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Review

A scoping review of coastal vulnerability, subsidence and sea level rise in Ghana: Assessments, knowledge gaps and management implications

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ABSTRACT

Coastal areas are home to a myriad of essential services. However, population growth and climate change along with their cascading impacts have had profound impacts on their topography and evolution. Consequently, many coastal regions, of which Ghana's coast is no exception, are incessantly plagued with hazards that are increasing in magnitude and frequency. Predominantly through the recurrence of floods and erosion, Ghana's coast is becoming increasingly susceptible to huge socio-economic implications considering its environment-dependent economy. Therefore, attempts have been made to assess Ghana's coastal vulnerability to comprehend the complexities underpinning the occurrence of these hazards. However, most studies attribute the recurrence of floods and erosion to global sea-level rise, but coastal land subsidence could also have significant impacts. Indeed, land subsidence is a major component of relative sea-level rise (rSLR) in many coastal cities worldwide. Drawing on extant literature, this scoping study provides an overview and evaluation of three thematic areas—SLR, subsidence and coastal vulnerability—within the Ghanaian context along with their existing relationships. Additionally, it seeks to also assess available knowledge and data and to identify crucial knowledge gaps which impede comprehensive risk assessment of Ghana's coast. The survey findings, however, indicate a significant understudy of the selected thematic areas albeit posing potential threats to Ghana's coast. It brought to light the absence of a ground-validated subsidence study; a non-identification of potential local subsidence drivers; a non-availability of a subsidence-infused coastal vulnerability assessment; non-existing studies on the combined effects of climate change and subsidence; and huge deficits in available data for numerical modelling of coastal subsidence. Guided by the identified knowledge and data gaps and the need to mitigate impacts, the study recommends a thorough assessment of rSLR and vulnerability; a continuous and long-term monitoring framework for rSLR and its drivers; a hybrid approach and review of coastal management strategies; and the reinforcement of conservational laws and conventions to avert the increasing vulnerability of Ghana's coast.

Author contribution

Conceptualization: S.Y.A., K.A.A., P.T., P.M.; Supervision: K.A.A., P.T., P.M., M.W.; Data Collection: S.Y.A; Visualization, S.Y.A; Writing—Original Draft Preparation: S.Y.A.; Writing—Review & Editing: K.A.A., P.T., P.M., M.W., E.M., P–N.J-Q.; Funding Acquisition: P.T., P.M. All authors have read and agreed to the published version of the manuscript.

1. Introduction

Coasts are dynamic systems, undergoing morphological changes at various spatio-temporal scales in response to geomorphological and oceanographical factors (Cowell et al., 2003; Nicholls et al., 2007). Coastal areas are regions of essential value home to a myriad of services. These services include enhanced transportation links, industrial and urban growth, revenue from tourism or recreational activities, and food production (Creel, 2003; Miller and Hadley, 2005). Coastal regions yield

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more than half of the global gross domestic product although constituting a mere 5% of the total landmass (Vörösmarty et al., 2009). Consequently, little over half of the world's major urban communities are situated in coastal areas, and 40% of the global population lives within 100 km of these zones (Nicholls et al., 2007; Durand et al., 2022). Urbanization and coastal population patterns are, therefore, anticipated to continue in the next years (Neumann et al., 2015). Chances are that these numbers have surged based on global population growth rates of 0.9% as of 2021 (World Bank Group, 2022).

The combined repercussions of a growing population and economic and/or technological advancement are threatening the sustainable use of the services provided by coastal areas (Creel, 2003). Climate change and several human interventions are major factors impacting the sustainable usage of coastal areas, and their ecosystem services and landforms—due to their settings, elevations and proximities to the sea (Danladi et al., 2017). In essence, coastal areas are increasingly having their makeup features, functioning, existence and services being threatened to points of complete collapse (Stouthamer and Asselen, 2015). Sea level rise (SLR)—a ripple effect of climate change—contributes enormously to the challenges facing coastal areas (Oppenheimer et al., 2019). SLR and its effects on low-lying coastal areas have gained the attention of scientists, governments, and managers of coastal regions on a global scale (IPCC, 2013; Sahin and Mohamed, 2014). Between 1901 and 1971, the average rate of sea level rise was 1.3 mm/yr, increasing to 1.9 mm/yr between 1971 and 2006, and accelerated to 3.7 mm/yr between 2006 and 2018 (IPCC, 2021). As a result, the global mean sea-level increased by 20 cm between 1901 and 2018 (IPCC, 2021). Current projections by 2100 range from 0.28 m to 1.01 m relative to 1995–2014, depending on the climate scenario considered, but higher values cannot be ruled out given the deep uncertainties on the future evolution of polar ice sheets (IPCC, 2021).

Sea level rise poses a hazard to coastal ecosystems, diminishes ecological services, and may eventually result in significant socioeconomic changes, particularly in low-lying coastal ecosystems that are particularly sensitive (Carnero-Bravo et al., 2018). Although climate change plays a significant role in increasing sea level (IPCC, 2021), it may be locally amplified by coastal land subsidence (Fig. 1a) triggered or enhanced by processes such as over-abstraction of groundwater (Gambolati and Teatini, 2015; Minderhoud et al., 2018); loading of compressible subsurface sediments (Chaussard et al., 2013); local and basin tectonics (Higgins, 2016); isostasy (Fowler and Ng, 2021); natural oxidation (Hooijer et al., 2012; Koster et al., 2018); sediment starvation through damming and coastal infrastructure (Syvitski et al., 2009; Dai et al., 2018). According to Ericson et al. (2006), a combination of both eustatic sea-level change and subsidence is traditionally referred to as relative sea-level rise (rSLR).

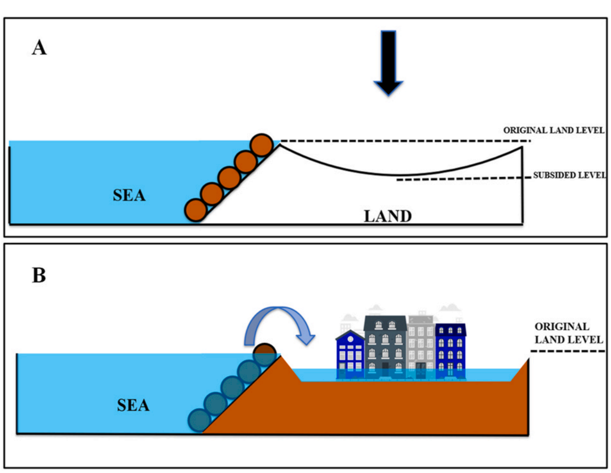

Fig. 1. Schematic illustration of (a) coastal subsidence and (b) flooding in subsided coastal areas even with coastal defence (brown disks).

Unlike climate change and its cascading impacts, little is known, however, about the full spatial variability of subsidence, its processes, drivers and rates—especially within an African context—despite its vast impact on regional landscapes and livelihoods. Some coastal areas are being confronted with the far more immediate threat of subsidence. The current rate of global mean sea-level rise (3.7 mm/yr over the period 2006–2018) is dwarfed by subsidence rates in some coastal areas as high as averages of 1.6 cm/yr (Erban et al., 2014) and >2.5 cm/yr (Minderhoud et al., 2017) within the Mekong delta; >3 cm/yr in Tianjin and Semarang (Wu et al., 2022); and 9.5 cm/year to 21.5 cm/year in Jakarta (Chaussard et al., 2013). Subsidence is, therefore, outpacing SLR and exacerbating prevalent coastal hazards and devastating impacts of climate change (Brown and Nicholls, 2015; Johnston et al., 2021; Restrepo-Ángel et al., 2021). The impacts of subsidence are, however, similar to that of SLR (Syvitski et al., 2009) and in most cases reinforce each other (Brown and Nicholls, 2015). Land subsidence magnifies local relative sea level change (Teatini et al., 2012; Ciro Aucelli et al., 2017; Tessler et al., 2018) and increases the likelihood of environmental concerns such as floods (Fig. 1b), erosion, wetland and biodiversity loss, degradation of fishing grounds, loss of infrastructure and buildings, loss of arable land, saline water intrusion, freshwater scarcity, and rapid shoreline retreat (Nicholls et al., 2007; Wang et al., 2012; Oppenheimer et al., 2019).

Land subsidence increases the risk of flooding from the major rivers and extends the coastal regions susceptible to storm surges and tidal inundation, especially when combined with sea level rise, severe rains (such as the monsoon), or storms (Chaussard et al., 2013; Abidin et al., 2015; Irawan et al., 2021). The most vulnerable will be populations inhabiting low-lying coastal zones (Wang et al., 2018; Edmonds et al., 2020). Currently, Durand et al. (2022) peg the global population living in flood-prone areas in coastal zones at 300 million. As global SLR will continue for centuries, the physical and social impacts on flood-prone areas are anticipated to get worse (Cannon et al., 2020). Countries with both low-lying coastal zones and environment-dependent economies will face far more challenging impacts (Cian et al., 2019; Edmonds et al., 2020). The sub-Saharan African coast—all of Africa except Northern Africa; includes the Sudan—which has 148,000 km^2 of low-elevation coastal zone and is inhabited by a population of almost 50 million (Neumann et al., 2015) along with poverty and rapid urban growth (Cian et al., 2019), will be severely impacted.

The geomorphological and coastal settings at local levels, determine the variance in responses to coastal hazards (Romine et al., 2016) hence requiring the adoption of bottom-up approaches that are locality-based. Along Ghana's coast, several studies have, however, mostly attributed findings on coastal hazards to climate change (Wiafe et al., 2013; Jayson-Quashigah, et al., 2013; Angnuureng et al., 2013; Tessler et al., 2015). Ghana's coast has incessantly been plagued with several coastal hazards that have altered its biophysical and socio-economic setting ranging from shoreline morphological change (Jayson-Quashigah et al., 2019), flooding (Fagotto, 2016; Appeaning Addo et al., 2018), loss of wetlands and aquatic ecosystems (Larbi et al., 2018) amongst a host of other consequential impacts that are increasing the vulnerability of the coast and impacting the socio-economic livelihoods of the populations therein (Yidana et al., 2010).

Over several years, numerous efforts have been undertaken to develop methods and policies for assessing the vulnerability of coastal regions to climate change and other associated factors (Rygel et al., 2006; Torresan et al., 2012; Appeaning Addo, 2014; Wolters and Kuenzer, 2015; Wu et al., 2016). Understanding vulnerability aids coastal scientists and policy-makers foresee the effects that a coastal hazard might have in a coastal zone (Klein and Nicholls, 1999; Husnayaen et al., 2018). To assess the level of Ghana's coastal vulnerability, efforts have been made to identify and evaluate the local drivers of coastal hazards. They include upstream catchment management (Boateng et al., 2012), sea level rise (Sagoe-Addy and Appeaning Addo, 2013), energetic swell waves (Almar et al., 2015), coastal erosion and its management (Appeaning Addo, 2015), groundwater extraction and population change (Armah et al., 2005).

The aforementioned factors driving change in Ghana's coast have been extensively investigated except for land subsidence and its contribution to the overall vulnerability of Ghana's coast. This scoping study, therefore, seeks to provide an overview and evaluation of relative sea-level rise and the vulnerability of Ghana's coast. Additionally, it seeks to also assess available knowledge and data and to identify crucial knowledge gaps which impede proper coastal risk assessment of Ghana's coast.

2. Study area

The coast of Ghana lies along the Gulf of Guinea in West Africa (Fig. 2), with its southernmost point at about 4°44' N. The coastline is about 550 km long and extends from 6°06' N and 1°12' E in the east where it is bordered by the Republic of Togo, to 5°05' N and 3°06' W in the west, where it is bordered by Côte D'Ivoire (Wiafe et al., 2013). It is generally a low-lying area, not more than 30 m above sea level, and has a narrow continental shelf extending outward to between 20 and 35 km except off Takoradi where it reaches up to 90 km (Armah and Amlalo, 1998).

The coastline lies along an Afro-trailing edge-type continental margin (Inman and Nordstrom, 1971) with over 90 coastal lagoons (Armah and Amlalo, 1998). Most of these are very small, less than 5 km^2 in surface area. The largest is the Keta Lagoon and with its associated lagoons namely, Angaw and Avu, cover a surface area of 702 km^2 (Armah, 1993). Ghana's coastal zone accounts for around 6.5% of the country's geographical area but contains 25% (Amlalo, 2006) (4.7 million) of the people based on the 2000 population census. However, the coastal population in the four coastal regions has increased based on data from the Ghana Statistical Service; 38% (9.3 million) of the Ghanaian population occupied the four coastal regions in the 2010 Population and Housing Census and made up 39.1% (12 million) of the population in the 2021 Population and Housing Census. The coastal zone houses around 80% of Ghana's industrial firms (Amlalo, 2006).

Previous studies by Ly (1980) divided the coastline into three zones based on geomorphic characterization (Fig. 3): the west coast made of flat and wide sandy beaches backed by coastal lagoons, mangrove forests, and depressional wetlands; the central coast stretching from Cape Three Points to Prampram and exhibiting alternations between rocky and sandy shores, with rocky headlands, bays and littoral sand barriers enclosing coastal lagoons; and the east coast from Prampram to the border with Togo, which is dominated by sandy beaches.

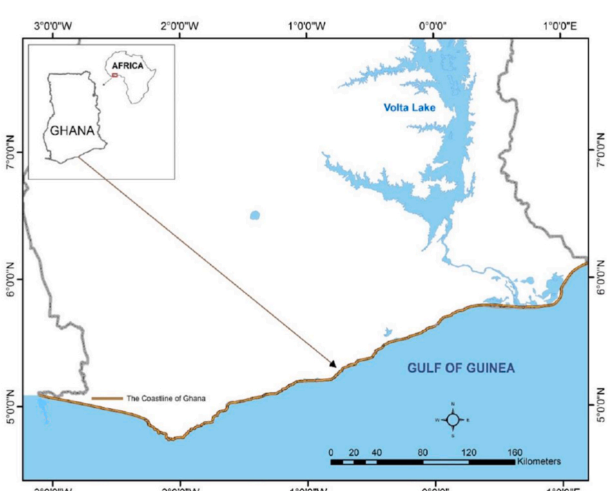

Fig. 2. The coastline of Ghana on the West African coast and the Gulf of Guinea (After Evadzi et al., 2017).

The coast is serrated by beaches and lagoons with rocky headlands and sandbars located between Cape Three Points and Tema (Ly, 1980) and bordered by the Atlantic Ocean/Gulf of Guinea. The coastal zone extends approximately 10 km inland and is enclosed by the 30 m elevation contour (Armah and Amlalo, 1998; Boateng, 2012) as shown in Fig. 3. The gulf is characterized by varying annual patterns of coastal upwelling and by an eastward-flowing current otherwise known as the Guinea Current as shown in Fig. 3 (Armah and Amlalo, 1998). A small westward-flowing counter-current lies beneath the Guinea Current at about 40 m depth and appears to turn to the southwest near the sea bottom (Longhurst, 1962).

The climate is tropical with a warm eastern belt and comparatively dry central belt and a wet southwestern corner which is hot and humid (EPA, 2004). The tide is regular and semi-diurnal, but the average range varies along the coast from 0.58 m at neap tide (Takoradi) to 1.32 m during Spring tide at Aflao (Wiafe et al., 2013). The tidal currents are low and generally have a small influence on coastal processes and morphological changes, except within tidal inlets (AESC, 1997). The significant height of waves generally lies between 0.9 and 1.4 but rarely attains 2.5 m or more (Wiafe et al., 2013). The most common amplitude of waves in the region is about 1.0 m but annual significant swells could reach 3.3 m in some instances (Wiafe et al., 2013).

Generally, there are six major types of coastal ecosystems along the coast: the sandy shore; the rocky shore; the coastal lagoon; the mangrove or tidal forest; the estuarine wetland; and the depression wetland. Semi-deciduous and wet ever-green secondary tropical forests are found predominantly on the Western coast (Armah and Amlalo, 1998) as shown by the Land Use/Land Cover map (LULC)—modified from FAO (2022)—in Fig. 4. Fringe forests are also found near the Ehunli and Akpuhu lagoons and the Kpani-Nyile, and the Cape Three Point Forest Reserve (Wiafe et al., 2013). The Central Coast, especially along the coast of Accra, is the most built-up area while the Eastern Coast is dominated largely by rainfed croplands and coastal savanna (grassland). The dominance of Cropland along the Eastern coast is corroborated by the economic activity report of the Population and Housing Census by the Ghana Statistical Service (2021) which pegs Agriculture, forestry and fishing activities at 33.17% of the working population in the Volta region—the highest economic activity at the easternmost coast.

Land uses along Ghana's coast include the increasing operation of Salt Pans for salt production along the Eastern coast, with instances of underground water extraction due to its higher brine concentration when compared to seawater (Atta-Quayson, 2018). The years between 2011 and 2013 saw the granting of over 20,000 acres of concession to three large-scale companies for the mining of salt around the Keta lagoon alone—a number which has increased to about six (6) companies in the Keta Municipal and Ketu South District alone (Atta-Quayson, 2018). In the Ada-Songor enclave as well, concessions have recently been sold to Electrochem Ghana Limited to expand operations and increase salt production (Lartey, 2022).

Other reported uses include beach sand mining which has led to coastal erosion (Mensah, 1997; Boateng, 2006, 2012; Appeaning Addo et al., 2008; Oteng-Ababio et al., 2011; Jonah et al., 2015); upstream river management and damming (hydroelectricity) which leads to a reduction in river flow and coastal sediment replenishment (Jonah et al., 2016). Additionally, groundwater abstraction from aquifers has drawn great attention in coastal areas such as the Keta Basin (Jorgensen and Banoeng-Yakubo, 2001; Helstrup et al., 2007). Over the past many years, almost all towns in the basin have relied on groundwater from perched shallow aquifers to supply both household and agricultural demands (Yidana et al., 2010). The Keta area's typical vegetable production systems include shallots, peppers, okra, tomatoes, and carrots, which are cultivated all year round and are irrigated with groundwater from small wells (Awadzi et al., 2008).

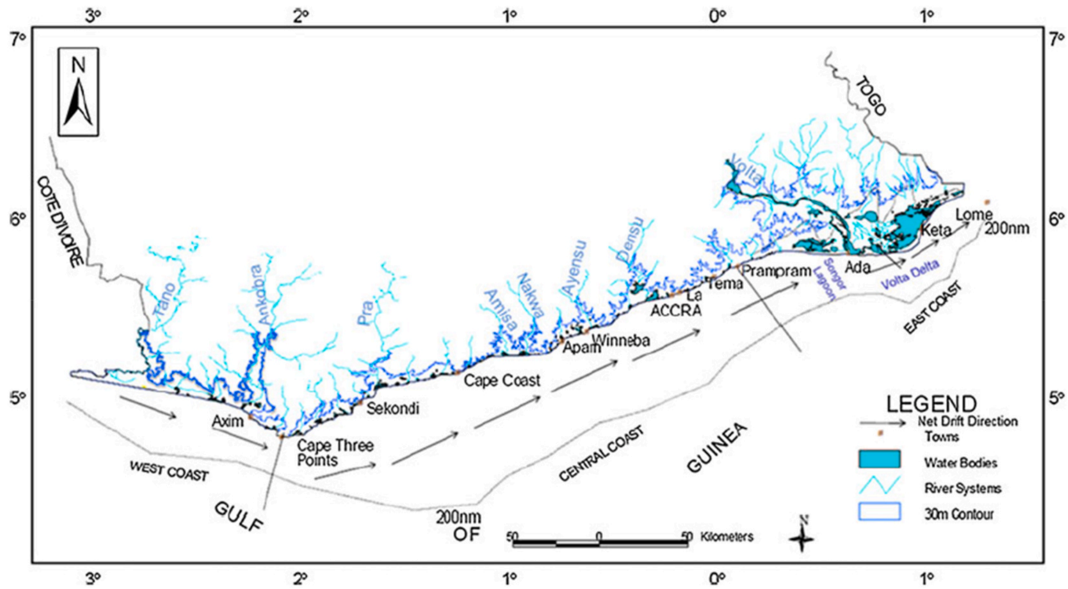

Fig. 3. Drainage, longshore current drift, and divisions of Ghana's coastline (After Boateng, 2012).

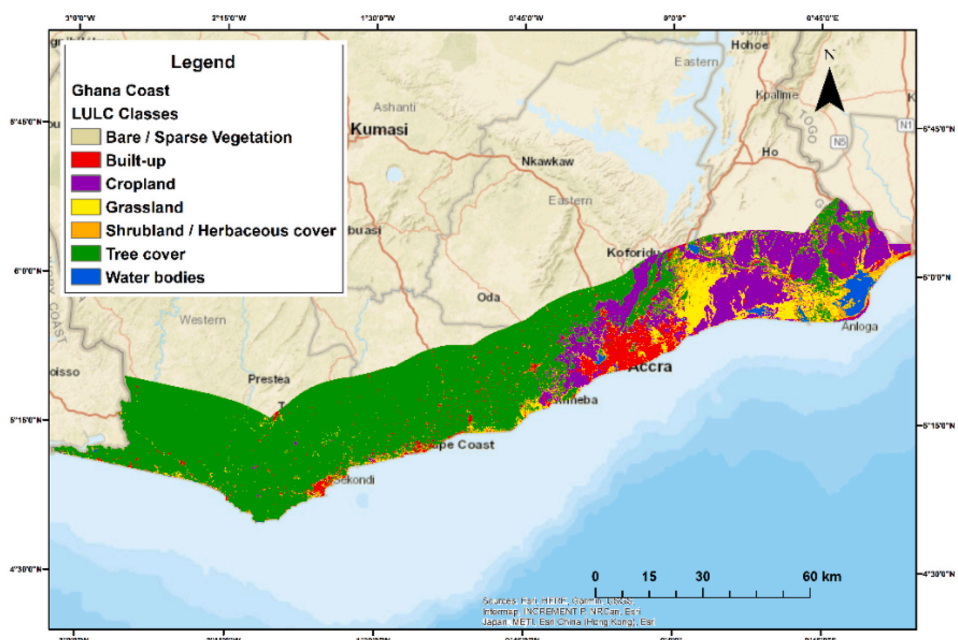

Fig. 4. A 100 m resolution land cover map of Ghana's coastal area.

3. An overview of subsidence, SLR and vulnerability assessments along Ghana's coast

3.1. Identification and selection of relevant studies

A desktop survey was conducted to access and peruse literature on the thematic areas of the scoping review. Various combinations of the keywords "land subsidence", "sea level rise" and "coastal vulnerability" were used to filter the search for relevant articles in online databases. The online databases adopted were Google Scholar, JSTOR, Directory of Open Access Journals (DOAJ), Scopus or Science Direct, general search in Google Web Search and some local book sources. To further filter the outcomes of the online search, the keyword "Ghana" was used along with the thematic areas to set geographic limits for the online search. Additionally, the "related articles" option in some databases and relevant references of selected articles were used to search for more literature. The last online survey was conducted on December 15, 2022. A total of hundred and five (105) records comprised of articles, books and online data sources were used for this study. Out of these records, only eleven (11) sources carried out assessments on the thematic areas along the coast of Ghana.

The results of the survey indicated a general limitation in the number of studies carried out on the thematic areas. Albeit posing potential coastal hazards to Ghana's coast, coastal subsidence and SLR are significantly understudied. A total of two (2) articles on land subsidence measurement in Ghana (Cian et al., 2019; Wu et al., 2022); three (3) articles on sea level rise estimation in Ghana (Sagoe-Addy and Appeaning Addo, 2013; Evadzi et al., 2017; Boateng et al., 2017) as well as a website estimate (NOAA, 2013); and four (4) articles on coastal vulnerability (Appeaning Addo, 2014; Boateng et al., 2017; Yankson et al., 2017; Babanawo et al., 2022) were all obtained and reviewed. In combining the keywords, a total of two (2) articles (Appeaning Addo, 2014; Boateng et al., 2017) run through the search combinations of "coastal vulnerability and SLR"; "coastal vulnerability and land subsidence"; and "coastal vulnerability and SLR and land subsidence". Only one (1) article (Ericson et al., 2006) was obtained for "land subsidence and SLR" as shown in Fig. 5.

3.2. Land subsidence assessments along Ghana's coast

Land subsidence, its detection, drivers and measurement are relatively grey research areas in Ghana. Although mentioned in some studies, not much research has been carried out on subsidence and its relation to the increasing trend in Ghana's coastal vulnerability. However, the review of available literature identified only two (2) articles on land subsidence measurement in Ghana—Cian et al. (2019) and Wu et al. (2022)—with both studies focusing on Ghana's capital, Accra. Cian et al. (2019) and Wu et al. (2022) both employed the use of the Interferometric Synthetic Aperture Radar (InSAR) technique. By utilizing multiple orbits of the satellite, the InSAR technique extracts the signal phase changes (interference) from SAR data that are collected in the same region during different periods (Erban et al., 2014; Pepe and Calò, 2017). More specifically, both studies resorted to the Persistent Scatterer InSAR (PS-InSAR) method based on the original Persistent Scatterer Interferometry (PSI) method proposed by Ferretti et al. (2001).

Wu et al. (2022) used only the C-band Sentinel-1 A/B— ~30 images between 2015 and 2020—whereas both the Sentinel-1 A/B and the C-band Environmental Satellite Advanced Synthetic Aperture Radar (Envisat-ASAR) were used by Cian et al. (2019), spanning a total period of approximately fifteen (15) years. Geographically, Wu et al. (2022) looked at ninety-nine (99) cities around the world whereas Cian et al. (2019) considered eighteen (18) coastal cities in Africa—including Accra, Ghana. Both studies used integration of the European Space Agency (ESA) Sentinel Application Platform (SNAP) software and the Stanford Method for Persistent Scatterers (StaMPS) software (Hooper et al., 2012) to make interferograms and extract time series of ground displacements from PS-InSAR respectively. Conclusively, both studies detected the occurrence of subsidence in Accra, however, only Wu et al. (2022) reported actual values with maximum subsidence rates exceeding 4 mm/yr (Fig. 6). However, in both articles, the measured deformation was expressed in the direction of the Line of Sight (LOS) of the SAR antenna and assumed the deformation to be in the vertical direction only—no horizontal land movements. In addition, there was no use of ground data to validate the InSAR-derived deformations in Accra, Ghana. The area circled in Fig. 6 shows locations with higher subsidence rates. These are upstream flood plains of the Sakumo II lagoon that have been heavily encroached upon and could be undergoing gradual compaction due to urban loading.

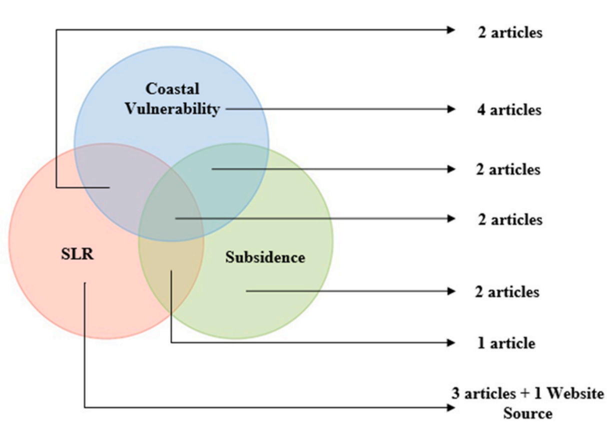

Fig. 5. A Venn diagram indicating the articles obtained from various online database searches using the keywords "SLR", "Subsidence" and "Coastal Vulnerability". Only articles on Ghana were considered.

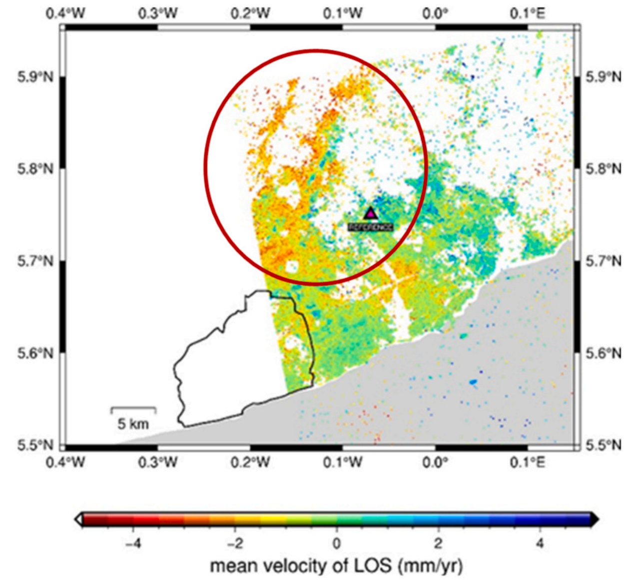

Fig. 6. Mean line of sight (LOS) velocity distributions (mm/yr) for portions of the Greater Accra Region, Ghana between 2015 and 2020 using Sentinel-1 A/B data. The black contour line is the boundary of the Accra Metropolitan District. (After Wu et al. (2022)).

Subsidence is more profound in some coastal landforms such as deltaic environments. Geologically, deltas such as Ghana's Volta Delta, have their surface geology predominantly covered by alluvial deposits. The surface geology of Ghana's Volta Delta comprises soft quaternary rocks and unconsolidated sediments of clay, loose sand and gravel deposits (Jayson-Quashigah et al., 2013). Alluvial deposits oxidate and compact under natural and human-induced influence. According to Higgins (2016), a layer of clay could compact at rates of up to 5 mm/yr for several decades with peat deposits being the most compressible. An area's surface geology, therefore, defines its subsidence regime. Other factors such as groundwater and hydrocarbon abstraction (Gambolati and Teatini, 2015; Kontgis et al., 2019); sediment trapping through coastal interventions and river damming (Vörösmarty et al., 2009; Schmidt, 2015); and land modifications that stall sediment compensations (Aagaard et al., 2021) all compound coastal subsidence. Unfortunately, these natural and human-induced pressures threaten coastal systems and the diverse array of ecosystems they host (Linham and Nicholls, 2010).

3.3. Relative sea level rise (rSLR) assessments along Ghana's coast

The review of available literature, however, suggests that no studies have been conducted on rSLR. No study has incorporated measured or estimated values of both SLR and land subsidence to determine the rSLR regime along any section of Ghana's coast or assessed the impacts thereof. The surging trend in coastal flooding or inundation along Ghana's coast (Appeaning Addo et al., 2018) has been alluded mostly to eustatic or steric sea level rise for decades without much consideration of land deformation being a probable influencer.

On a global scale, Ericson et al. (2006) assessed the implications of Effective sea-level rise (ESLR) on some forty (40) deltas, including Ghana's Volta delta. The methodology employed was based on the definition of ESLR as the combination of eustatic sea-level rise, the natural rates of fluvial sediment deposition and subsidence, and any accelerated subsidence due to groundwater and hydrocarbon extraction, which is not compensated by deposition of fluvial sediment. Unlike rSLR which is a combined effect of sea-level rise and local vertical land motion, ESLR encompasses the concept of rSLR and other potential factors such as rates of fluvial deposition. ESLR is, therefore, a more comprehensive measure of sea-level change. Ericson et al. (2006) attempted to incorporate both SLR and land subsidence in their study, however, the methodology used relied on some assumptions which included uniform eustatic SLR, natural subsidence and accelerated subsidence across the extent of each delta. The Eustatic SLR estimate, based on Church and Gregory (2001), Douglas and Peltier (2002), and Miller and Douglas (2004), was pegged at 2 mm/yr for all deltas. In the absence of reliable data on the Volta delta, the natural subsidence rate was pegged at 2.5 mm/yr—a mean value of the other deltas with published rates. In estimating the accelerated subsidence, a factor of three times the natural subsidence rate to define the upper limit of the potential accelerated subsidence was used following Milliman et al. (1989) and Milliman (1997). Conclusively, the study pegs the rate of ESLR in the range of 3–5 mm/yr (Fig. 7). Based on the baseline ESLR estimates extrapolated from 2000 through 2050, the study predicts that 1.12% of the Volta Delta will be lost to sea level incursion and also identified sediment trapping as the dominant factor in the ESLR rates estimated.

Aside from the aforementioned study by Ericson et al. (2006) which attempted to incorporate both SLR and subsidence into ESLR estimations, all other assessments on sea-level change along Ghana's coast have only considered eustatic SLR. Evadzi et al. (2017) statistically quantified the effect of sea level on the Ghana coastline by first performing trend analysis of sea surface height (SSH) data for Ghana by integrating satellite-derived data from TOPEX/Poseidon, Jason-1, and Jason-2/OSTM spanning about twenty (20) years (1993–2014) and proceeds to make future projections to the year 2100 based on corrected SLR projections of IPCC AR5 for Ghana. Findings from the trend analysis of the annual mean of SSH from the satellite observation data indicated an increasing sea-level trend of 2.52 ± 0.22 mm/yr and that the sea level has risen by about 5.3 cm (1993–2014) and accounts for 31% of the observed annual coastal erosion rate (about 2 m/yr) in Ghana.

Aside from the satellite-derived eustatic SLR estimates by Evadzi et al. (2017), a few studies used tidal gauge data to estimate eustatic SLR (Sagoe-Addy and Appeaning Addo, 2013; Boateng et al., 2017). Data from the Permanent Service for Mean Sea Level (PSMSL) indicated the availability of tidal gauge data at three locations along Ghana's coast—Accra, Tema and Takoradi (PSMSL, 1980, 1982, 2013)—but the time coverage is limited, the series are incomplete and do not span the most recent years. The data span of Tema was from 1963 to 1982 whereas that of Takoradi was from 1929 to 1992 and partly in 2007, 2008, 2009, 2011 and 2012 (Fig. 8). The quality of historic monthly tidal data from the Accra tidal gauge is questionable with data spanning from 1922 to 1938. In Takoradi, there was a discontinuity in acquired data where the tide gauge was operational until the 1990s when it completely broke down (Fig. 8a). Only visual staff readings were taken between 1998 and 2004 (Nkebi, 2006). Prior to its breakdown in the 1990s, it had malfunctioned after 1974 as shown in Fig. 8a. At the Tema port (Fig. 8b), the demolition of the tidal recorder's housing unit due to reported expansion works led to the truncation of data by 1990 (Nkebi, 2006). Due to the relative reliability and longevity of tidal data from the Takoradi port, Sagoe-Addy and Appeaning Addo (2013), NOAA (2013) and Boateng et al. (2017) all sourced the Takoradi tidal data for their SLR estimates.

Using annual means from 1930 to 1969, Sagoe-Addy and Appeaning Addo (2013) estimated a rate of 3.34 mm/yr at a 95% confidence interval using a linear regression model (Fig. 9). NOAA (2013) estimated 3.32 mm/yr with a 95% confidence interval of $\pm$ 0.5 mm/yr based on monthly mean sea level data from 1929 to 1969 (Fig. 10). Boateng et al. (2017) estimated a SLR rate of 2.1 mm/year using monthly mean sea level data from 1925 to 1970. However, the estimate by Boateng et al. (2017) could be erroneous considering the >3 mm/yr rates estimated by the other two studies (Sagoe-Addy and Appeaning Addo (2013) and NOAA (2013)) and that tidal data collection at the Takoradi port only begun in 1929, not 1925. All studies excluded data after 1970 from their linear trend analyses.

3.4. Coastal vulnerability assessments of Ghana's coast

The coastlines—and by extension, coastal zones—undergo dynamic changes and sporadic damage as a result of episodic occurrences caused by riverine and coastal processes (Nguyen and Takewaka, 2020). The most vulnerable areas within the coastal zone are the low-lying coastal communities and ecosystems. Vulnerability assessments along the coast of Ghana, have been carried out on various spatial scales from the entire coastline (Boateng et al., 2017) to regional (Appeaning Addo, 2014) and district scales (Yankson et al., 2017; Babanawo et al., 2022) to assess the susceptibility of the coastal zone to coastal hazards. However, several studies along Ghana's coast have mostly attributed research findings on the impacts of coastal hazards to climate change and its cascading effects (Appeaning Addo and Adeyemi, 2013; Wiafe et al., 2013; Jayson-Quashigah, et al., 2013; Angnuureng et al., 2013; Tessler et al., 2015).

Index-based coastal vulnerability (CVI) assessments have been carried out by Boateng et al. (2017) and Appeaning Addo (2014) along Ghana's entire coast and the regional capital—Greater Accra—respectively. In computing their CVIs, Boateng et al. (2017) used eight geologic and physical process variables namely: geomorphology, shoreline change rate, coastal slope, geology, sea-level change, local subsidence, mean significant wave height and mean tidal range, and incorporated population density as well. Aside from replacing coastal slope with elevation and excluding SLR and population density, Appeaning Addo (2014) used the same set of variables in computing a

Fig. 7. Global distribution of effective sea-level rise (ESLR) under baseline conditions for 40 deltas. The arrow and ellipse indicate the location of Ghana's Volta Delta and the estimated range of ESLR respectively. The upstream drainage basin for each delta is highlighted in grey (Modified after Ericson et al. (2006)).

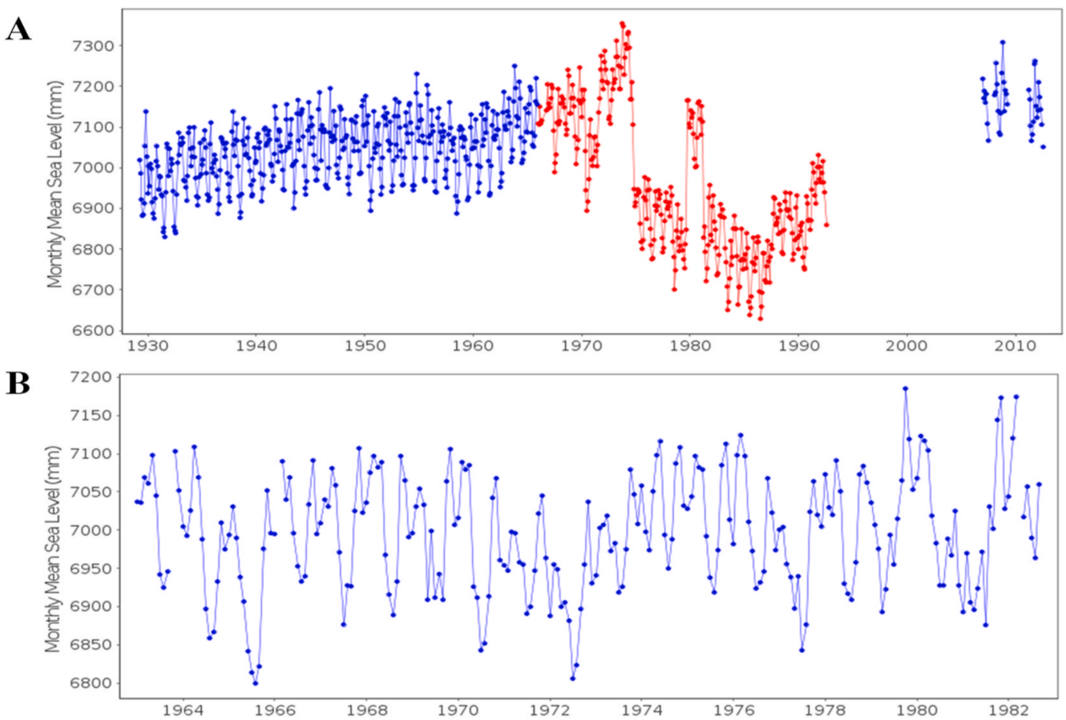

Fig. 8. Monthly tidal gauge data plot of sea level from (A)Takoradi port and (B) Tema port, Ghana (PSMSL, 1982, 2013).

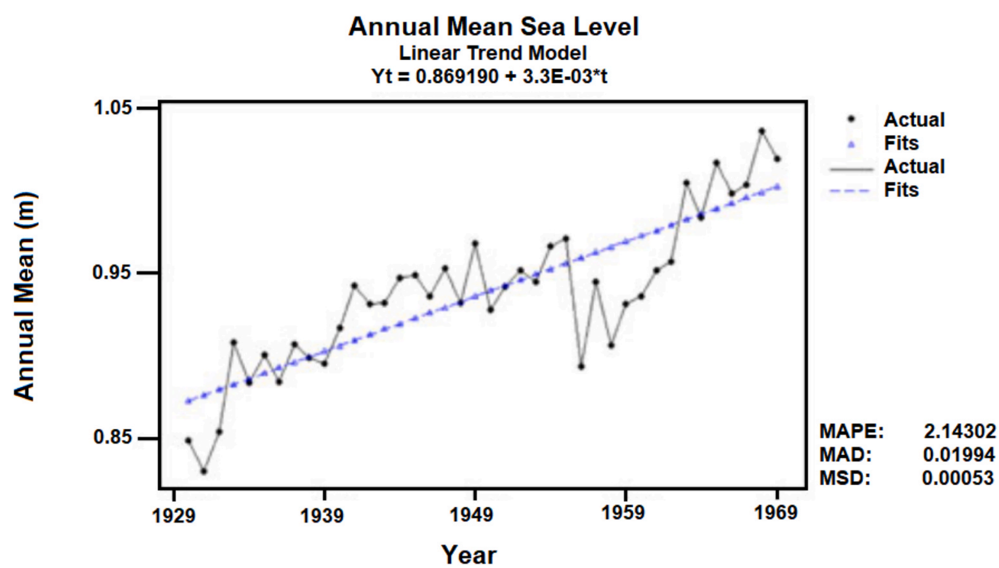

Fig. 9. Sea-level gauge data and linear trend model for annual mean sea level at Takoradi (Sagoe-Addy and Appeaning Addo, 2013).

CVI to SLR. Data on all variables used in the aforementioned studies were either obtained through direct measurement (in situ and remotely sensed) or as secondary data sourced from reliable institutions.

The subsidence rates were adopted from global trends reported by Syvitski et al. (2009) as 2 mm/yr and from average tidal gauge data (≤1 mm/yr) in the case of Appeaning Addo (2014) and Boateng et al. (2017) respectively. The CVI results by Boateng et al. (2017) based on percentile categorization indicated that 36% of Ghana's entire coastline was identified to be *very highly vulnerable*, covering Jomoro District (Western Region), Cape Coast District (Central region), and three coastal districts (Dangbe East, Keta and Ketu) at the eastern coast (Fig. 11). 15% of the coastline was considered *highly vulnerable*. The CVI findings from Appeaning Addo (2014) showed that the Western coast of Accra was a high-risk area for increasing rSLR (Fig. 12), however, the entire coastal zone of Accra was classified as a medium-risk area. Geology, geomorphology and relatively low elevation were identified as the major factors increasing the risk level, especially along the Western coast.

Wu et al. (2022) reported an InSAR-measured maximum subsidence rate of >4 mm/yr in Accra compared to the subsidence rates of 2 mm/yr and ≤1 mm/yr adopted by Appeaning Addo (2014) and Boateng et al. (2017) respectively. This could suggest a CVI underestimation of a more vulnerable coastline in their respective studies. However, the results of the CVI assessment of the Greater Accra coastal frontage by Boateng et al. (2017) largely corroborated the CVI assessment of the Accra coast by Appeaning Addo (2014). The slight variations, especially along the Eastern coast of Accra, was due to the exclusion of socio-economic parameter (population) in the CVI assessment by Appeaning Addo (2014). The studies further propose an integration of appropriate

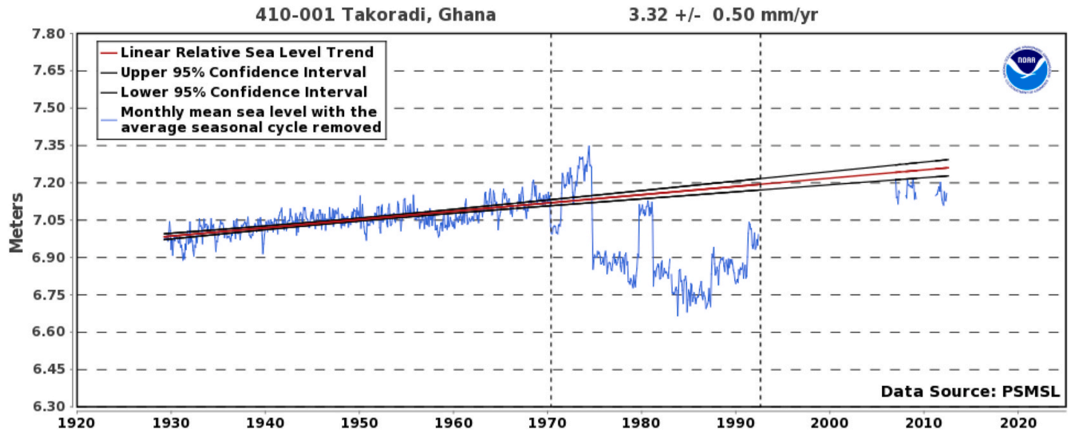

Fig. 10. Tidal gauge data and linear trend model for monthly mean sea level (NOAA, 2013).

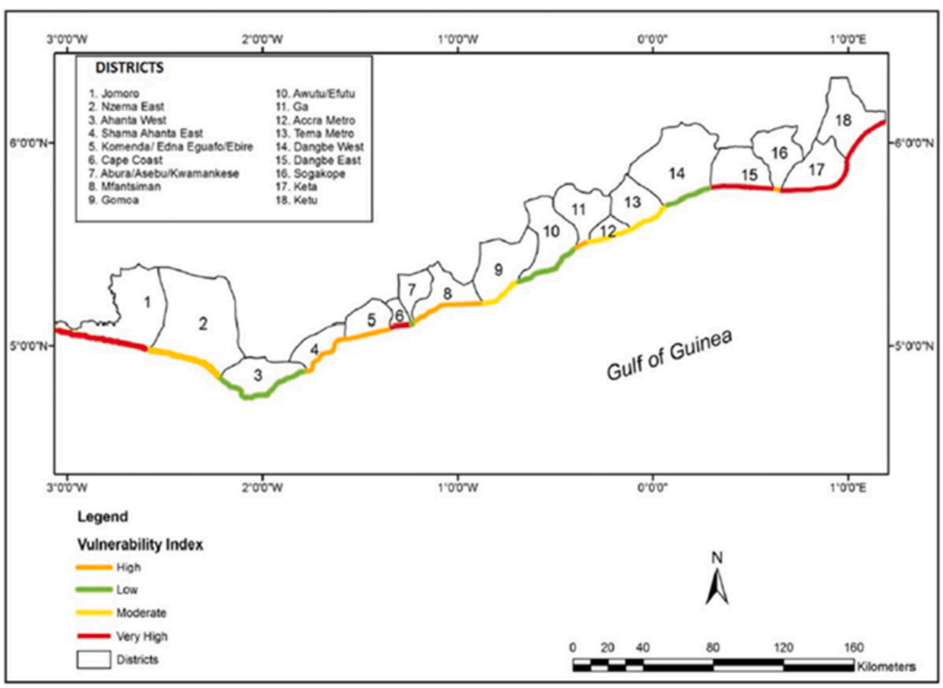

Fig. 11. Ghana's coast showing various degrees of vulnerability and related coastal districts (Boateng et al., 2017).

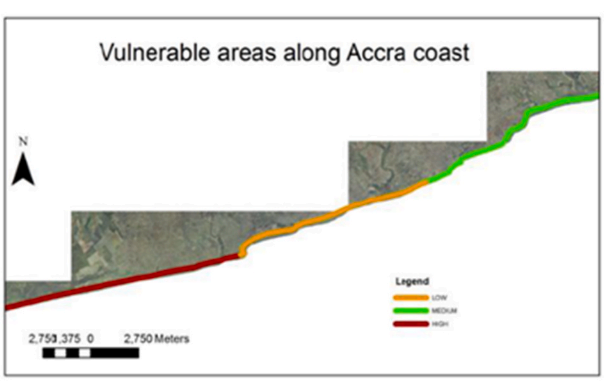

Fig. 12. Degrees of vulnerability along the Accra coast (Appeaning Addo, 2014).

adaptive responses and a holistic management plan which includes the adoption of nature-based solutions such as beach nourishment; relocation of inhabitants in vulnerable areas; and implementation of a setback boundary to minimize coastal development and interference with natural coastal processes.

Yankson et al. (2017) and Babanawo et al. (2022) both adopted the indicator-based flood vulnerability indices approach at the district level—Greater Accra Metropolitan Area (GAMA) and Ketu South Municipality respectively. Both studies deployed GIS and mixed-method research approaches which included Focus Group Discussions (FDGs) and household surveys—300 and 354 households for Yankson et al. (2017) and Babanawo et al. (2022) respectively. Using seven indicators and sub-components, Yankson et al. (2017) aggregated the indicators and their sub-components into the IPCC's three contributing factors of vulnerability—exposure, sensitivity, and adaptive capacity. The indicators were then standardized and transformed into scores ranging from 0 to 1 to compute the composite vulnerability index which ranged from 0.16 to 0.65 for eight (8) communities in the GAMA. Babanawo et al. (2022) followed the same methodology and computed the composite vulnerability index ranging from 0.1 to 0.64 for five (5) communities in the Ketu South Municipality—Blekusu and Salakope being the least and most vulnerable respectively. In the respective study areas, both studies showed appreciable levels of vulnerability to floods. However, only Yankson et al. (2017) incorporated climate variability, dwelling type and measured physical attributes such as elevation, slope, the distance of households to the sea and local drainage which could determine the vulnerability extent of coastal communities to floods. The findings of Babanawo et al. (2022) on the other hand, were generally based on the experiences or perceptions of the respondents which could be highly biased, speculative or prejudicial.

4. Identified knowledge & data gaps and implications for coastal management

4.1. Knowledge gaps

The review of available literature on land subsidence, SLR and coastal vulnerability in Ghana's coastal area brought forth the following knowledge gaps.

- No SLR rate assessments are based on reliable and recent tidal gauge data. The most recent tidal gauge data used in literature was obtained in 1970.
- The absence of ground-validated subsidence study for Ghana's coastal zone and absolute rSLR rate measurements owing to SLR and accurate land deformation measurements.
- No identification and assessment of natural and human-induced factors driving coastal land subsidence in Ghana.
- The non-availability of a comprehensive coastal vulnerability assessment study along Ghana's coast that incorporates measured subsidence values as an input variable.
- The non-existing studies on the respective share of global climate change and coastal land subsidence in an attempt to understand the complexity underpinning the periodic flooding and erosion incidences along some sections of Ghana's coast, and how subsidence could be exacerbating the magnitude and frequency of climate change-driven coastal hazards and vice versa.

4.2. Implications for coastal management

In an attempt to understand the complexities underpinning the surging trend in coastal hazards along Ghana's coast, the knowledge and data gaps identified would likely impair the effective implementation of coastal management strategies aimed at reducing impacts on life and property. Non-existing or inadequate data and knowledge on the aforementioned gaps would significantly obscure a holistic understanding of the processes driving coastal hazards along Ghana's coast, and prevent the adoption of efficient management or mitigation strategies. This review offers a new perspective—especially within Ghana's context—of the potential that coastal processes such as land subsidence–with little to no attention—have in exacerbating coastal hazards and vulnerability. Therefore, it buttresses the need to critically assess the knowledge and data gaps and offer solutions to stall direr ramifications in the future should the gaps persist.

SLR estimates from tidal gauges provide ground validation for remotely-sensed altimetry and offer historic-to-present dataset options. However, the discrepancies or gaps in Ghana's tidal gauge SLR datasets has truncated data for over forty years which would have otherwise provided long-term historic dataset and localized baselines for multi-temporal projections. Studies such as Church et al. (2004), have reconstructed tidal gauge datasets to fill up data voids, however, these estimations may be far-fetched reflections of actual trends and may have implications for management strategies that use them. It is therefore essential to continuously obtain SLR data for accurate rate estimations. With the advent of new methodologies, it is worth noting that coastal altimetry and video camera collection systems have shown promise in supplementing tidal gauge data, enabling more accurate measurements of sea level, as shown by Angnuureng et al. (2022) and Abessolo et al. (2023). A combination of these multiple measurement techniques would, however, provide a comprehensive understanding of sea level dynamics, thus enabling more effective decision-making in coastal management.

Knowledge gaps on coastal land subsidence could also be detrimental to coastal vulnerability and inhabitants therein. Empirical evidence is provided by several findings where subsidence rates are far outpacing SLR rates (Chaussard et al., 2013; Erban et al., 2014; Minderhoud et al., 2017; Wu et al., 2022). By closely monitoring coastal land subsidence, scientists, engineers, and policymakers can make informed decisions to mitigate risks, protect communities and infrastructure, and ensure the sustainable development of coastal regions in the face of changing environmental conditions. Identifying its drivers helps direct efforts and ensures effective monitoring of the most predominant drivers. This will set benchmarks and provide readily available data required for future deltaic studies, trend analysis and models that will allow the setup of alert warning systems or forecasts in response to coastal hazards. Additionally, it will ensure that interventions rolled out are long-lasting, backed by science and data, and tailor-made to an area's specific vulnerability needs rather than adopting a panacea approach to several issues. This, therefore, accentuates the need to comprehensively assess subsidence, its potential drivers and its close association with climate change, especially along low-lying coastal zones that are frequently plagued with coastal hazards. Excluding coastal subsidence and its related attributes from coastal management strategies along Ghana's coast will therefore portend their inefficiency and subsequent failure.

5. Data requisites for rSLR projections

In predicting rSLR, adequate data is needed to build a numerical model to simulate land subsidence and to define process-based projections of subsidence according to different scenarios and updates of rSLR projections. An in-depth analysis of rSLR along Ghana's coast, to understand drivers and processes, will require a database on ground-surface (elevation, subsidence), subsurface data (geology, hydrogeology, geomechanics), and hydrological information (piezometric head, groundwater withdrawals). Elevation data have been obtained from academic field surveys; survey consultants of the West African Gas Pipeline Project; and the Volta River Authority, operators of Ghana's hydroelectric dam shown in Fig. 13 below—along Ghana's eastern coast. Within the framework of the ENGULF research project (AFD, 2022), six of these ground measurements were used for the assessment of different satellite-derived DEMs (Hauser et al., 2023). Although based on a very small number of ground control points, results show that the CoastalDEM (version 2.1) and FABDEM performed above average in absolute (in meters), and relative (profile of elevation) coastal elevation assessment. The impact of using these two DEMs for the assessment of exposure of the Volta delta to rSLR is left for future work. Unfortunately, other data requisites such as hydrographical data on groundwater levels, wellheads, and groundwater consumption are not available after reaching out to relevant institutions such as the Hydrologic Department, Water Resource Commission and the Water Research Institute. Therefore, for the future development of numerical models to simulate land subsidence processes, these data requirements have to be independently sourced.

6. Conclusion

A review of the literature on the three thematic areas, SLR, subsidence and coastal vulnerability in Ghana highlights their interconnectedness in the relevant studies identified in the scoping process. Understanding their magnitude and relationships will ensure a better understanding of the complexities underpinning the occurrence of

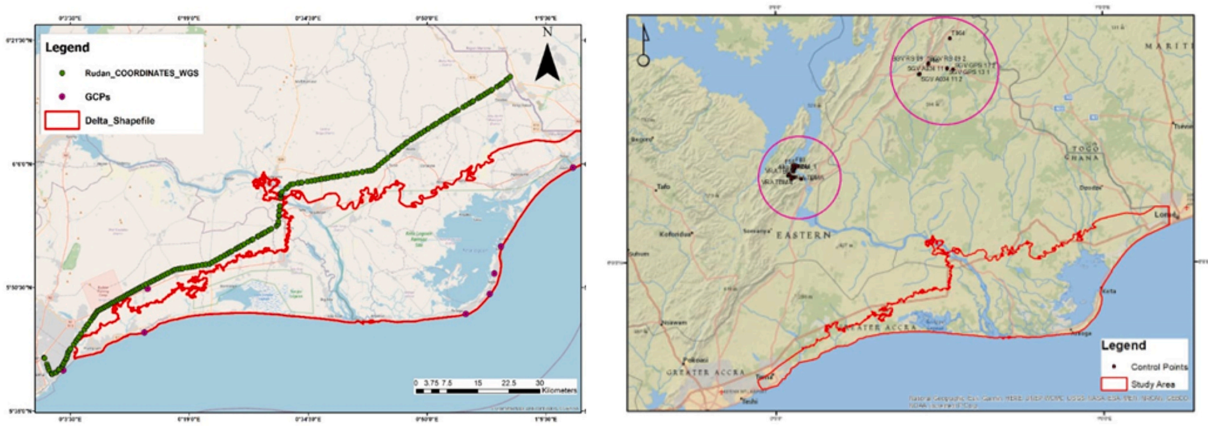

Fig. 13. Geographic locations of multiple elevation measurements along Ghana's eastern coast. The red contour indicates the boundaries of the Volta Delta.

coastal hazards plaguing coastal zones. The results obtained for each thematic area indicate the occurrence of both land subsidence and SLR along Ghana's coastal area—culminating in rSLR. The prevalence of the rSLR poses a serious threat to the biophysical attributes of Ghana's coastal area and the socio-economic livelihoods therein, of which some are already being manifested in incessant coastal flooding, erosion events and a loss of ecosystem services. Despite the threats rSLR poses, the survey findings have revealed a significant understudy of SLR and subsidence in Ghana. The limitations in available literature are that SLR and subsidence assessments were based on unreliable (old) tidal gauge data and unvalidated InSAR assessments respectively. A synthesis of vulnerability assessments also identifies a significant portion of Ghana's coast—eastern and western sections—as vulnerable. Using more recent and reliable tidal data and validated land deformation data will likely reveal relatively higher rSLR rates that reflect the compounding impacts of coastal hazards in recent times, especially on low-lying sandy coasts along Ghana's coastline. This scoping study, therefore, provides insight into rSLR and raises awareness about the need to ascertain its drivers for the effective implementation of a coastal management plan by policy-makers and planners. To avert or minimize the occurrence of devasting coastal impacts, especially on life and livelihood, it is imperative to proactively assess and monitor, over long periods, the general status of coasts while adopting comprehensive efforts directed at understanding the complexities underpinning coastal interactions and subsequent impacts. In attempting to address the identified knowledge and data gaps, this study recommends the set-up of several continuous GPS stations and elevation benchmarks to monitor land deformation; the establishment of long-term and accurate SLR-monitoring tidal stations; employment of advanced InSAR measurements that consider both vertical and horizontal motion components; the mapping of aquifers and routine hydrographical data collection on groundwater levels, wellheads, groundwater consumption and estimating recharge rates.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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