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Vulnerability of Ghana's Coast to Relative Sea-level Rise: A Scoping Review

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Vulnerability of Ghana's Coast to Relative Sea-level Rise: A Scoping Review

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Abstract
Coastal areas are regions of essential value that are home to a myriad of 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 both magnitude and frequency. Predominantly through the recurrence of floods and erosion, Ghana's coast is increasingly becoming susceptible, with huge socio-economic implications considering its environment-dependent economy. Several previous attempts have been made to assess Ghana's coastal vulnerability to comprehend the complexities underpinning the occurrence of these hazards. Most studies blame 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 in many coastal cities worldwide. Drawing on extant literature in Ghana, this scoping study provides an overview of three crucial and interrelated dimensions: sea-level rise, subsidence and coastal vulnerability. We also identify crucial knowledge gaps which impede comprehensive risk assessment of Ghana's coast. The survey findings indicate a significant understudy of these issues 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 combined effects of climate change and subsidence; and huge deficits in available data for numerical modelling of coastal subsidence. A case study of the Volta delta using the PS-InSAR technique and Global Positioning System (GPS) surveys is also provided. It establishes the occurrence of subsidence. Interferograms of Sentinel-1 data from 2016 to 2020 indicated deformation rates ranging from -9.16 mm/yr to 1.77 mm/yr, with a majority of persistent scatterers (99.81%) showing land subsidence. Guided by the identified knowledge and data gaps and the need to mitigate impacts, the study recommends a thorough assessment of relative sea-level rise and coastal vulnerability; a continuous and long-term monitoring framework for drivers of change; a review of coastal management strategies; and the establishment of continuous GPS stations, tidal stations, elevation benchmarks.

Keywords
Land subsidence, relative sea-level rise, coastal vulnerability, InSAR, Ghana

Original version
English

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Résumé

Les zones côtières sont des régions essentielles offrant une myriade de services. Cependant, la croissance démographique et le changement climatique, avec leurs effets en cascade, ont eu de profondes répercussions sur leur topographie et leur évolution. Aussi, de nombreuses régions côtières, et celle du Ghana ne fait pas exception, font face à des risques d'une ampleur et fréquence croissantes. La côte ghanéenne devient de plus en plus vulnérable, principalement en raison de la récurrence des inondations et de l'érosion, ce qui a d'énormes implications socio-économiques pour le pays, dont l'économie est tributaire de l'environnement. Plusieurs travaux antérieurs ont donc cherché à évaluer cette vulnérabilité, afin de comprendre les complexités sous-jacentes à l'émergence de ces risques. La plupart des études mettent en cause l'élévation globale du niveau marin, mais la subsidence côtière pourrait également avoir des impacts significatifs. En effet, la subsidence est une composante majeure de l'élévation relative du niveau de la mer dans de nombreuses villes côtières à travers le monde. S'appuyant sur la littérature existante au Ghana, notre étude de cadrage fournit un aperçu des connaissances actuelles sur trois aspects essentiels et intriqués : montée du niveau marin, subsidence et vulnérabilité côtière. Nous identifions également les lacunes cruciales qui empêchent une évaluation complète des risques sur la côte ghanéenne. Les résultats montrent que ces problématiques sont sous-étudiées, malgré la menace potentielle qu'elles représentent pour la côte ghanéenne. Notre étude met en lumière l'absence d'étude sur la subsidence validée par des données de terrain ; la non-identification des potentiels moteurs locaux de la subsidence ; l'absence d'évaluation de la vulnérabilité côtière incluant la subsidence ; l'absence d'études sur les effets combinés du changement climatique et de la subsidence ; et d'importantes lacunes dans les données disponibles pour modéliser la subsidence côtière. Une étude de cas pour le delta de la Volta, utilisant la technique PS-InSAR et des relevés du système de positionnement global (GPS) est également fournie et montre la présence de subsidence. Les interférogrammes des données Sentinel-1 de 2016 à 2020 indiquent des taux de déformation allant de -9,16 mm/an à 1,77 mm/an, avec une majorité de diffuseurs persistants (99.81 %) montrant une perte d'élévation. Compte tenu des lacunes identifiées en matière de connaissances et de données et de la nécessité d'atténuer les impacts, nous recommandons une évaluation approfondie de la hausse relative du niveau marin et de la vulnérabilité côtière, la mise en place d'une surveillance continue et à long terme des facteurs de changement, un examen des stratégies de gestion côtière et la mise en place de stations GPS, de stations marégraphiques et de repères d'élévation en continu.

Mots-clefs

Subsience, montée relative du niveau marin, vulnérabilité côtière, InSAR, Ghana, revue

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Introduction

General context of the study

The coastline of the Gulf of Guinea is lowly elevated and is particularly vulnerable to erosion and sea-level rise (PRLEC-UEMOA, 2010). Many capital cities are located along the coast, including megacities with millions of inhabitants such as Lagos, Abidjan and Accra. Population projections for these cities suggest a staggering demographical increase in the coming decades (United Nations, 2018). In Ghana, Benin, Togo, and Nigeria, most of the economic activities are located within the coastal zone. The entire coastline is currently experiencing alarming coastal erosion rates, up to several meters per year (e.g. Croitoru *et al.*, 2019). The main causes of these phenomena are generally linked to human activities: sand extraction, decrease in sedimentary input from rivers due to upstream dams, port developments or even coastal protection structures that accentuate erosion downstream (Abessolo et al., 2021). As a result, the problem is well-studied in the region and various programs aim to put in place coastal protection measures, such as the West African Coastal Areas Management Program (WACA) from the World Bank.

On the other hand, studies of impacts and vulnerability to sea-level rise (SLR) in the context of climate change appear to be more limited. One can find in the literature various studies conducted on a very local scale (e.g. Appeaning Addo & Adeyemi (2013); Idowu & Home (2015); Dossou & Glehouenou-Dossou (2007)) or sub-regional (e.g. Onwuteaka (2014) and Musa (2018) for the Niger Delta). Some global studies also give orders of magnitude on the risks of submersion for the countries of the Gulf of Guinea (Dasgupta *et al.* (2007); Brown *et al.* (2009); Kulp & Strauss (2019)). However, this work suffers from important limitations, linked among other things to the use of inaccurate satellite altimetry data. Recent advances in global elevation data (Hooijer & Verminnen, 2021; Hawker *et al.*, 2022) provide exciting opportunities to re-evaluate coastal elevation and assess potential sea-level rise vulnerability of this fast-developing region.

In addition, new research shows that while sea level is rising as a result of global warming, the majority (51-70%) of the present-day *relative* sea-level rise (rSLR) experienced by people worldwide is caused by land and coastal city sinking, i.e. land subsidence (Nicholls *et al.*, 2021). Globally coastal land subsidence is critically under-quantified and the Gulf of Guinea region, where data on subsidence is completely lacking (Herrera-Garcia *et al.*, 2021), is no exception to this. This underlines the importance of including vertical land motion component to climate change-driven SLR to assess the complete effect of rSLR.

In this context, the ENGULF[1] (Coastal land subsidENce in the GULF of Guinea) research program aims at improving the assessment of exposure to relative sea-level rise along the Gulf of Guinea's coastline by providing new data and knowledge on coastal subsidence in the area. Preliminary work of this program was conducted with three main objectives: 1) Improving the coastal elevation assessment and assessing current scientific literature on coastal vulnerability for the Gulf of Guinea region; 2) Identifying the main knowledge gaps and critical geographical areas; 3) Assessing current knowledge on coastal land subsidence in Nigeria and Ghana. This study presents the results of the Ghana case while the regional assessment and the Nigeria case are presented in Hauser *et al.* (2023) and Ikuemonisan *et al.* (2023) respectively.

Coastlines facing sea-level rise

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 that are 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,

[1] https://www.afd.fr/en/carte-des-projets/engulf-program-assessing-exposure-relative-sea-level-rise-along-gulf-guinea

2005). Coastal regions yield 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 global SLR 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).

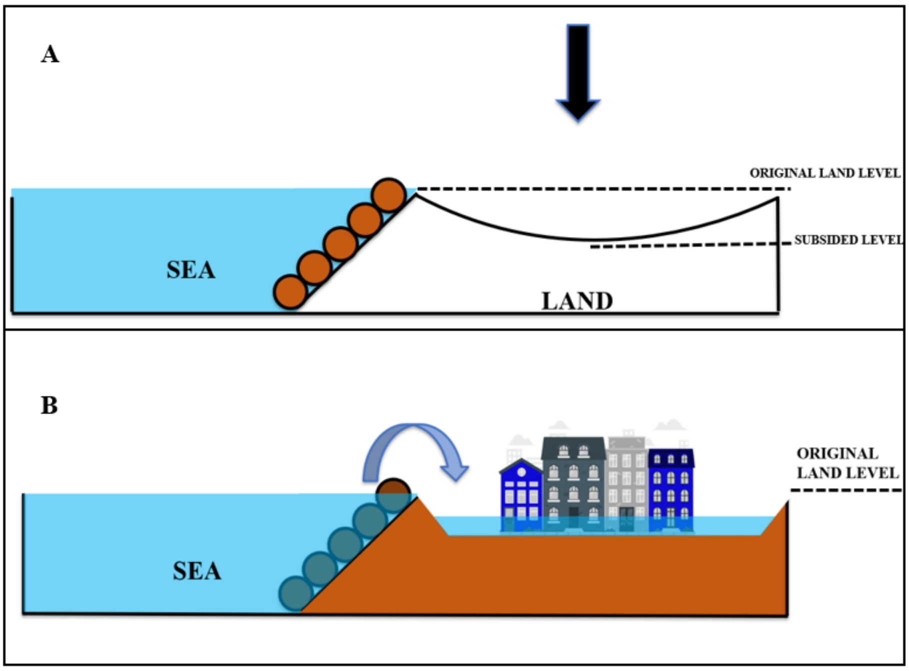
Sea-level rise poses a hazard to coastal ecosystems, diminishes ecological services, and may eventually result in significant socioeconomic changes, particularly in low-lying coastal ecosystems that are particularly sensitive (Carnero-Bravo *et al.*, 2018).

Land subsidence: an amplifier of sea-level rise

Although climate change plays a significant role in increasing sea-level (IPCC, 2021), it may be locally amplified by coastal land subsidence (Figure 1.a) 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).

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) 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), as it 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 (Figure 1.b), 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).

Figure 1: ***Schematic illustration of (A) coastal subsidence and (B) flooding in subsided coastal areas with coastal defence (brown disks).***



Credit: Selasi Yao Avornyo, 2022.

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 SLR, 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.

Ghana's coastlines facing coastal hazards

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.*, 2018b), 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).

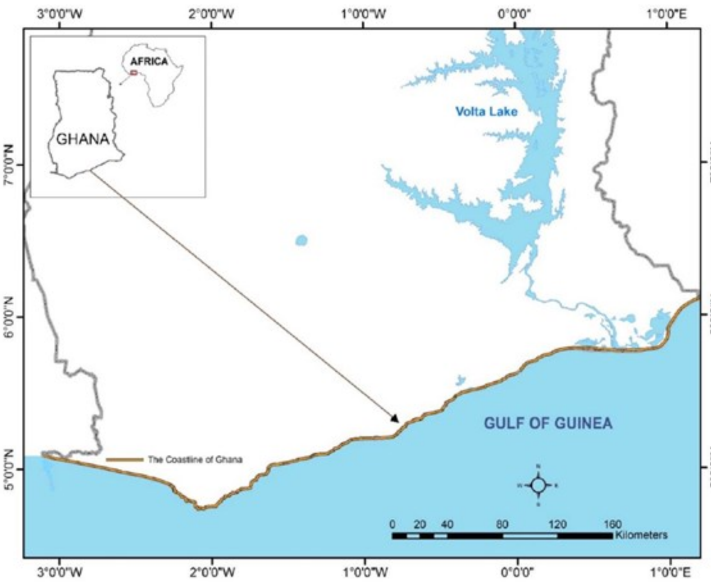
Over several years, numerous efforts have been undertaken to develop methods and policies for assessing the vulnerability of coastal regions to climate change and other associated factors (Rygel *et al*., 2006; Torresan *et al*., 2012; Appeaning Addo, 2013; Wolters and Kuenzer, 2015; Wu *et al*., 2016). Understanding vulnerability enables coastal scientists and policy-makers to 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), SLR (Sagoe-Addy and Appeaning Addo, 2013), energetic swell waves (Almar *et al*., 2015), coastal erosion and its management (Appeaning Addo, 2015), population change and groundwater extraction leading to salinization (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 that influences the vulnerability of Ghana's coast and to carry out a local case study to determine the rSLR regime. 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.

1. Study area

The coast of Ghana lies along the Gulf of Guinea in West Africa (Figure 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, 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).

Figure 2 : The coastline of Ghana on the West African coast and the Gulf of Guinea



Source: after Evadzi *et al.* (2017)

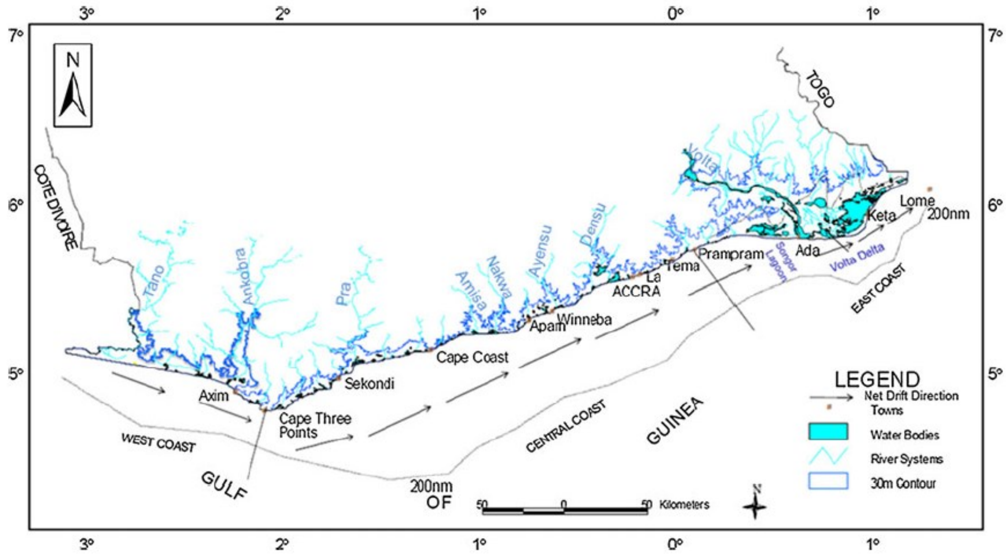
The coastline lies along an Afro-trailing edge-type continental margin (Inman and Nordstrom, 1971) with over 90 coastal lagoons (Armah and Amlalo, 1998). Most of these are very small, less than 5 km^2 in surface area. The largest is the Keta Lagoon and with its associated lagoons namely, Angaw and Avu, 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 contained 25% (Amlalo, 2006) (4.7 million) of the people in 2000 (2000 population census). Since then the coastal population in the four coastal regions has further increased: 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 conducted by the Ghana Statistical Service (2021). The coastal zone houses around 80% of Ghana's industrial firms (Amlalo, 2006).

The coastal zone extends approximately 10 km inland and is enclosed by the 30 m elevation contour (Armah and Amlalo, 1998; Boateng, 2012b) as shown in Figure 3. The gulf is characterized by varying annual patterns of coastal upwelling and by an eastward-flowing current otherwise known as the Guinea Current (Figure 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).

Previous studies by Ly (1980) divided the coastline into three zones based on geomorphic characterization (Figure 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.

Figure 3 : Drainage, longshore current drift, 30 m elevation contour and divisions of Ghana's coastline.



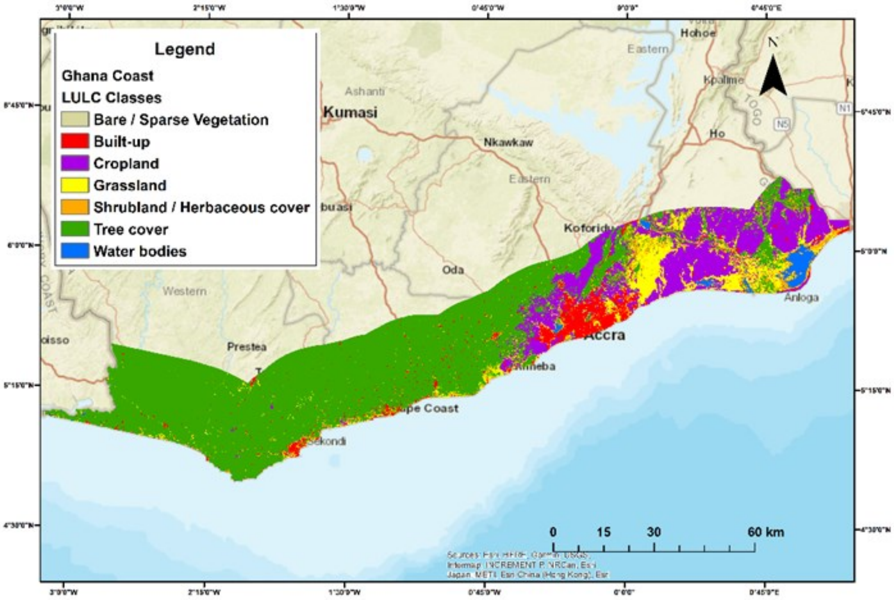
Source: after Boateng (2012b).

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) in Figure 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, 2012a; 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).

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



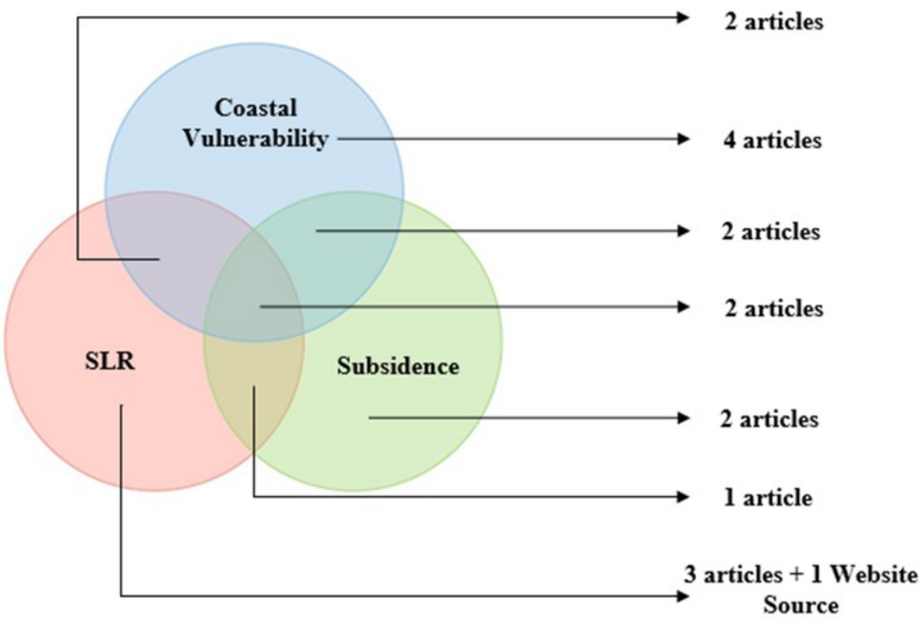
Source: FAO (2022).

2. An overview of rSLR and vulnerability assessments along Ghana's coast

2.1. 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 and general search in Google Web Search. 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 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 land subsidence and SLR, especially, 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 source (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 Figure 5.

Figure 5 : Venn diagram of the literature study.



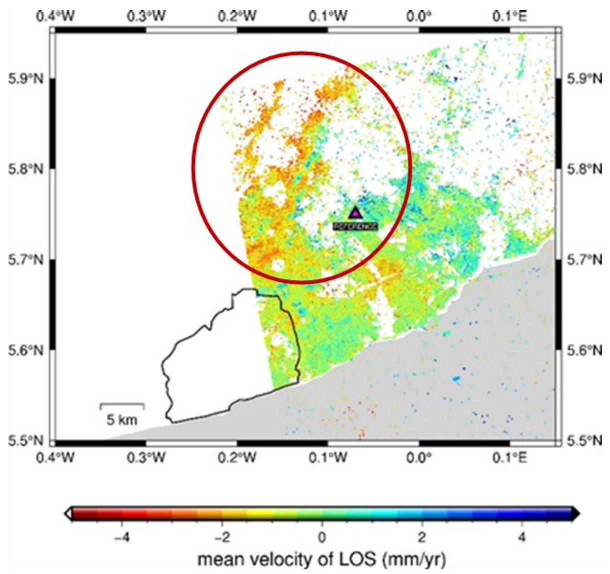
A Venn diagram indicating the articles obtained from various online database searches using the keywords "SLR", "Subsidence" and "Coastal Vulnerability". Only articles on Ghana were considered.

2.2. 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 (Figure 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 Figure 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.

Figure 6 : Mean line-of-sight (LOS) velocity distributions (mm/yr) for portions of the Greater Accra Region, Ghana between 2015 and 2020



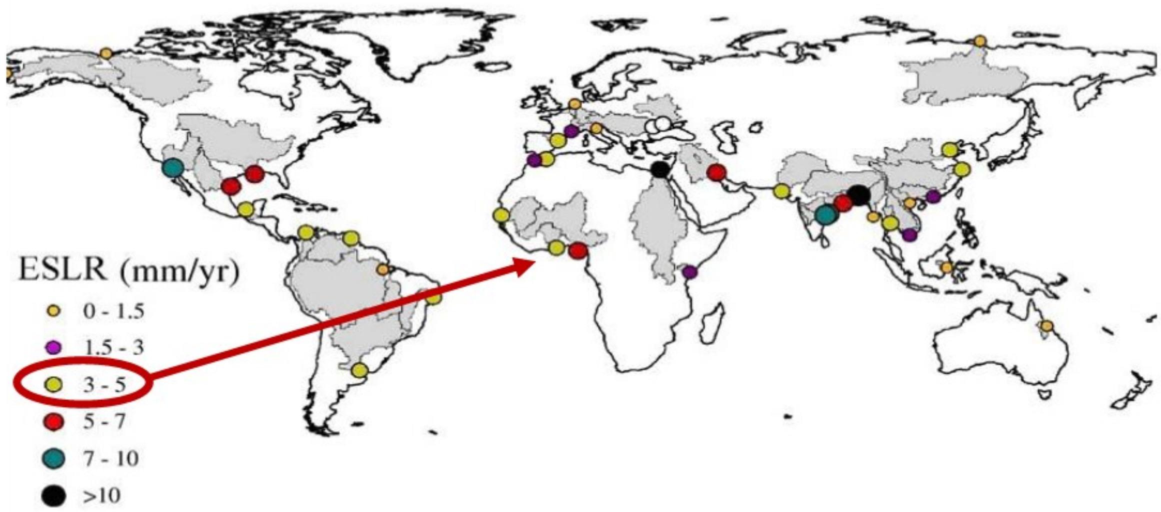
Data: Sentinel-1 A/B. The black contour line is the boundary of the Accra Metropolitan District. Source: Wu *et al.* (2022).

2.3. Relative sea-level rise 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 *et al.*, 2018b) has been alluded mostly to eustatic or steric SLR 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. An attempt was made to incorporate both SLR and land subsidence in the 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 *et al.* (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 to 5 mm/yr (Figure 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.

Figure 7 : Global distribution of effective sea-level rise (ESLR) under baseline conditions for 40 deltas

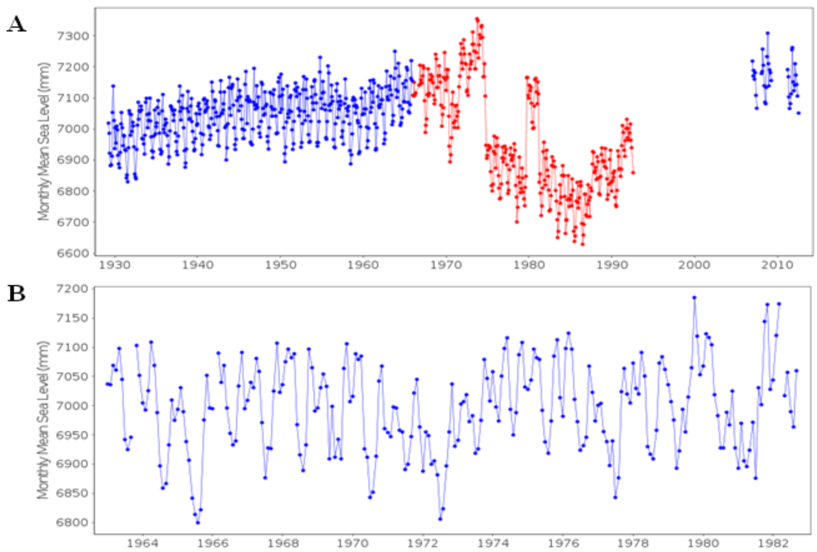


The arrow and ellipse indicate the location of Ghana's Volta Delta and the estimated range of ESLR respectively.
The upstream drainage basin for each delta is highlighted in grey (Modified after Ericson *et al.* (2006)).

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 to 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 relative 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 (Figure 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 (Figure 8.a). 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 Figure 8.a. At the Tema port (Figure 8.b), 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.

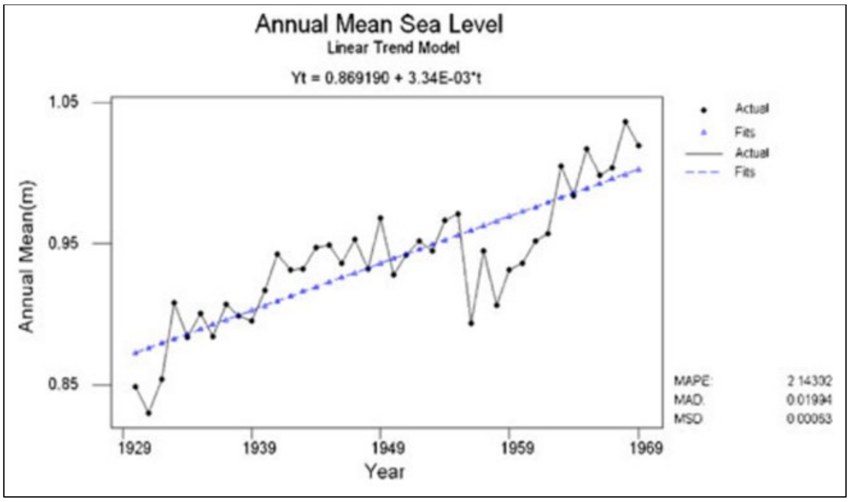
Figure 8 : Monthly tidal gauge data plot of sea-level at Takoradi and Tema ports.



(A) Takoradi port from 1929 to 2012 and (B) Tema port from 1963 to 1982, Ghana (PSMSL, 1982; 2013).

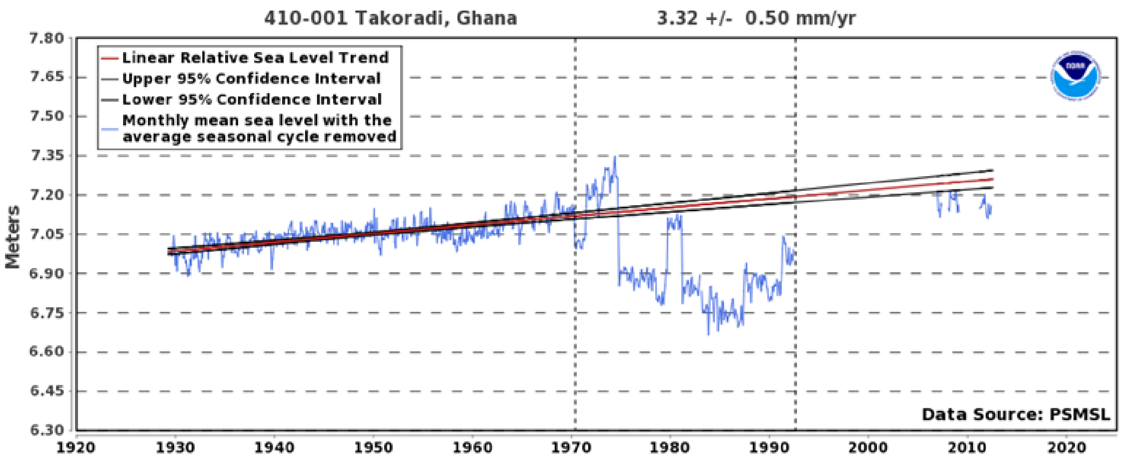
Using annual means from 1930 to 1969, Sagoe-Addy and Appeaning Addo (2013) estimated a rate of 3.34 mm/yr at a 95 % confidence interval using a linear regression model (Figure 9). NOAA (2013) estimated 3.32 mm/yr with a 95% confidence interval of +/- 0.5 mm/yr based on monthly mean sea-level data from 1929 to 1969 (Figure 10). Boateng *et al.* (2017) estimated a relative 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.

Figure 9 : Sea-level gauge data, annual mean, at Takoradi port, 1930-1969.



Sea-level gauge data and linear trend model (3.34 mm/yr) for annual relative mean sea-level rise from 1930 to 1969 at measured at Takoradi port (Sagoe-Addy and Appeaning Addo, 2013).

Figure 10 : Tidal gauge data, monthly mean, at Takoradi port, 1929-1969.



Tidal gauge data and linear trend model (3.32 mm/yr) for monthly relative mean sea-level at Takoradi from 1929 to 1969 (NOAA, 2013)

2.4. Coastal Vulnerability Assessments of Ghana's Coast

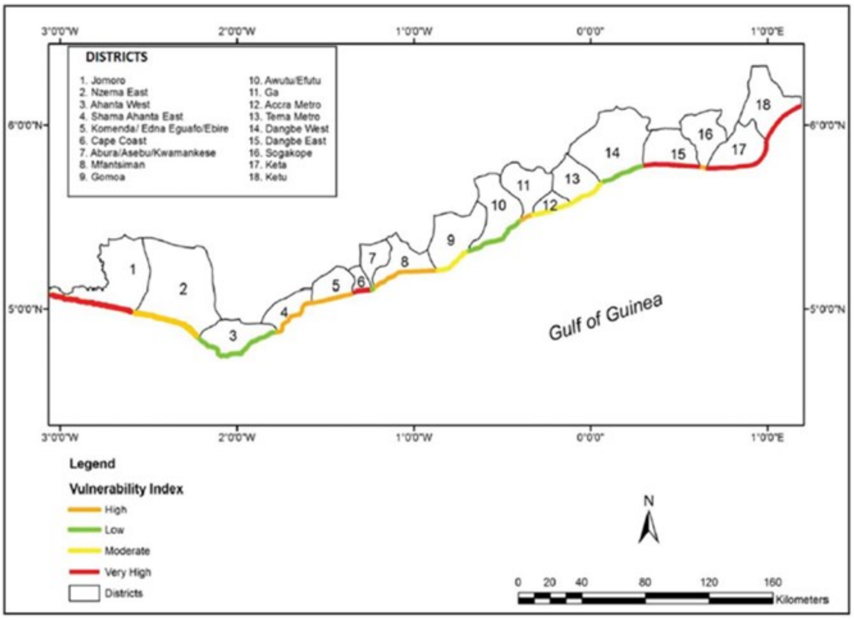
The coastlines—and by extension, coastal zones—undergo dynamic changes and sporadic damage as a result of episodic occurrences caused by riverine and coastal processes (Nguyen and Takewaka, 2020). The most vulnerable areas within the coastal zone are the low-lying coastal communities and ecosystems. 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 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 (Figure 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 to increasing rSLR (Figure 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.

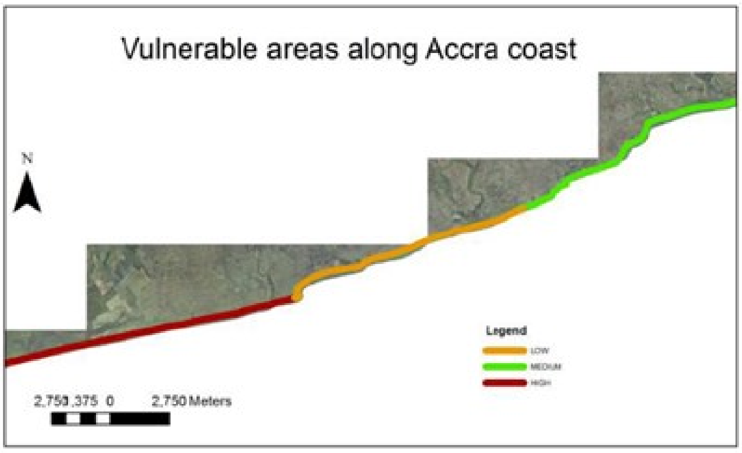
Wu *et al.* (2022) reported an InSAR-measured maximum subsidence rate of >4 mm/yr in Accra (2015 and 2020) compared to the subsidence rates of 2 mm/yr and ≤1 mm/yr adopted by Appeaning Addo (2014) and Boateng *et al.* (2017) respectively. This could suggest a CVI underestimation of a more vulnerable coastline in their respective studies or an increase in contemporary subsidence. 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 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.

Figure 11 : Ghana's coast showing various degrees of vulnerability and related coastal districts.



Source: Boateng *et al.* (2017).

Figure 12: Degrees of vulnerability along the Accra coast.



Source: Appeaning Addo (2014).

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 0.65 to 0.16 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.

3. A case study: InSAR study of Ghana's Volta Delta

The Volta delta is a dominant feature on the eastern coast of Ghana that has influenced the hydrodynamics and sediment regime over several decades (Boateng, 2009). Geologically, the study area has soft quaternary rocks and unconsolidated sediments of clay, loose sand and gravel deposits (Jayson-Quashigah *et al.*, 2013). The Delta comprises a diverse array of ecosystems such as barriers or lagoons, wetlands, shelf zones, mangroves, and marshes. Unfortunately, the diverse array of ecosystems is being threatened by natural and human-induced pressures (Linham and Nicholls, 2010).

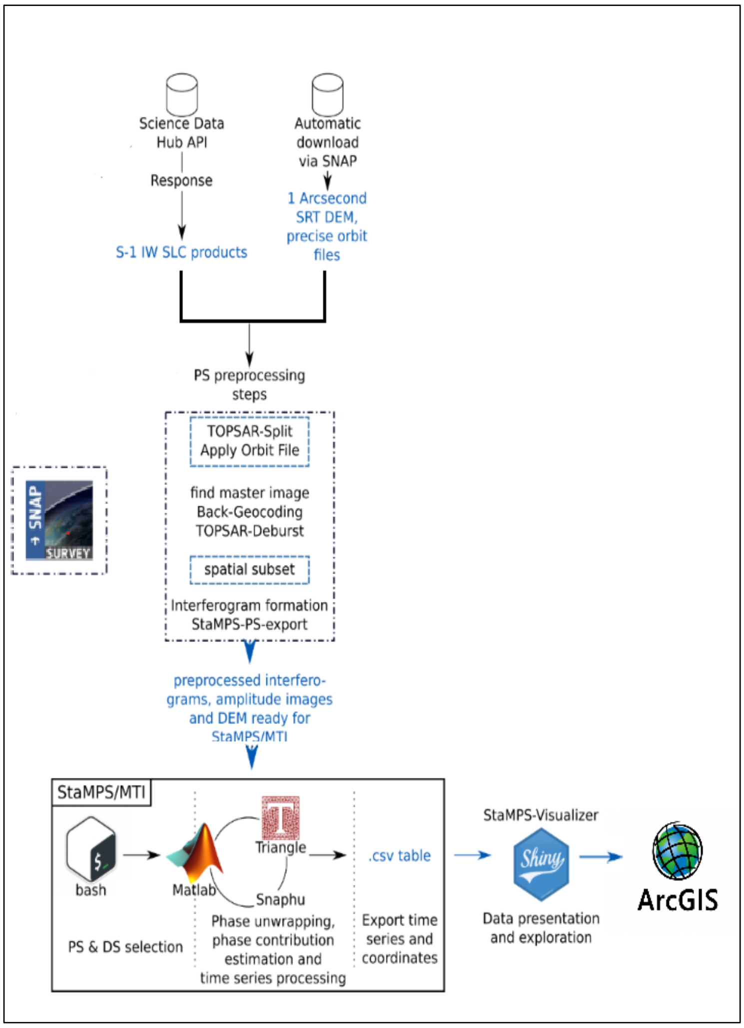
Globally, the vulnerability or exposure of deltas to storm surge, SLR, salinization, flooding and coastal erosion have been pegged to increase at alarming rates (Tessler *et al.*, 2015) with degrading impacts on coastal morphodynamics, ecosystems and livability. In recent times, the Volta delta has experienced relatively higher rates of storm surges, flooding or inundation incidences dotted along its coastline (Appeaning Addo *et al.*, 2018b). The region is currently experiencing increased storm surge activities and erosion (Appeaning Addo, 2015; Akpabli, 2017). According to the Shuttle Radar Topographic Mission (SRTM) dataset, about 88% of the Volta delta's area is below 5 m elevation (landward limits defined in Appeaning Addo *et al.* (2018a)) and stands the risk of being completely flooded by 2300, in the absence of climate change mitigation (Brown *et al.*, 2018). This is the case for many deltas across the globe, such as the Mekong delta (Erban, *et al.*, 2014; Minderhoud *et al.*, 2015) and the Ganges-Brahmaputra delta (Syvitski *et al.*, 2009), where subsidence has been identified as a major amplifier of rSLR. The case study, therefore, aims to assess altimetric changes in Ghana's Volta delta, by establishing the subsidence regime and measuring this against changing sea-levels to improve the understanding of the frequent flooding and erosion events in the region.

3.1. Data and method of InSAR processing and GPS calibration

The satellite data used are Sentinel-1 (S1) Single Look Complex (SLC) Synthetic Aperture Radar (SAR) images which are freely accessible on the Copernicus Science Hub online platform—356 SAR images in total along three (3) swaths from 2016-2020. The InSAR technique employed for this study was the Persistent Scatterer Interferometry (PSI) technique based on the Permanent Scatterer algorithm by Ferretti *et al.*, (2001) and following the workflow of Höser (2018) and Cian *et al.* (2019) as shown in Figure 13. The PSI analysis was done using the Sentinel Application Platform (SNAP) software, Version 8 and the Stanford Method for Persistent Scatterers (StaMPS)/Multi-Temporal InSAR open-source toolbox, Version 4.1b (Hooper *et al.*, 2012).

InSAR measures relative displacement between a point of interest and a selected reference point or value, hence requiring the use of a stable reference point. To select the reference point, the entire process was run using the area mean as a reference value to identify the most relatively stable persistent scatterers (PS). The process was re-run using the mean value of the most stable PS velocity and all other PS velocities within a 100 m radius as the reference value. Global Positioning System (GPS) survey on seven (7) Ground Control Points (GCPs) was employed as a geodetic method to calibrate the results obtained from the InSAR processing technique (Teatini *et al.* 2012; Amato *et al.*, 2020). The GPS-derived deformation rates were estimated from two measurement timestamps, 2009 and 2021, on the same set of GCPs. In the absence of PSs at exact geolocations of the GCPs, the InSAR-derived velocities within a 100-metre radius about each GCP were averaged and compared with the GPS deformation rates to estimate the errors. The InSAR velocities were post-processed and calibrated using the error margin obtained from GPS measurements at all seven GCPs.

Figure 13: Workflow for PSI pre-processing and processing steps along with software packages and interfaces.



Adopted and modified from Höser (2018).

3.2. Results of InSAR and GPS Analysis

All GCP locations indicated subsiding deformation trends, the highest being recorded at Keta at a rate of -5.36 mm/yr followed by Tegbi and Woe, which recorded estimates of -3.90 mm/yr and -2.81 mm/yr respectively. The least, however, was recorded at the Great Ningo GCP (-0.05 mm/yr) as shown in Table 1. The table also indicates the number of PSs found in each radius, InSAR-derived velocities, and the total error margin (±2.75) between the two datasets—GPS and InSAR rates.

Table 1 : GPS-derived deformation rates for each GCP used for InSAR error estimation for the case study.

Town	Elevation (m) (06/2009)	Elevation (m) (04/2021)	GCP Deformation Rates (mm/yr)	100 m Buffer about Each GCP		
				PS Number	InSAR Mean (mm/yr)	Error (mm/yr)
Great Ningo*	5.2292	5.2286	-0.05	-	-	
Anloga*	3.4324	3.4000	-2.70	-	-	
Woe	1.5613	1.5276	-2.81	28	-0.00288	
Tegbi	0.9964	0.9847	-3.90	11	-0.2954	±2.75
Keta	2.8950	2.8307	-5.36	5	-2.94928	
Denu*	3.2872	3.2610	-2.18	-	-	
Aflao	2.9572	2.9334	-1.98	20	0.20691	

The error is estimated as the average absolute difference between the GCP deformation rates and the mean InSAR velocities within a 100-m radius of each GCP (Tomás *et al.*, 2014)

* The GCP buffers that did not contain any PSs.

The number of persistent scatterers (PS) generated from the PSInSAR methodology was 119,477 in total with an areal PS density of 66.52 PS/km^2 — excluding the water-covered surfaces. The relatively low PS density obtained was due to decorrelation caused by the areal dominance of vegetation (Teatini *et al.*, 2012), which is characteristic of the Volta delta. Along the Sentinel-1 line of sight (LOS), the initial PS deformation velocities indicated uplifting rates as high as 4.53 mm/yr. The delivery of sediment load to the delta has reduced by 92.32% post-construction of the Akosombo Dam in 1964 (Amenuvor *et al.*, 2020), and with no reported estimates of neotectonics in the Delta, an uplifting rate of 4.53 mm/yr for a five-year dataset can be considered imprecise, hence requiring calibration. The calibration with the GPS-InSAR error margin indicated deformation velocities that ranged from subsiding rates of -9.16 mm/yr to uplifting rates of 1.77 mm/yr (Figure 14) with 99.81% of PSs indicating subsidence.

The proximity of subsiding and uplifting PSs in some locations can be attributed to low population density and patchy distribution of built-up areas, which could be experiencing subsidence, and usually interspaced with uninhabited or undeveloped areas that could be stable or uplifting. The subsiding PSs were mostly found along the coast with some dotted in the central sections of the Delta. Areas mostly located within the floodplains of the two dominant lagoons (Keta and Songor Lagoons) and the lower delta plain, recorded subsiding velocities exceeding -8 mm/yr. The coastal areas of the Delta are the economic hub and relatively more populated. A minor increase in subsidence-related inundation extents can produce cascading impacts that may be direr when compared to only SLR scenarios. Based on the dominance of PSs with subsiding rates, the Volta Delta is classified as a subsiding delta. Figure 15 shows the time series plot for the top twenty (20) most subsiding locations within the study area

Figure 14 : Map view of the line of sight (LOS) mean velocities of PSs in the Volta delta.

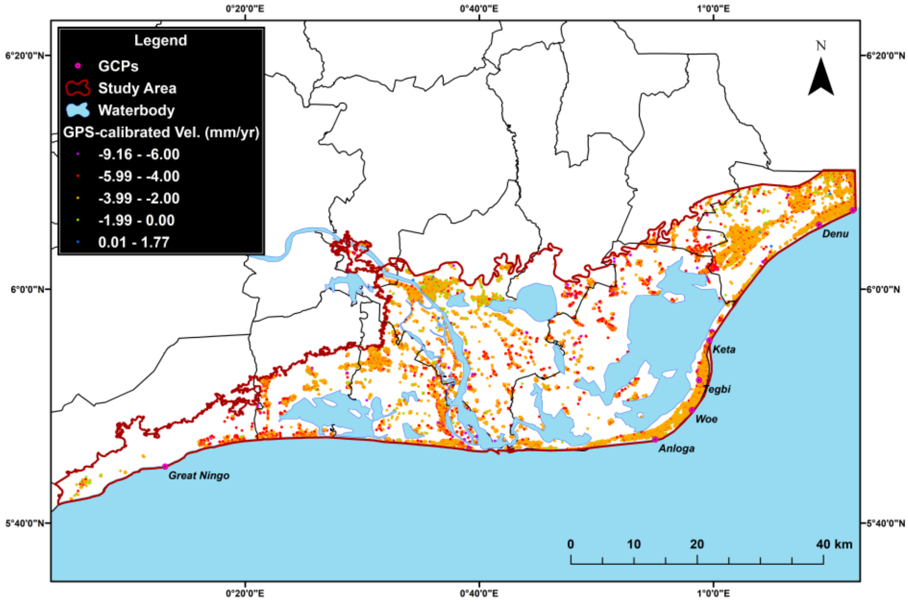
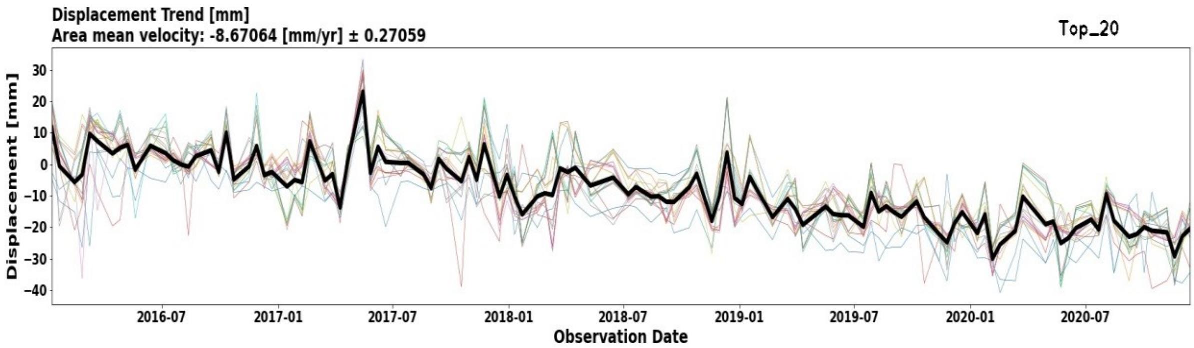


Figure 15 : Deformation trend plot for the top 20 locations with the highest subsiding PS velocities.



4. Identified knowledge gaps and data availability for future study

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:

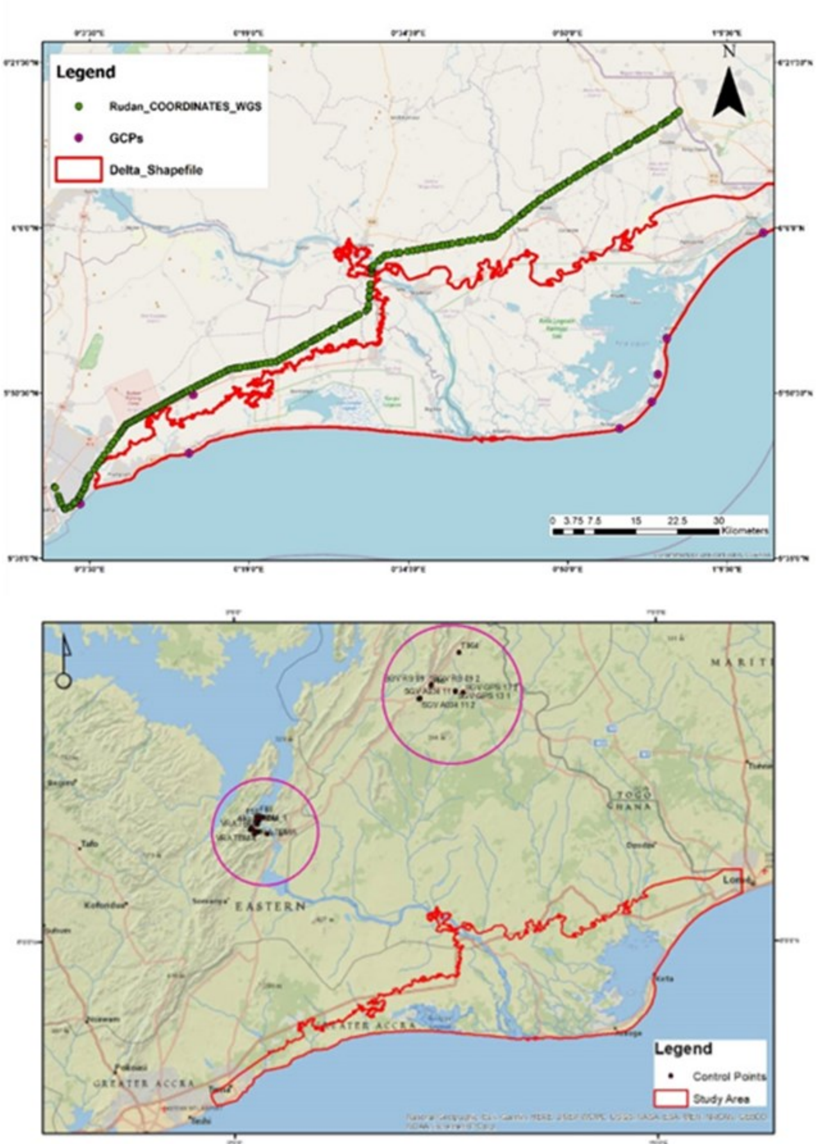
- No SLR rate assessments are based on reliable and recent tidal gauge data. The most recent tidal gauge data used in literature was obtained in 1970.
- The absence of ground-validated subsidence data for Ghana's coastal zone and absolute rSLR rate measurements owing to SLR and accurate land deformation measurements.
- No identification and assessment of natural and human-induced factors driving coastal land subsidence in Ghana.
- The absence of a comprehensive coastal vulnerability assessment study along Ghana's coast that incorporates measured subsidence values as an input variable.
- The absence of studies on the respective share of global climate change and coastal land subsidence in an attempt to understand the complexity underpinning the periodic coastal 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. Data availability for future study

Assessing the exposure of the Volta Delta to rSLR requires good-quality elevation data. 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 Figure 16 below. Within the framework of the ENGULF research project, six of these ground measurements were also used for the assessment of different satellite-derived digital elevation models (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 assessment of exposure of the Volta delta to rSLR using these two DEMs is left for future work.

Unfortunately, other data requisites for in-depth analysis of coastal land subsidence 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, such data requirements would have to be independently sourced.

Figure 16: Geographic locations of multiple elevation measurements along Ghana's eastern coast. The red contour indicates the boundaries of the Volta delta.



5. 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 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 policymakers 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 rate.

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Abbreviations

ESA	European Space Agency
GCP	Ground control points
GPS	Global Positioning System
InSAR	Interferometric synthetic aperture radar
PS	Persistent scatterers
RSLR	Relative sea-level rise
SLR	Sea-level rise

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