the shoreline around the ASDP still is erosive in large parts (Fig. 4).

Among the other processes affecting the sedimentary budget of the coast, sand mining is known to take place along the coastline of Ghana and was particularly intensive in the late 1980s to 1990s when the construction sector was on the rise (Mensah 1997). No systematic assessment of their effects exists so far, although there have been reports of rapid erosion and road damage in the context of sand mining activities (Mensah 1997). Jonah et al. (2015) implied that sand mining is the leading cause of coastal erosion along the Cape Coast of Ghana. In the present study, we cannot distinguish the specific effect of sand mining from the other influences, namely, delta dynamics or the effect of coastal protection measures. Trstenjak (2016) observed the signs of sand mining activities in several parts of the study area, namely, in Dzita in the east of the Volta River mouth (shoreline sections S1 and S2). There, particularly intensive beach sand mining activities took place for the production of hundreds of building blocks, with the consequence of a marine incursion and flooding of the depression produced by the removal of sand. Trstenjak (2016) learned through interviews with locals that this was the first time this area was affected by flooding. Also, between Keta and Kedzi (sections S6 and S7), she identified sand mining activities, usually close to settlements, indicating that people do not go far to mine the sand. Our results also indicate ongoing erosion in the eastern part of S1 and S2. However, current erosion is less substantial than it was historically before the dam construction. Similarly, it is not possible to identify whether sand mining activities are relevant for coastal dynamics in the west of S5

because of the construction of the groins driving accretion patterns or whether the effect of sand mining is seen further to the east in S5 and S6 where severe erosion is happening. With our approach, it is impossible to tear the causal contributions of the different factors apart. Nevertheless, anecdotal evidence like the flooding of Atiteti after intensive sand mining activities points to a relevant contribution of sand mining to the coastal erosion observed in Eastern Ghana. Adding to the complex dynamics, groundwater extraction is another reason for (indirect) shoreline retreat in the Keta area, as it leads to increased coastal subsidence. In the Keta lowlands, irrigation of agricultural land is widespread (Yaka 2017) and is suspected of contributing to local subsidence (Appeaning Addo et al. 2018). In addition, no data are available on the coastal subsidence that may be triggered by the prospected oil and gas exploitation. However, such activities will likely increase the subsidence rates (Setordzi and Nyavor 2015).

Similar coastal defense measures, including groins jetties, seawalls, and breakwaters, have been implemented in other countries in West Africa along the coastline of the Bight of Benin and further to the west (Côte d'Ivoire, Gambia, and Senegal) (Angnuureng et al. 2013; Laïbi et al. 2014; Ndour et al. 2017). The experiences there are similar in that local solutions lead to consequential effects along adjacent coastlines so that individual countries face continuously growing erosion rates (Alves et al. 2020). Hard engineering approaches, in many cases, result in a reduction of sediment transport downdrift and massive erosion (Angnuureng et al. 2013; Ndour et al. 2017), while soft methods allow the sediment to be transported by drift (Alves et al. 2020). Alves et al. (2020) suggest a "sediment-cell scale coordination" approach that understands the source-to-deposition system as a dynamical entity with the transient beaches and barriers being part of dynamic stability. As Alves et al. (2020) point out, a lack of adequate monitoring contributes to the problem as changes are noticed too late when an erosive situation has already been established. Our study demonstrates that long-term reconstructions can add to or even substitute lacking monitoring in order to better understand the complex dynamics on a scale that allows to assess and avoid the export of erosion to other regions or countries.

Conclusion

While coastal erosion rates in Eastern Ghana are among the highest recorded globally, rapid accretion also takes place in the sedimentary system along the coastline studied. In contrast to previous studies, we here show that local erosion rates of the Keta Municipal District were already high before the construction of the Akosombo and Kpong dams. The reconstruction of historical shorelines undertaken here shows that the dams are not the main drivers for

the high erosion rates observed in the study area. Rather, our study demonstrates that the coastline studied undergoes dynamic morphological changes typical for delta systems.

In addition, human interventions tend to initiate dynamical responses of the system of considerable magnitude that can be difficult to manage if not detected as such. In particular, hard engineering solutions such as groins can lead to accretion at the expense of erosion down-current. There is a need for a broader coastal management plan for the sea defense structures to improve efficiency, reduce the flanking effects and the shift of erosion to the east. In addition, to better understand the dynamics behind the high coastal erosion rates in the area, the effect of other human activities such as (beach) sand mining and the construction of ports (in particular the Tema port) need to be examined more closely. Monitoring is mandatory as an early warning system for coastal dynamics and unintended effects of protection measures. However, our study demonstrates that the reconstruction of historical coastlines in the context of interventions is a powerful tool for observing coastal dynamics in the absence of monitoring.

Author contribution HW and MF conceptualized the original proposal; TM, AR, and HW structured and shaped present study; TH, AS, AR, EC, P-NJ-Q, TM-S, KT, and BL undertook the fieldwork; HW, MF, TM, AR, and KA-A supervised the work; AS, KT, and BL wrote their MSc thesis in the context of the project; TM, AS, AR, and KT led the data analyses; HW led the writing of the manuscript; all authors contributed to the writing process; AS, TM, and AR prepared the figures.

Data availability Data are available at https://doi.org/10.5281/zenodo.7621198.

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Declarations

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