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Mapping and assessment of coastal infrastructure for adaptation to coastal erosion along the coast of Ghana

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Abstract

Globally, coastal managers are challenged to make informed decisions when selecting coastal infrastructure to respond to climate-induced sea-level rise and associated coastal hazards like coastal erosion and flooding. Classifying the types of coastal infrastructure permits the comparison of their potential efficiency, environmental and socioeconomic impacts, and long-term response to sea-level rise. At present, information on coastal infrastructure implemented along the coastal area of Ghana is not known thus creating a research gap to catalog this information. To achieve this, we combined satellite images from Google Earth Pro and the use of ArcGIS capabilities to conduct a national assessment of coastal infrastructure and its distribution along the coast of Ghana. Even though similar approaches have been applied in different geographic contexts, this article focuses on evaluating coastal infrastructure in Ghana. Results show that between 2004 and 2022, at least 110 km or approximately 20% of the coast of Ghana has been protected using grey infrastructure, distributed as groins 35.9 km (6.5%), revetments and seawalls 50 km (9%), and jetties and port breakwaters 25 km (4.5%) of the 550 Km coastline. These do not include the numerous private recreational infrastructure that could increase coastal vulnerability. The increasing use of grey infrastructure, particularly seawalls, and revetments along the coast has adverse impacts on overall coastal evolution and causes socioeconomic challenges. This study supports coastal managers to review coastal adaptation policy and develop shoreline management plans for the coast of Ghana.

Highlights

- At least 152 structures were mapped comprising 112 groynes (9 groyne systems), 20 revetments, and 20 jetties at ports and new fishing harbours.
- At least 110km (20%) of the 550 km coastline is protected using grey infrastructure.
- Maps and a coordinates database of implemented coastal infrastructure were developed to support coastal management decisions.

Keywords Coastal infrastructure, Sea-level rise, Coastal erosion, Grey infrastructure, Ghana

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1 Introduction

Coastal infrastructure is fundamental to protect coasts against climate-induced sea-level rise (SLR) and associated coastal hazards such as storms, coastal flooding, and erosion. Consequently, coastal managers are challenged to plan to adapt to SLR by choosing the appropriate coastal adaptation policy (Hill 2015; Powell et al. 2019; Sutton-Grier et al. 2015) under different SLR scenarios (IPCC 2021; 2022). Four generic coastal management policies or strategies can be used for coastal zone protection, namely, hold the line, advance the line, managed realignment, and no intervention approaches as established by the United Kingdom (UK) Shoreline Management Plans (SMP) (DEFRA 2006b, 2006a; Rangel-Buitrago et al. 2018). These policies can be implemented using any of the three categories of coastal infrastructure, that is, green (natural/soft), grey (hard-engineered), and hybrid (combined green and grey) infrastructure (Hill 2015; Sutton-Grier et al. 2015).

Grey infrastructure or hard-engineered infrastructure has traditionally dominated shoreline protection, trusted for providing immediate coastal protection and standardised implementation (Hill 2015; Sutton-Grier et al. 2015). However, contemporary trends in coastal protection support green and hybrid infrastructure because they provide both coastal protection, ecosystem services, and help to build the resilience of coastal communities (Bouw & Eekelen 2020; Currin 2019; Hill 2015; NOAA 2015; Powell et al. 2019; Sutton-Grier et al. 2018). The paradigm shift from hard engineering to green and integrated infrastructure has challenged coastal planners and managers to make decisions to balance coastal protection and sustainability. However, in Ghana, hold the line strategies and ad hoc implementation of coastal works still dominate, largely due to the absence of SMPs (Jonah et al. 2016; Wiafe et al. 2013). among other factors that contribute to increased coastal vulnerability in the wake of increasing SLR and the frequency and severity of extreme coastal hazards (Bongarts Lebbe et al. 2021; IPCC 2021).

Indeed, SLR, as much as coastal erosion and flooding have emerged as global challenges of the 21st Century for coastal countries (Bongarts Lebbe et al. 2021). Coastal erosion management has generated into a developmental challenge, especially in developing countries. In West Africa, coastal erosion is a major regional developmental challenge that is responsible for the rapid loss of valuable coastal land and properties. It is estimated that, on average, at least \$3.8 billion of coastal land is lost annually due to coastal erosion and flooding (World Bank 2019). In Ghana, the coastline is eroding at an average rate of 2 m/per year with some erosion hotspots experiencing erosion as high as 17 m/year (Angnuureng et al. 2013). The impacts include damage to transport infrastructure, destruction of coastal land and houses (Appeaning Addo 2021a, b; Appeaning Addo et al. 2008), threatening port infrastructure and tourism (world heritage) infrastructure like castles and forts (Vousdoukas et al. 2022), and the destruction of natural ecosystems like wetlands, sandy beaches, and dunes (see Fig. 1). Coastal erosion also escalates environmental migration and affects the livelihoods of coastal communities (Appeaning Addo & Appeaning Addo 2016).

With approximately 50% of the coastline of Ghana vulnerable to sea-level rise (Boateng et al. 2016; Wiafe et al. 2013), coastal protection becomes a priority to protect coastal communities, land, and property against climate-induced coastal hazards such as flooding and coastal erosion. As a result, since the completion of the Keta Sea Defence Project (KSDP) in 2004, several sea defence projects (SDPs) were implemented along the coast to respond to severe coastal erosion. However, implementation of coastal defences primarily uses hold the line strategy and grey infrastructure for coastal protection without due regard to coastal sustainability aspects, and in most cases, this has caused coastal erosion migration, created new erosion hotspots, and complicated coastal management.

The sustainability of coastal infrastructure has taken centre stage in recent times, triggering rigorous weighing of the benefits and shortcomings of green and grey infrastructure (Hill 2015; Powell et al. 2019; Sutton-Grier et al. 2018). Although grey infrastructure boasts immediate coastal protection and standardised engineering (Sutton-Grier et al. 2015), it has many unsustainable setbacks. Grey infrastructure causes coastal erosion migration to downdrift areas (Alves et al. 2020; Angnuureng et al. 2013; Appeaning Addo 2015), restricts horizontal and vertical beach access thereby contributing to coastal squeeze and disappearing, and contributes to reducing beach aesthetics and local tourism (Pilkey & Cooper 2014). Along the coast of Ghana, the construction of the port and seawall at Takoradi on the West coast, drastically altered wave patterns and induced coastal erosion to areas in Accra, Ada, and Anlo (Akyeampong 2001). In addition, grey assets lack dynamic coastal protection (Hill 2015; Powell et al. 2019; Rangel-Buitrago et al. 2018; Sutton-Grier et al. 2015), and are void of ecosystem benefits. These and many other drawbacks have prompted contemporary research and coastal adaptation policies to support natural and hybrid infrastructure that offers both protection and coastal resilience (Bouw & Eekelen 2020; Bridges et al. 2021; Browder, Ozment, et al., 2019; Cohen-Shacham et al. 2016; Sutton-Grier et al. 2015).

Several SDPs have been implemented between 2004 and 2022 along the coast of Ghana and there are planned and ongoing projects (GIPC 2020). Apart from coastal

Fig. 1 Impacts of coastal erosion to unprotected natural coasts (**a**) A fast eroding beach at Atiteti beach, Eastern coast (**b**) Aftermath of tidal flood and severe erosion at Anlo beach, Western coast (**c**) Once a stable beach, the Brenu beach in Central coast is recently fast eroding, and (**d**) a threatened community at Ada Foa at the mouth of the Volta Estuary have no option but to relocate

protection infrastructure, coastal settlements are increasing due to population growth and rural–urban migration (GSS 2021). Moreover, there are tourism and fishing structures that are not appropriately set up along the coast. During the past decade, new fishing harbour projects have been constructed as an economic drive to modernise fish landing sites, but also as a form of coastal protection for the surrounding communities. Nevertheless, despite their intended purpose, the situation has not improved and new areas are emerging as hotspots. One possible reason could be the fact that lessons learnt about the environmental effect of grey infrastructure on the coast, their efficiency, and their characteristics have not been given policy consideration.

In light of the increase in climate-induced coastal hazards and the implemented coastal developments, this research set out to investigate the extent of coastal infrastructure along the coastline of Ghana. We employed the capabilities of GIS, remote sensing, and in-situ observation to map the spatial distribution of coastal infrastructure Our results indicate that between 2004 and 2022, at least 20% progress of the coastline has been protected using hard-engineered infrastructure mainly groynes and revetments. In line with contemporary research (Bridges et al. 2021; Hill 2015; Sutton-Grier et al. 2015, 2018) and observing the continued use of hold the line strategies and grey infrastructure, we recommended adaptive coastal management and hybrid infrastructure to improve the effectiveness of currently implemented strategies and enhance coastal management along the Ghanaian coast.

2 Materials and methods

2.1 Study area descriptions

The coast of Ghana (Fig. 2) extends from 6°06' N, 1°12'E at the border with Togo to 5°05'N, 3°06'W at the border with Cote D'Ivoire. The coast is divided into three geomorphic regions, namely Eastern, Central, and Western regions. However, for coastal erosion management, the 550 km coast is divided into four coastal administrative regions, that is, Western, Central, Greater Accra, and Volta (Wiafe et al. 2013).

The Eastern coast of Ghana Extends from 6°06' N, 1°12'E at the border with Togo (Aflao) to approximately 5° 43′ 0″ N, 0° 6′ 0″ E, at Prampram, and covers approximately 149 km (Armah 2005; Boateng et al. 2016). It is characterised by sandy coasts, open sandy beaches that are exposed to relatively high-energy wind-driven waves and influenced by the deltaic estuaries of the Volta River (Wiafe et al. 2013). Therefore, the Eastern coast

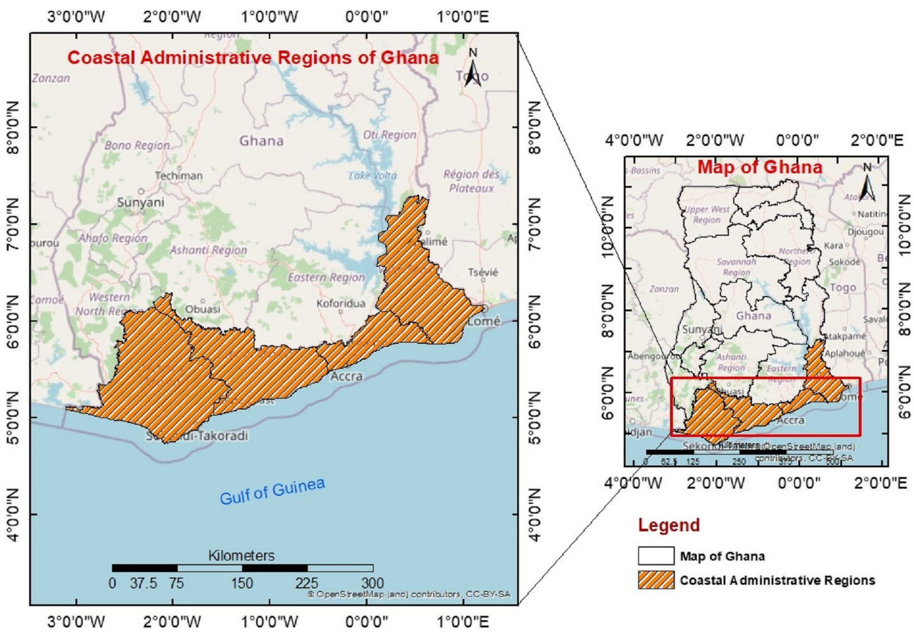

Fig. 2 Map of Ghana showing the four coastal administrative regions

is relatively more vulnerable to coastal flooding and erosion than other sections of the national coastline. Consequently, the Eastern coast has had more coastal protection projects than other areas of the coast. The Central coast is the longest geomorphic region and extends from Cape Three Point to Prampram. It is characterized by rocky coasts with bays, sand barriers, and coastal lagoons. The Western coast stretches from New Town at the border with Cote d'Ivoire to Cape Three Point, a distance of 85 km. It is characterized by sandy coasts with gently sloping beaches (Armah 2005; Boateng et al. 2016). The major human anthropogenic activities that contribute to coastal erosion and land degradation along the coast of Ghana are salt panning, mangrove deforestation (UNEP 2007; Mensah 2013), and sand mining (Jonah et al. 2016, 2017), damming and unregulated mineral mining (*Galamsey*), and the construction of sea defences (Angnuureng et al. 2013; Alves et al. 2020).

Currently, 25 coastal districts make up the coast of Ghana (see. Figure 3). Ordinarily, each coastal district (should) have the mandate for coastal erosion management (Wiafe et al. 2013) through multidisciplinary and stakeholder approaches to mitigate environmental and socioeconomic impacts of coastal hazards. However, in most cases, coastal infrastructural projects are implemented by the central government using ad hoc reactive approaches without properly studying coastal processes and environmental impacts leading to challenges like coastal erosion migration (Angnuureng et al. 2013; Appeaing Addo 2021a, b; Wiafe et al. 2013).

Given the implementation of coastal defences in most of the coastal regions over the last two decades, a comprehensive understanding of the spatial distribution of coastal protection projects is essential to support coastal management decision-making.

2.2 Data collection and processing

Data was collected using various methods including secondary reports, remote sensing, and in-situ observation to identify and classify coastal infrastructure and their attributes (e.g. date of construction, length, breadth, condition, etc.). From Google Earth Pro, the coastal grey infrastructure locations were digitized into Keyhole Markup Language (KMZ) placemark files, and classified into groynes or groyne fields (Fig. 4), seawalls, revetments, and jetties (Fig. 5).

In addition, the geographic coordinates attributes were retrieved into comma-separated values (CSV) files, and imported into ArcGIS for processing.

In Ghana, the grey coastal infrastructure is mostly constructed using rock (granite boulders), with exceptions at port areas where concrete is used. The structures were mapped for each of the three geomorphic areas, Eastern, Central, and Western coasts. GIS provided a quicker and simplified methodology for time series analysis, permitting the gathering and analysis of satellite imagery, mapping, and visualisation of the national coastal infrastructure. In addition, original images (Fig. 6) were also captured at sites using an unmanned aerial vehicle (UAV). Other primary data relating to the condition of

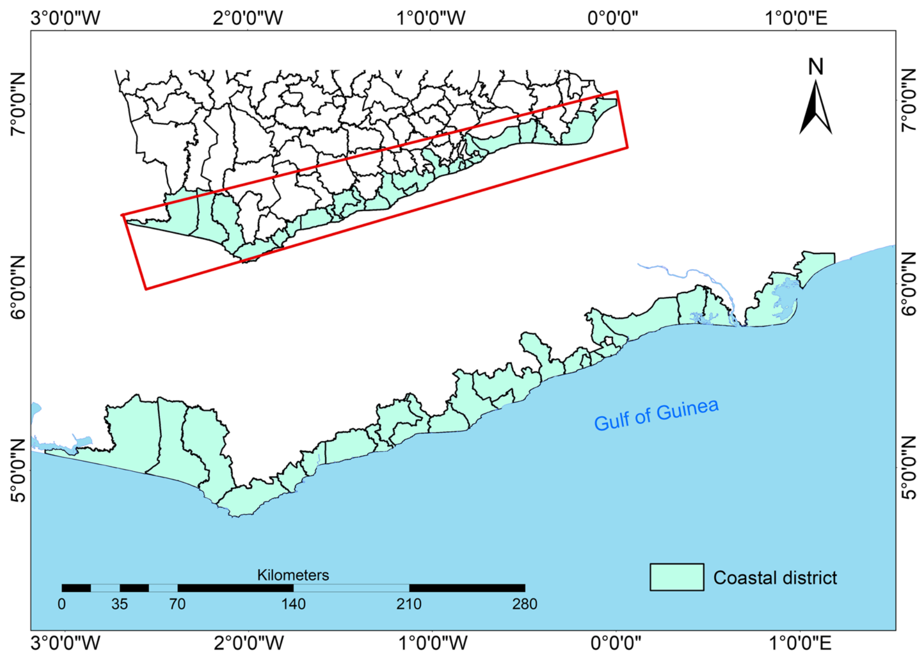

Fig. 3 Coastal map showing the 25 coastal districts along the coast of Ghana

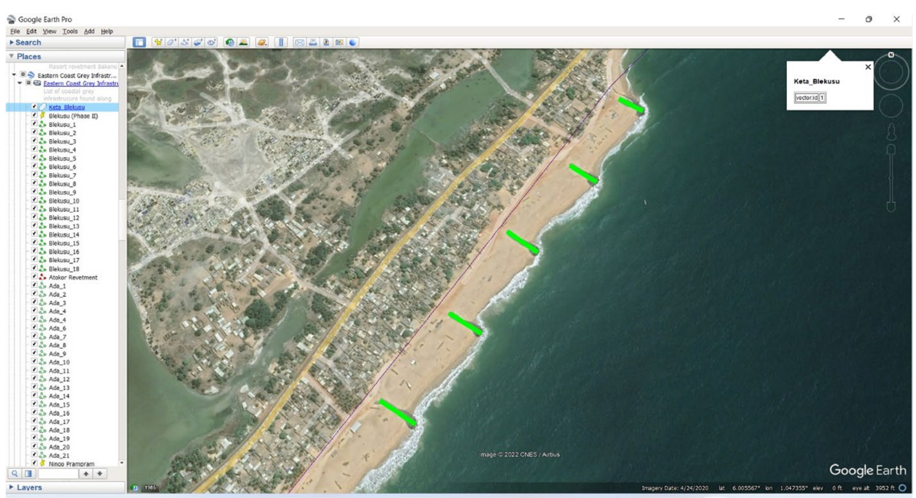

Fig. 4 Screenshot showing digitization of groyne fields and creation of KML files at Blekusu, along the Eastern Coast

defences were acquired through in-situ observation and interviews.

Onsite verification confirmed the types of coastal defences, structural changes over time, and the approximate dimensions and alongshore beach distance covered by hard structures. Table 1 summarises the information on the coastal grey infrastructure, classified by coastal region and coastal district.

At the time of this study, roughly 18 out of the 25 coastal districts have implemented coastal protection projects. Since grey infrastructure along the coast is mostly constructed using granite boulders, no further classification was possible.

Data processing involved converting KML files in ArcGIS using the KMZ to Layer conversion tool. Other procedures included importing CSV files in ArcGIS, loading layers, creating shapefiles, and generating maps to visualize locations and the national distribution of coastal infrastructure along the coast of Ghana. Mapping the infrastructure was important to provide a national

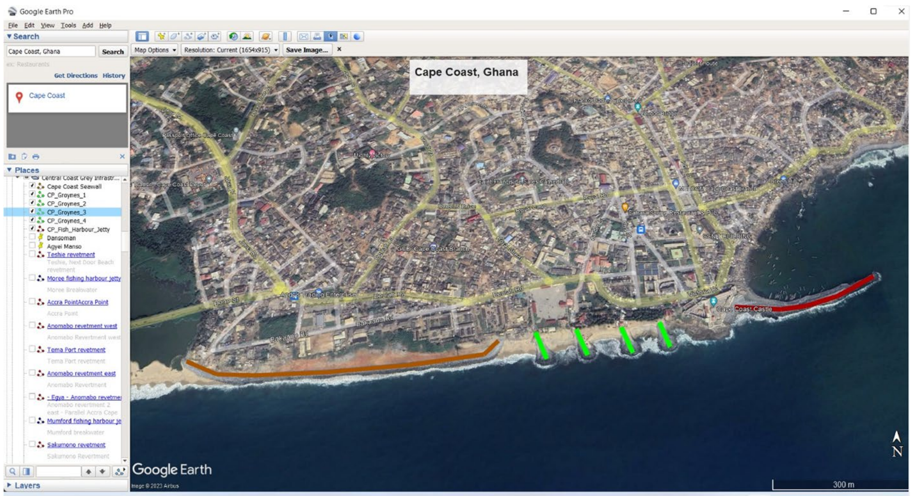

Fig. 5 Screenshot showing digitising of the groyne field and seawall at Cape Coast from Google Earth Pro

Fig. 6 The groyne field at Blekusu captured using UAV, May 2022. The groyne field was implemented to stabilise the Blekusu shoreline against severe erosion, a result of erosion migration from Keta Sea Defence

account and complete panorama of the current coastal infrastructure along the coast of Ghana, necessary to support coastal planning, coastal vulnerability assessments, and review of coastal adaptation plans and to end the ad hoc implementations of coastal protection as coastal management solutions in Ghana.

3 Results

3.1 Grey infrastructure distribution along the Eastern Region

The coastal infrastructure locations were mapped according to the three geomorphic areas: Eastern, Central, and Western coasts. The results show that the Eastern coast *(*Fig. 7) is dominated by groyne fields with varying field sizes), with five major groyne systems implemented at Ada, Ningo Prampram, Atorkor, Keta, and Blekusu.

The groyne field at Ada East comprises 22 groynes covering an alongshore distance of approximately 16 km (Bolle et al. 2015). The groynes have an approximate length of 90 m, and inter-groyne distance of nearly 200 m. At Atorkor, the groynes have an average groyne length of 80 m, spanning 2.5 kms of beach, and interspaced on average at 190 m. Similarly, at Blekusu, the groyne field covers approximately 4 km of beach, interspaced at approximately 190 m. A total of 14 groynes have also been installed at the New Ningo Prampram and 7 groynes at Old Ningo covering a beach distance of approximately 3.5 km and 1.5 km, respectively. This highlights the trend of coastal hardening along the Eastern coast. It is also apparent that to achieve hybridization of these groyne fields, beach nourishment, however expensive, is inevitable.

Table 1 Summary of types of coastal grey infrastructure classified by coastal region and districts showing totals per district and the alongshore distance covered by revetments, seawalls, and groyne fields and length of jetties

Coastal Area	District name	Types of coastal grey infrastructure								
		Groynes			Revetments/seawalls			Jetty/Port breakwater		
		Type	Total	Beach distance	Type	Total	Beach distance	Type	Total	Length
Western Coast	1. Ahanta West	Rock	1	10	-	-	2,400	Rock	1	2,175
	2. Sekondi-Takoradi	Rock	1	10	Rock	6	10,000	Concrete	4	5,481
	3. Shama East	Rock	1	10	Rock	3	7,000	-	0	
	4. Komenda Edna Agufo	Rock	12	3,800	Rock	5	6,500	Rock	2	310
Central Coast	5. Cape Coast Metro	Rock	4	600	Rock, Gabion	3	4,500	Rock	1	400
	6. Abura—Asebu	-	-	-	-	-	-	Rock	2	368
	7. Mfantisman	Rock	6	1,200	Rock	3	3,800	Rock	2	268
	8. Gomoa West	Rock	1	10	Rock	1	500	Rock	1	375
	9. Gomoa East	Rock	1	10	Rock	1	500	-	-	
	10. Accra Metropolis	Rock	2	100	Rock	1,662	660	Concrete	1	393
	11. LaDade Kotopon	-	-	-	Rock	1	300	-	-	-
	12. Ledzokuku	Rock	2	100	Rock	1	300	-	-	-
	`13. Tema Metropolis	-	-	-	Rock	3	5,000	Concrete	1	1,604
	14. Kpone Katamanse	-	-	-	Rock	1	2,700	Rock	1	268
Eastern Coast	15. Ningo Prampram	Rock	21	6,500	Rock	2	300	-	-	-
	16. Ada East	Rock	22	16,000	-		-	-	-	-
	17. Keta Municipal	Rock	20	2,600	Rock, Gabion	2	3,800	-	-	-
	18. Ketu South	Rock	18	4,000	-	-	-	-	-	-

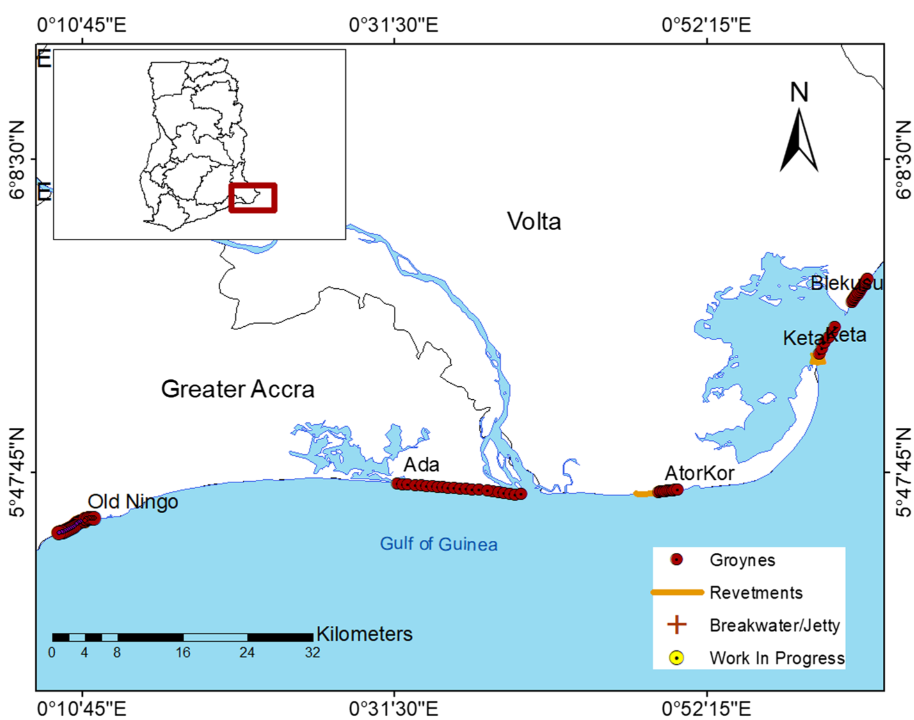

Fig. 7 Grey infrastructure distribution along the Eastern coast. Work in progress represents ongoing coastal protection projects

3.2 Grey infrastructure distribution along the central coast

Revetments are by large the dominant coastal grey infrastructure along the Central coast (Fig. 8), Revetments are intermittently used to protect the coast from Elmina, Cape Coast, Anomabo, Glefe, and Sakumono, through to Accra and Tema areas. They are implemented solo and sometimes alongside other grey structures.

In addition to revetments, groynes were implemented at Cape Coast, Anomabo, and Elmina. At Cape Coast (Oasis beach), the groyne field comprises four giant trapezoidal groynes with an approximate beach coverage of 0.6 kms, groyne length of nearly 60 m, an approximate inter-groyne distance of 70 m, and an average height of 2.5 m. Despite their function to help build up the beach, coastal erosion is persistent between the groynes, seemingly invalidating the primary purpose, that is, to stabilise and build up the beach.

Adjacent to the groyne field at Cape Coast, a seawall was constructed covering a beach distance of approximately 0.8 kms (see Fig. 5). The seawall stretches from Fosu Lagoon to Oasis beach, completely closing and restricting access to the beach. Similarly, at Anomabo SDP, a groyne system of seven trapezoidal groynes was linked to a one-kilometre revetment to stabilise the Anomabo coast against severe coastal erosion.

3.3 Grey infrastructure distribution along the Western coast

The Western region is the least armoured coast, with major coastal defences along the Axim and Sekondi-Takoradi foreshore and port infrastructure (port breakwaters and jetties) at Takoradi deep port and Sekondi-Takoradi Naval base. This coast experiences significantly low-energy waves and is comparatively less threatened by coastal erosion. The Axim SDP and Sekondi-Takoradi seawall represent the major coastal projects along the Western coast, Fig. 9.

However, despite offering immediate protection, the seawall has completely restricted beach access and the impacts on coastal local artisanal fisheries need to be fully investigated. At Axim (Fig. 10), a 5 km sea defence project comprising seawall and revetments is near completion.

3.4 Construction of new fishing harbours and future implications

At least 15 new fishing harbours are under construction along the coast, increasing the number of grey structures. Twelve constructions (Axim, Dixcove, Winneba, Senya Beraku, Elmina, James Town, Gomoa Fetteh, Moree, Mumford, Teshie, and Keta) commenced in 2012 with an estimated total construction cost of $200 million (Hydro International 2012), and three new fishing harbours

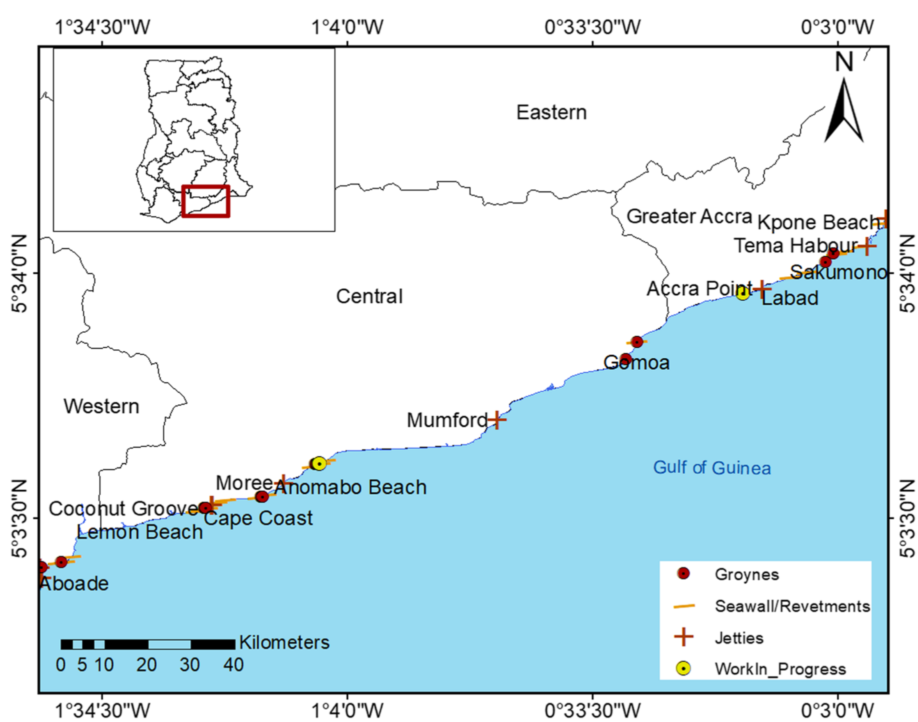

Fig. 8 Grey infrastructure distribution along the Central coast is dominated by revetments. Work in progress represents ongoing coastal protection projects

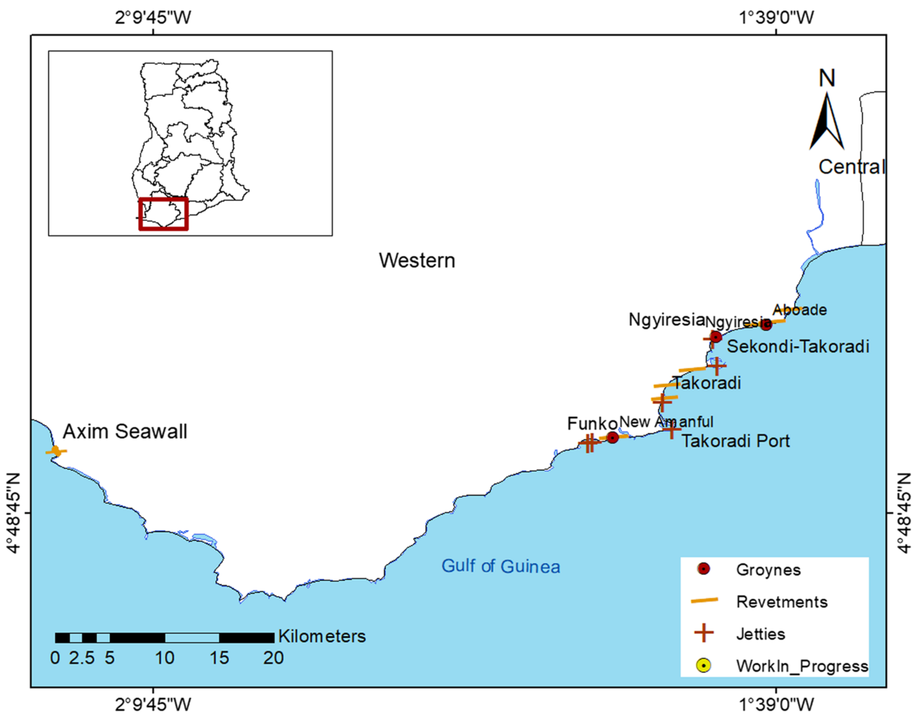

Fig. 9 Distribution of grey infrastructure along the Western coast showing the concentration of grey at Axim and Sekondi-Takoradi. Work in progress represent ongoing coastal protection projects

commenced in 2021, namely Osu, Mfantseman, and Otuam (Ghanaports 2021), see Fig. 11. These projects were rolled as a government economic drive to modernise fisheries production, provide sanctuary to fishing boats against strong waves, tides, and storm surges, but also to protect the communities at these areas.

Among other impacts, the construction of port infrastructure is attributed to the destruction of coastal habitats, alteration of the coastal hydrology and wave patterns (Akyeampong 2001), and coastal erosion migration to downdrift areas (Angnuureng et al. 2013). It is apparent that the dredging and construction of new fishing harbours will continue to worsen this trend and needs further investigation.

3.5 Mangrove distribution (coastal green infrastructure) along the coast of Ghana

Green (natural) infrastructure along the coast of Ghana is characterised by seagrasses, salt marshes, and mangroves forests (Fig. 12). Mangroves are omnipresent along the coast of Ghana, especially in Ramsar sites such as the Muni Lagoon, Densu delta, Sakumo Lagoon, Songor Lagoon and Anlo-Keta lagoon (UNEP 2007). Other areas with major mangroves (and salt marshes) include Benya lagoon along the Central coast and Amanzule Wetlands, Half Asssini, Ellembelle, and Whin Estuary along the Western coast. Six species of mangroves, namely Acrostichum aureum, Avicennia germinans, Conocarpus erectus, Laguncularia racemose, Rhizophora harrisonii, and Rhizophora racemosa are found in Ghana (UNEP 2007). Mangroves' total area coverage is estimated to range from 137km^2 (UNEP 2007) to 140km^2 (Ajonina et al. 2014), with an estimated national economic value of $6 million per year from mangrove harvesting and related marine fisheries (Ajonina et al. 2014).

Mangroves are an important natural coastal ecosystem for coastal erosion and flooding protection. They are also central to providing ecosystem services to coastal communities, including the provision of timber, fuel wood, charcoal, and medicine. The protection and regulation functions of mangroves include coastal flooding, erosion, and storm control. Moreover, mangroves and saltmarshes provide many co-benefits such as improving primary productivity, provision of fisheries habitats, improving water quality, and climate change mitigation through carbon sequestration and storage (Sutton-Grier et al. 2015). The detailed research on mangroves in West Africa (UNEP 2007) and along the Greater Amanzule Wetlands in Ghana (Ajonina et al. 2014) has been well documented. In Ghana, mangroves and other natural infrastructure provide a great opportunity for integrated infrastructure, including living shorelines, but implementation has been slow. Presently, natural and nature-based projects are being piloted using ecosystem-based

Fig. 10 Construction of the 5 km Axim Sea Defence Project is almost entirely completed

adaptation, landscape management, and mangrove afforestation and reforestation, but the extent of these projects is yet to be appraised.

3.6 Assessment of the distribution of groyne fields along the coast of Ghana

In Fig. 13, groyne systems are charted according to the geomorphic region and coastal district, based on the current state of the coastal protection. Results indicate that the majority and largest groynes fields were implemented along the Eastern Coast at Ada East (22 groynes), Ningo Prampram (21 groynes), Atokor (13 groynes), Keta Municipality (Six groynes), and Ketu South (18 groynes).

Despite serving their purpose, groyne fields along the Eastern coast are also linked to a chain of erosion migration (Angnuureng et al. 2013). In-situ findings show that since the implementation of the KSDP, coastal erosion has migrated to Blekusu, in Ketu South. After the implementation of the Blekusu (Phase I) coastal protection, new severe erosion hotspots are now being recorded at downdrift places like Agavedgzi, and Denu, creating new demands for coastal protection.

The concentration of groyne fields along the Eastern region is possibly linked to high erosion rates, hence the need to protect vulnerable coastal communities. In terms of cumulative beach coverage, groyne systems cover a distance of approximately 29 km of the Eastern coast compared to 5.1 km and 1.7 km for the Central and Western coasts respectively (Fig. 14).

3.7 Assessment of the distribution of revetments along the coast of Ghana

Revetments are common along the coast of Ghana due to their simplicity and ease of construction using granite rock (Alves et al. 2020). The beach distance coverage by revetments (Fig. 15) is charted according to geomorphic coast and coastal district, again, based on the current state of the coastal protection.

Most of the revetments installed typically cover relatively long distances. However, despite their easy design and implementation, maintenance is required, but the maintenance plans of the installed infrastructure in Ghana are not transparent due to the lack of SMPs and budgetary constraints, factors which ultimately contribute to the faster deterioration of implemented assets.

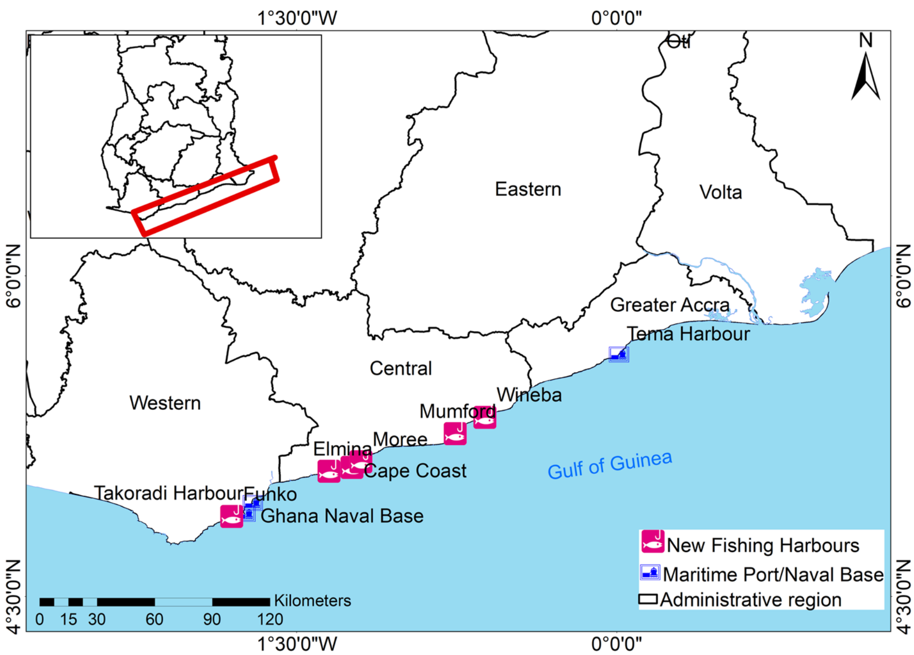

Fig. 11 Ports and new fishing harbour infrastructure along the coast of Ghana. We argue that the construction of many new fishing harbours may significantly alter coastal processes and sediment dynamics, induce more coastal erosion to downstream communities, and create new challenges

3.8 Tourism infrastructure and the increasing need for coastal protection

Tourism infrastructure (UNESCO World Heritage Sites, castles, forts, beach hotels, and resorts) is increasingly threatened by SLR, necessitating coastal protection along the coast of Ghana. In this study, we mapped 22 UNESCO World Heritage sites comprising 3 castles and 19 forts. These castles are Cape Coast Castle, St. George's d'Elmina Castle, and Christiansborg Castle. The forts include Fort Good Hope, Fort Patience, Fort Amsterdam, Fort San Sebastian, Fort William, and Fort James among others mapped in Fig. 16 (a). In addition to castles and forts, the demand for coastal protection is also correlated to the increase in the number of beach-side tourism infrastructure. In this study, we identified a random sample of 100 beach-side resorts Fig. 16 (b) which are vulnerable to coastal erosion and in need of coastal protection likely using grey infrastructure.

Currently, the castles are threatened by SLR and this confirmed recent research that 70% of African heritage sites are threatened by SLR by 2050 (Vousdoukas et al. 2022). Although Elmina Castle, Cape Coast Castle, and Fort Dutch Komenda have significant coastal protection in their neighbourhood. Given the IPCC SLR projections (IPCC 2021), and persistent erosion and flooding, we envisage the demand for coastal protection to increase. Currently, beachside hotels and resorts like Elmina Coconut Grove, Bay Resort, Cape Coast Oasis beach resort, and Anomabo Beach Resort are protected, but there is high confidence for more coastal protection from onsite interviews. We consider that this information is essential for economic planning and assessment of coastal vulnerability. Despite the legitimacy of this demand, we also argue that future implementation must take due consideration of the environmental, social, and economic sustainability aspects and ultimately the sustainability of coastal management in Ghana.

4 Discussion

Over the past decade, there has been an increase in coastal infrastructure along the coast of Ghana using hard-engineered infrastructure, mostly groynes, revetments, seawalls, and jetties. Most of the defences are implemented using rocks. However, gabion revetments, hybrid groynes, and bags of sand are notable e.g. at Volta Estuary. Wood and concrete installations are rare, possibly due to the associated high costs of construction and maintenance. Revetment and groyne fields are the commonest, and precisely, two accounts of seawalls were identified at Sekondi-Takoradi and Cape Coast.

The increase in coastal grey infrastructure along the coast of Ghana confirms the predominant use of hold the line strategies and the ad hoc implementation of grey infrastructure for shoreline protection (Boateng et al. 2016; Jonah et al. 2016; Wiafe et al. 2013). Given that virtually all the hard structures were constructed during the

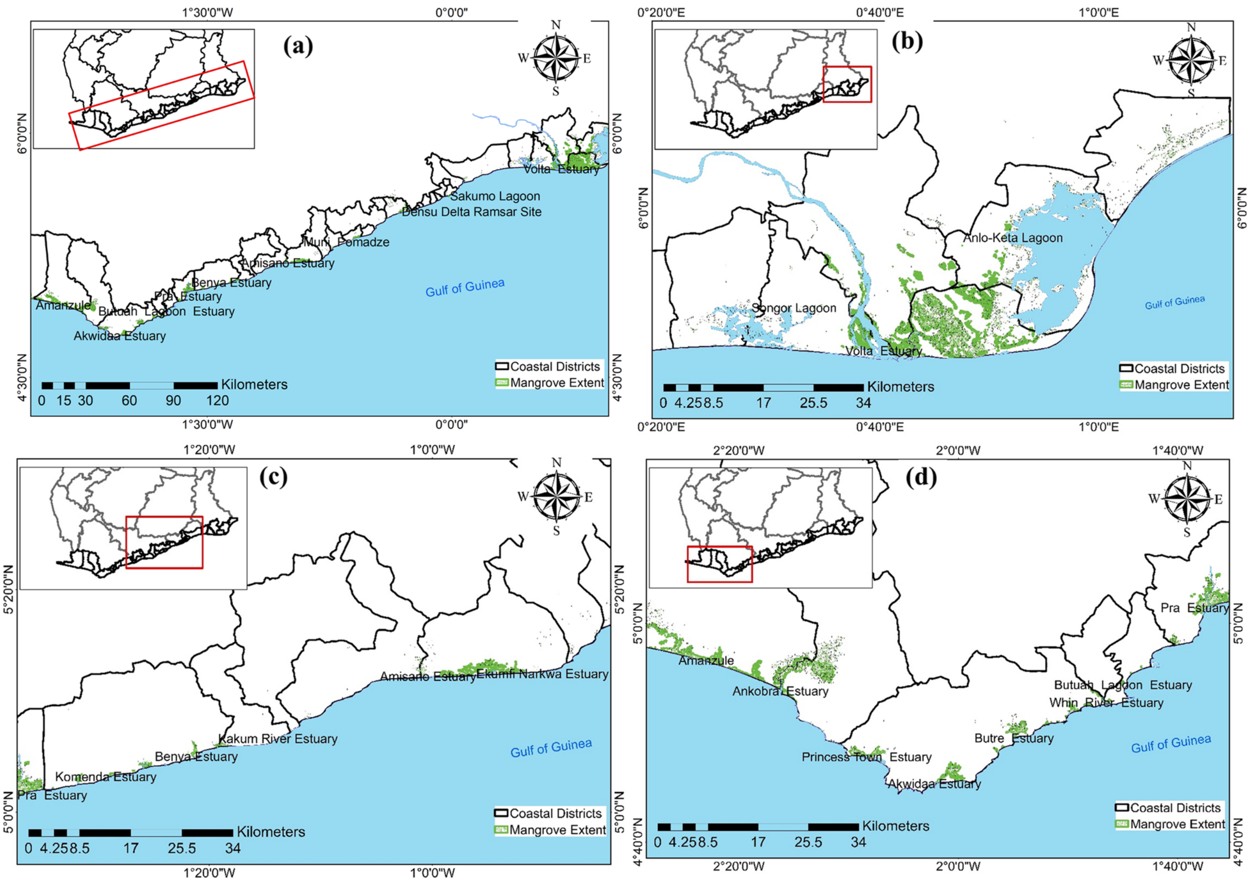

Fig. 12 Mangroves extent along the coast of Ghana showing (**a**) entire coast of Ghana (**b**) Eastern coast (**c**) Central coast and (**d**) Western coast

Region/District	Gryones/District
Western Region	**3**
Ahanta West	1
Sekondi-Takoradi	1
Shama	1
Central Region	**20**
Accra Metropolis	2
Cape Coast Metro	4
Gomoa East	1
Gomoa West	1
Komenda Edna Eguafo	4
Ledzokuku	2
Mfantisman	6
Eastern Region	**83**
Ada East	22
Keta Municipal	19
Ketu South	18
Ningo Pram	24
Approximate Total	**106**

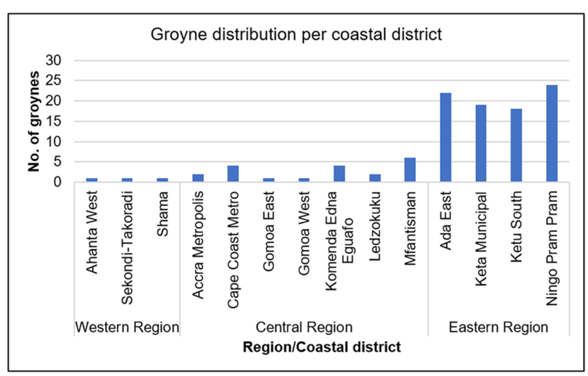

Fig. 13 Distribution of groyne fields along the coast of Ghana classed by geographic area and coastal district

last decade, the entire coast could be protected using grey infrastructure if the rate of coastal hardening persists. Notably, the absence of SMPs is a major concern as some sections of the coast are armoured (hold the line strategy), while other adjacent areas of the coast are unjustifiably unprotected (no active intervention) making them vulnerable to coastal erosion migration. This echoes earlier research on the need for properly instituted SMPs (Boateng et al. 2016; Wiafe et al. 2013). In addition, the current trend of new fishing harbours will further affect longshore transport and induce coastal erosion to previously un-eroding downdrift areas, possibly dictating a new trend in overall shoreline evolution along the coast.

Despite the obvious need for coastal protection, grey infrastructure has many disadvantages documented in research. These include the migration of erosion

Region/District	Sum of beach coverage(Km)
Central	**5.1**
Cape Coast	0.6
Komenda Edna Eguafo	3.8
Mfantisman	0.7
Eastern	**29.1**
Ada East	16
Keta Municipal	2.6
Ketu South	4
Ningo Prampram	6.5
Western	**1.7**
Ahanta West	0.3
Sekondi-Takoradi	0.7
Shama	0.7
Grand Total of beach coverage	**35.9**

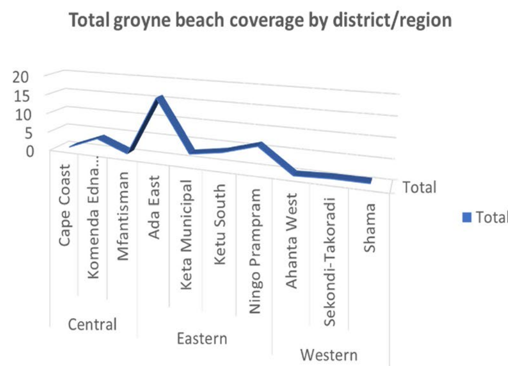

Fig. 14 Comparison of groyne field beach coverage along three coastal geographic regions in Ghana

Region/District	Beach extent (Km)
Central Region	**20.86**
Accra Metropolis	0.66
Cape Coast Metro	4.5
Gomoa	0.5
Komenda Edna Egu	6.5
Mfantsiman	3.7
Tema Metropolis	5
Eastern Region	**5.0**
Keta Municipal	3.8
Kpone Katamanso	0.3
La Dade Kotopon	0.3
Ledzokuku	0.3
Ningo Prampram	0.3
Western Region	**23.4**
Ahanta West	2.4
Nzema East	4
Shama	7
Takoradi	10
Grand Total	**49.26**

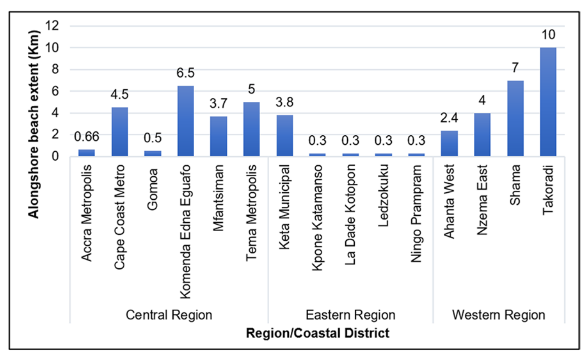

Fig. 15 Cumulative beach distance coverage by revetments along the coast of Ghana

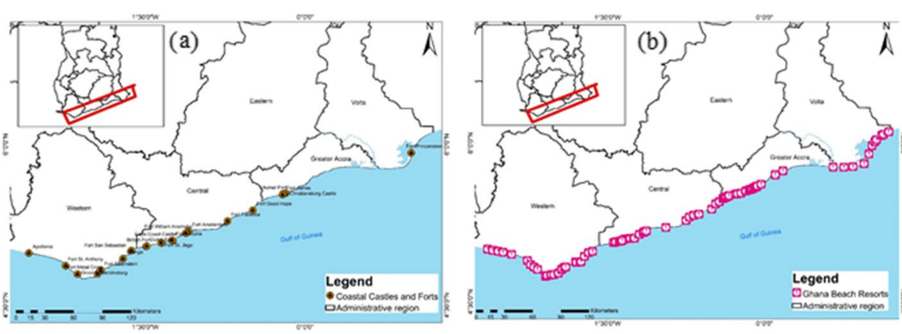

Fig. 16 Map of tourism infrastructure showing (**a**) UNESCO Heritage Sites comprising castles and forts, and (**b**) beachside hotels and resorts along the coast of Ghana. This infrastructure is exposed to SLR and coastal erosion, and may also increase demand for new coastal protection

(Angnuureng et al. 2013), loss of beaches and related utilities such as tourism (Pilkey & Cooper 2014), invasion of structures by ghost crabs and other alien species that completely alters the species diversity (Glasby et al. 2007; Powell et al. 2019). Locally, grey infrastructure is attributed to the loss of fish landing sites and local beach seine fishing, the migration of sea turtles and other biota that ordinarily thrive live on sandy beaches. Therefore, the environmental and socioeconomic impacts of coastal grey infrastructure need to be fully investigated in future research.

Coastal change is inevitable and therefore requires constant planning and monitoring (Currin 2019; NOAA 2015). As such, coastal authorities are recommended to consider hybrid engineering with nature and nature-based infrastructure (Bouw & Eekelen 2020; Cohen-Shacham et al. 2016; Sutton-Grier et al. 2018) for sustainable coastal protection and resilience. Given the national outlook of coastal hardening, the review of the short, medium, and long-term coastal management objectives along the coast of Ghana needs to be adequately addressed to establish SMPs that can effectively solve issues of erosion and flooding and future SLR projections (Alves et al. 2020; IPCC 2022; 2021). SMPs are necessary to systematically put an end to ad hoc coastal engineering using grey infrastructure along the coast of Ghana.

The impacts of hard-engineered infrastructure have already been identified in research (CGIES Task Force 2015; Rangel-Buitrago et al. 2018; Sutton-Grier et al. 2015), and the endless possibilities of integrating green and grey infrastructure (Bouw & Eekelen 2020; Browder, Gartner, et al., 2019; Cohen-Shacham et al. 2016; Currin 2019; Sutton-Grier et al. 2018). Therefore, institution of proper SMPs (DEFRA 2006b, 2006a) that are region specific would support adaptive coastal management and implementation of hybrid infrastructure. Fixing the void of SMPs (Wiafe et al. 2013) and the ad hoc and political implementation of coastal works should resolve the "piecemeal", "fix and forget" approaches that are currently at play to improve adaptation to coastal change. Special regard must be given to coastal roads, seaports, coastal aquifers, and other strategic infrastructure that are increasingly vulnerable under current and future SLR scenarios (IPCC 2021, 2022).

Hybridisation opportunities exist for currently installed coastal protection infrastructure (groynes, seawalls, and revetments) which are currently functional, but are vulnerable to future sea-level rise. In this context, options exist for (1) nourishment of groyne fields using dredged material, although this may be hindered by high cost; (2) piloting and implementation of living shoreline at riverine and estuarine areas where road infrastructure, mangrove, and saltmarsh ecosystems already co-exist, e.g. Kakum river estuary, and leverage triple defence benefits (CGIES Task Force 2015; Sutton-Grier et al. 2015); (3) Restoration of wetlands and mangrove ecosystems using ecosystem-based approaches may be prioritised. To expedite implementation and drive towards hybrid infrastructure, SMPs and Environmental Impact Assessments (EIA) can be aligned with national climate change adaptation plans, such as the Ghana National Adaptation Plan (NAP), (EPA 2020). This can be done observing other recommendations set out in regional studies on coastal management e.g. West Africa Coastal Area Management (WACA) (Alves et al. 2022, 2020; World Bank 2017a, 2017b).

5 Conclusion

This study established the intensification of hard-engineered projects along the coast of Ghana during the past two decades (2000–2022). During this time, coastal grey infrastructure was used to protect approximately 20% of the coast against coastal erosion. This study mapped the national distribution of coastal infrastructure along the coast of Ghana which was fundamental to influence changes in coastal management policy and decision-making. The results show that groynes, seawalls, and revetments dominate the coastal infrastructure typologies used to hold the line against the impacts of SLR along the coast of Ghana. Groyne fields particularly dominate the Eastern coast, while revetments are sparsely spread along the entire coast. Despite providing immediate coastal protection, grey infrastructure has a myriad of downsides that include aggravated coastal erosion migration to downdrift areas, irreversible coastline modifications, access restriction to the beach, loss, and damage to natural ecosystems, shortcomings which have impacts to coastal sustainability. The opportunities for adaptive management and hybrid infrastructure were discussed. Considering the severity of coastal erosion and flooding hazards along the coast, we recommend the development of holistic shoreline management plans to end the ad hoc implementation of coastal defences along the coast of Ghana.

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Authors' contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Blessing Charuka and Donatus Angnuureng. The first draft of the manuscript was written by Blessing Charuka and reviewed Donatus Angnuureng and Samuel K.M. Agblorti. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author.

Declarations

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

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