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Mapping vulnerability and risk of Ghana's coastline to sea level rise

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Abstract

Coastal erosion and flooding are major threats to coastal dwellers, and the situation is predicted to worsen as a result of the impacts of climate change and associated sea level rise. In order to identify the level of vulnerability of various sections of Ghana's coastline for planning and future hazard management, a coastal vulnerability index approach was adopted for the creation of the relative vulnerability map. The coastal vulnerability variables used include geomorphology, coastal elevation, geology, local subsidence, sea level rise, shoreline change rates, mean tidal range, mean wave height and population density of the coastal areas. Risk factors were assigned to the various variables and all the factors were combined to calculate the coastal vulnerability for the coastal front of each administrative district along the coast. The outcome was used to produce a vulnerability index map of coastal districts in Ghana. The results revealed that parts of the central coast and the eastern coasts of Ghana were the most vulnerable. It was identified that about 50% of the 540 km shoreline of Ghana is

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vulnerable. This assessment will facilitate the long-term adaptation planning and hazard mitigation to inform the management of Ghana's coast.

Keywords: Ghana's Coast, Coastal vulnerability, Coastal mapping, climate change, coastal adaptation, coastal management

1. Introduction

Coastlines are highly dynamic and geomorphologically complex systems, which respond in various ways to extreme weather events (Balica et al. 2012). This is due to several factors such as wave height and direction, wind speed, water depth, sediment supply, removal and transport sediments along the coast, strength of tides, rates of relative sea level change. Other factors include rainfall frequency and the intensity of extreme meteorological and climate events such as storm surges (Boateng 2012a). Furthermore, coastal ecosystems are also particularly sensitive to the increase in sea surface temperature, ocean acidification, salt water intrusion, rising water tables and to altered runoff patterns (IPCC 2007; 2014). Climate change has an influence over all these drivers and therefore introduces further vulnerability to coastal systems.

Potential impacts of sea-level rise on coastal areas include shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, and threats to cultural and historic resources as well as coastal infrastructure (IPCC 2007; 2014; Boateng 2012a). Predicted accelerated global sea-level rise has generated a need to determine the response of coastlines to sea-level rise (Pendleton et al. 2004).

Analysis of Ghana's sea level records from the port of Takoradi between 1925 and 1970 (Figure 1) provide evidence of the rate of sea level rise (2.1mm/yr), which is consistent with global estimates (Nicholls and Misdorp 1993; IPCC 2007; Woodworth et

al. 2009). The data between 1970 and 1996 on Figure 1 looks irregular and unreliable due to the reported aging and technical problem with the tidal gauge. The gauge eventually broke down during 1996 and a new one was not installed until 2008. The loss of data between 1996 and 2008 makes is difficult identify the actual sea level rise at present. However, without any intervention, it is expected that the relative sea level rise per year over the next 100 years would be about 3mm/yr. African Centre of Meteorological Application for Development (ACMAD), (2016) has projected that warming of the Africa continent will be $1.5^{o}c$ by 2050 and could rise to about $3^{o}c$ by 2100. This will aggravate the effects and intensify of the impact of climate change on the continent. These could increase the intensity and frequency of tidal wave and storm and potentially cause inundation of the low lying coastal areas. Already, several of the anticipated impacts of accelerated sea level rise identified by the IPCC 2014 have been experienced in Ghana (GEPA 2000). In fact, climate change and associated impacts of rising sea level, increased storm and torrential rainfall and flooding have already affected coastal habitat, bio-diversity and socio-economic activities in Ghana (GEPA 2000; Appeaning-Addo et al. 2008; Appeaning-Addo 2013).

In order to address the negative impacts of climate change and the associated rise in sea levels, policy makers, coastal managers and opinion leaders need evidence-based information on current status and forecasts of coastal vulnerability. Determining coastal vulnerability hot-spots allows for proper implementation of long term policy, such as

restriction of development in vulnerable areas, as well as allocation of resources in the short term.

According to Gornitz et al. 1994 and DEFRA 2006 effective coastal management requires the ability to plan the response to climate change variations in both the short-term and the long-term, since any change in climate processes will ultimately affect the coastal zone in some way. The assessment of coastal vulnerability to climate change is therefore key to sustainable coastal management. However, the prediction of the future response of coastal zones to changes in sea level rise or storm intensity requires information on the past and current state of the coast (DEFRA 2006). This provides information for the appropriate response to the threats that rising sea levels pose.

The IPCC 2001; 2014 defines vulnerability as the propensity or predisposition to be adversely affected. It encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Vulnerability therefore, is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. An assessment of coastal vulnerability involves the analysis of the scope and severity of the potential bio-geophysical effects of climate change and sea-level rise. They include increasing probability of flood events of particular magnitude; erosion; gradual/rapid inundation of low-lying areas and wetlands (sea level rise or storm event); rising water tables; saltwater intrusion and biological effects. Although a viable quantitative predictive approach is not available, the relative vulnerability of different coastal environments to

sea-level rise may be quantified at a regional to national scale using basic information which include geomorphology, geology, rate of sea-level rise, past shoreline evolution and socio-economic parameters (Thieler and Hammer-Klose 2000; Appeaning-Addo, 2013; McLaughlin, et al. 2002).

This paper examines the relative vulnerability along the entire coast of Ghana. There are very few previous studies of coastal vulnerability in Ghana. These studies have covered only small section of the coastline (Boateng 2012a; Appeaning-Addo 2013). There is the need to assess the vulnerability of the entire coastline to the predicted rise in sea level to enable coastal managers and Government to develop an adaptation policy for the entire coast. This paper aims to provide detailed assessment of vulnerability along the entire coast of Ghana (540km). In Ghana, it is the responsibility of the coastal local authority (coastal district) to manage their coastal frontage (Boateng 2006). Therefore to make this assessment useful and relevant to district coastal managers, the results of the vulnerability assessment are presented on a district scale. This district level presentation will facilitate effective adaptation planning, coordination and sustainable management of the coast at a district level. This detail assessment (district level vulnerability), whilst necessary, has not been done in previous studies (Boateng 2012a; Appeaning-Addo 2013).

This paper reviews coastal vulnerability assessment approaches and then adopts the coastal vulnerability index approach for the assessment of Ghana's coast. The physical variables as well as population density along the coast were considered in the coastal

vulnerability index. This index according to Pendleton et al. 2004 and Yin et al. 2012 provides an objective technique for the evaluation of coastal vulnerability for long-term planning by scientists and coastal managers. Coastal communities in Ghana are more vulnerable to climate change than inland communities because, in addition to meteorological parameters, they are affected by changes in oceanic parameters, especially increases in sea level, wave heights and storms. Hence, this paper discusses coastal management options for Ghana based on the results of the vulnerability assessment.

2. Material and methods

The coast of Ghana has been divided into Eastern, Central and Western coasts based on their geomorphology (Figure 2). The **Eastern coast** stretches about 140km from the border with the Republic of Togo to Prampram. It is a high-energy coast with wave heights often exceeding 1 m in the surf zone (Ly 1980; Wellens-Mensah et al. 2002). The **Central coast** represents a medium energy environment interspersed with embayed coasts, rocky headlands and sand bars or spits enclosing coastal lagoons. It consists of 310km of shoreline extending from the west of Prampram to the estuary of River Ankobra near Axim. The **Western coast** covers 90km of shoreline and it is a low energy beach. It consists of a flat and wide beaches backed by coastal lagoons. The coast extends from the estuary of the Ankobra River to the border with Cote d'Ivoire.

The coast of Ghana comprises of several rock formations of different eras (Boateng 2012b). These range from the earliest Precambrian to the Quaternary period (Benneh and Dickson 1988; Lawson 1956; Lewis 1964). The geology of the various parts of the coast determines the resistance to erosion processes (Figure 3). The soft geological formations such as the unconsolidated Quaternary materials in the southeast, and the shale in the Accra area, are less resistant than stronger geological formations like the granite complex at Dixcove and Cape Three Points (Boateng 2012b).

The three key components that define vulnerability are exposure, sensitivity, and adaptive capacity. These provide a suitable starting position to explore possibilities for vulnerability assessment, but they are not operational. Therefore, a vulnerability assessment should start by defining the policy or objective as clearly as possible, and to choose the scope and methods accordingly (Ramieri et al. 2011). Several methodologies used for the assessment of coastal vulnerability have been identified in the literature. The three most commonly used method are: Indicators (Ramieri et al 2011), Coastal Vulnerability Index (CVI) (Gorntiz and White 1992; Yin et al. 2012) and GIS or computer based models (Ramieri et al. 2011).

The indicator-based approaches express the vulnerability of the coast by a set of independent elements or indicators that characterise key coastal issues such as coastal

rivers, development pressures, state, impacts, responses, exposure, sensitivity, risk and damage. These indicators are in some cases combined into a final summary key indicator. This approach allows the evaluation of different aspects related to coastal vulnerability within a consistent assessment context (Ramieri et al. 2011).

The Coastal Vulnerability Index-based approach in contrast, expresses coastal vulnerability by a one-dimensional and generally unitless risk/vulnerability index. This index is calculated through the quantitative or semi-quantitative evaluation and combination of different variables.

The GIS or computer based model uses dynamic computer model tools for analysing and mapping vulnerability and risks of coastal systems to climate change. This approach can be roughly divided into sector models and integrated assessment models. Sector models are those focusing on the analysis of coastal vulnerability related to a particular coastal process (e.g. coastal erosion or saltwater intrusion in freshwater systems) and therefore not directly dealing with the evaluation of coastal vulnerability to multiple climate change impacts (Ramieri et al. 2011). Integrated assessment models conversely aim to evaluate the vulnerability of coastal systems to multiple climate change impacts, including the cross-sector analysis of the interaction among different impacts and/or changes in other factors affecting the coastal system (mainly the socio-economic context and adaptation measures) (McLaughlin and Cooper 2010)

In this paper, the CVI was the method applied because it is one of the most commonly used and simple methods to assess coastal vulnerability to sea level rise, in particular due to erosion and/or inundation (Gornitz et al. 1991). In addition, the CVI provides a simple numerical basis for ranking sections of coastline in terms of their potential for change that can be used by managers to identify regions where risks may be relatively high. Furthermore, CVI results can be displayed on maps to highlight regions where the factors that contribute to shoreline changes may have the greatest potential to contribute to changes in shoreline retreat (Ramieri et al. 2011). In addition, the approach has been applied to Accra coast, a small section of Ghana's coast by (Appeaning-Addo 2013. This provides an opportunity to apply the method to the entire coast of Ghana and compare the results to Appeaning-Addo's 2013 assessment, so as to verify the consistency of the methodology and the reliability of the results of the coast of Accra.

The CVI approach is not immediately discernible since the final index does not enable the understanding of assumptions and aggregations that led to its calculation. Thus, a clear explanation of the quantification processes has been provided to support the proper use of coastal variables.

 An important methodological step in the application of the CVI method is the identification of key variables or significant driving processes influencing coastal vulnerability and coastal change in general (Gornitz et al. 1991). Three prong-

approaches were used in the variable identification and quantification. Firstly, an analysis of topographic and geologic maps of the coast was carried out to ascertain shoreline relief. The map assessment was followed by an appraisal of satellite images and orthophotos of the coast. This appraisal confirmed some of the variables identified from the map and also provided additional features that could not be identified from the map (see section 2.1 for scales of the maps). Field observation was carried out for ground truth of identifiable features.

According to Pendleton et al. 2004, seven variables strongly influence coastal evolution. These are geomorphology, shoreline change rate, coastal slope, geology, relative sea-level change/local subsidence, mean significant wave height and mean tidal range. These variables have been classified into geologic variables and physical process variables. The geologic variables are geomorphology, geology, shoreline change rate and coastal slope. These account for the shoreline's relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding, respectively. The physical variables include significant wave height, tidal range, and sea-level, all of which contribute to the inundation hazards of a particular section of coastline over time scales from hours to centuries. Another important variable which is mostly absent is the socio-economic parameter, which includes population (Gornitz et al. 1993; McLaughlin et al. 2002). Socio-economic parameters (e.g. population at risk) were included in the assessment.

2.1 Geologic Variables

The geomorphology of the entire coast of Ghana was interpreted from 2005 orthophotos taken at a scale of 1:10,000 (see Table 1). The main features that were identified include sandy beaches, rocky, estuaries and lagoons. The geology was extracted for the entire coast from the Geological Map of Ghana at a scale of 1:1,000,000 (Geological Survey Department 2009). The coastal elevation was generated from 50-foot interval topographic data merged with bathymetric data.

Shoreline rate of change was calculated using 1974 and 2005 high water mark proxy positions. The rates of change were calculated at 100m intervals using the end point rate method in the Digital Shoreline Analysis System (DSAS 4.2). The rates were then averaged for each district along the coast of Ghana.

2.2 Physical Process Variables

Relative sea level rise along the coast of Ghana is in conformity with the global trend at a historic rate of 2mm/yr (GEPA 2000; IPCC 2007; Appeaning Addo et al. 2008) and current global rate is estimated at 3.4mm/yr (NASA 2016). Average local subsidence rate of ≤ -1mm/yr for the entire coastline was estimated from Takoradi and Tema tide gauge stations data obtained from the Survey Department of Ghana. The current

estimate of 3.4mm/yr was used in this study since there are no current estimates for the coast of Ghana. The significant wave height along the coast is reported to be 1.2m (Wellens-Mensah et al. 2002). The average tidal range along the coast of Ghana was estimated to be about 1m (Boateng 2012a; Mitchell, Boateng and Couceiro 2016).

2.3 Population variable

Population density was derived from the 2000 population and housing census data for Ghana. This was preferred to the current 2010 data because of changes in district boundaries which are yet to be fully rectified. The highest density along the coast was highly variable, with Accra Metropolitan Assembly having the highest density and others like Tema and Shama also recording relatively high densities.

The risk variables are ranked on a linear scale from 1 to 5 in order of increasing vulnerability to sea level rise (Klein and Nicholls 1999). A value of 1 represents the lowest risk and 5 represent the highest risk. Several formulae exist for computing CVI (Table 2). The formula adopted for this study was the square root of product mean (CVI_5). The CVI_5 has been widely used in other applications at the local, regional and supra regional level (e.g. Thieler and Hammar-Klose 2000; GEPA 2000; Thieler et al. 2002), because it is relatively insensitive to variations in one risk factor, while still being able to produce usable results when differences occur within several factors (Gornitz et

al. 1994). The adopted formula was formulated in an excel spreadsheet and it was used to calculate the values of the vulnerability variables as well as the analysis of the results.

3. Results

Table 1 presents the eight (8) identified coastal variables and the ranking of the vulnerability index variables. The results of the vulnerability assessment have been presented in Figure 4.

The calculated CVI_5 ranged between 15.49 and 86.60. The index was divided into four levels based on percentiles (Pendleton et al., 2004) as follows:

- Below 32: low vulnerability;

- Between 32 and 41: moderate vulnerability;

- Between 42 and 51: high vulnerability; and

- Above 52: very high vulnerability.

Relating the results to the to the coastline, it can be identified in Figures 4 and 5 that out of a total coastline of 540km, 36% of the coastline was identified to be **very high** vulnerable. The very high vulnerability areas cover Cape Coast district in the Central

region, Jomoro district in the Western Region and three coastal districts (Dangbe East, Keta and Ketu) at the eastern coast (towards Togo border) (Figures 4 and 6). These sections of the coast have at least two or more of the following, high energy, generally very low lying relief with sandy barrier confining lagoons at the backshore (Figures 2 and 3). Erosion rates are mostly **very high** (between 3.4. and 3.9m/yr) along the eastern coastal areas (Boateng 2012b). These very high risk factors make the coastal population and properties at the backshore very vulnerable to future storms and sea level rise (Figure 6).

Ga and Sogakope districts in Greater Accra region, Nzema East district in the Western region and three other districts in the Central region were identified to have **high** vulnerability (Figure 4).These areas with high vulnerability represent about 15% of the coastline (Figure 5). The results of vulnerability of Greater Accra coastal frontage was consistent with the previous vulnerability assessment of that section of the coast by Appeaning-Addo 2013 (Table 3).

However, the slight variation of the vulnerability results for Eastern Accra coast in Appeaning-Addo 2013 (Table 3) and Tema Metro (district 13, Figure 4) in this study, can be attributed to the exclusion of the socio-economic parameter (population) in the former's assessment. This implies that the CVI methodology would deliver consistent outcome if the same variables/parameters were applied. The remaining coastline,

mainly the West and Central coast (Figures 2 and 4), has vulnerability that varied from low (26%) to moderate (23%) and represent about 49% of the coastline.

The relatively **low or moderate** vulnerability of the West and Central coast is partly due to the presence of hard geology and high relief at the backshore (shown by the closeness of the 30m contour to the coast (Figure 2) which reduce significantly, the landward advance of the coastline. In addition, relatively low population density of the coastal area (Figure 6) also indicates a lower risk to life and properties. However, settlement close to rivers and lagoon inlets in these areas may be threatened by rising sea levels and flooding from heavy precipitation in the hinterland. Elevation along the central coast is higher compared to the eastern and western sections of the coastline (Figure 2). The very high and high vulnerability areas cover 51% of the coastline while the moderate and low vulnerability cover 49% respectively (Figure 4 and 5).

Factors such as sea level rise, tidal range and wave height were relatively less variable along the entire coast and hence did not play much role in determining vulnerability. The other variables (elevation, geology, geomorphology and especially erosion and population) played a major role in the determination of the relative vulnerability.

4. Discussion

The outcome of the vulnerability assessment shows that about 50% of Ghana's coast is highly vulnerable and therefore there is a need to pursue integrated management to

adapt the coastline. Particularly, there is a need to reduce the potential impact of climate change and associated sea level rise. Different adaptation policy options could be considered in Ghana (Figure 7). Besides, it is important to avoid placing an additional burden of responsibility on future generations by unnecessary development on vulnerable coastal areas, thereby increasing the number of areas to be artificially protected in the long-term (DEFRA 2001). It is imperative therefore, that vulnerable coastal lands along Ghana's coast are not developed in a way that will warrant future artificial protection (Norcross-Nu'u et al. 2008). Present settlements and developments that are located in areas with the risk of flooding, coastal erosion and potential cliff instability might consider accommodation policies or perhaps retreat, depending on the level of risk (Walsh et al. 2004). In order to assess the potential risk of sea level rise to the shoreline and integrate an appropriate adaptive response to the very high vulnerable areas, there is a need for Ghana to develop a holistic management plan for the coastline similar to the UK Shoreline Management Plans (DEFRA 2006; Boateng 2006).

It can be identified from Figure 2 and 4 that the very high vulnerable areas may be very sensitive to sea level rise due to the low elevation. It indicates that 1m sea level rise is likely to submerge more than half of the frontage of the entire eastern coast from Ada to the Togo border at Aflao (Figures 2 and 4). All towns and cities between Ada and Aflao may be submerged by 1m sea level rise. It has been predicted that relative sea level is likely to rise to about 1m by 2100 (GEPA 2000; IPCC 2014; DeConto and Pollard, 2016). This implies that over 50% of Ghana's East coast (Figure 2) could be under

water by 2100. Additionally, much of these areas are actually at risk of flooding at present since any storm surge, which raises the water level to about 1m or more causes flooding and destructions to significant areas of the East coast (Ghana News Agency [GNA] 2012; Citifmonline 2015). Given this flood risk, it is important to identify and pursue adaptive policies to reduce the general risk associate with climate change.

Ghana could pursue an adaptive coastal management plan that seeks to achieve the following key policies outlined after Boatman et al. 2008, DEFRA, 2006 and Walsh et al. 2004:

- Manage the risks affecting life and properties in very high vulnerable areas.

- Protect the existing developments that are vulnerable based on a baseline analysis of long-term sustainability and the impacts of the physical environmental.

- Ensure that adaptation plans and policies comply with the national and international legislation with minimum compromises with respect to the natural environment, navigation, human rights and cultural heritage.

- Implement management policies that allow for future flexibility in response to changes in physical conditions and in socio-economic circumstances at the frontage of the vulnerable shoreline

- Ensure that management plans for any section of the coastline considers potential impacts on adjoining coastline (including neighbouring countries; Togo and Cote d'Ivoire),

- Encourage continuous monitoring of waves conditions, sea levels, and beach sediment as well as coastal defences.

The map appraisals and field observations identified that Ghana has many coastal settlements close to coastal lagoon inlets and settled barrier beaches (example in Figure 8). Some of the lagoons have permanent and temporally closed inlets that hinder both flood and ebb tidal exchange. This implies that coastal settlements at the sides of these inlets are at risk of flooding from fresh water from lagoon catchment resulting from high rainfall at the hinterland as well as seaward flooding resulting from tidal wave and storm surge. This makes defending the coastal frontage of towns at the sides of lagoons against the rising sea level not only economically expensive, but technically difficult. A possible option is to retreat landwards.

The threat of the rising sea levels does not only affect the coastal settlements but also the conservation interest at the backshore. For example, Volta delta and Keta Lagoon in the east as well as Amansuri Ramsar site in the west are special conservation sites under the threat of sea level rise. Should conservation sites be abandoned and left to natural environmental forces? In fact, the issues at the very high vulnerable areas at the East coast in particular are very complex and require participatory consultation with all stakeholders to make the appropriate decision. We recommend retreat as the appropriate policy option for the very high vulnerable areas based upon the available information and predicted sea levels in the future. However, there are uncertainties in

the sea level rise prediction and knowledge gaps on the physical processes of the area. Overall, it is expected that inputs from consultations with stakeholders and future research would confirm the retreat policy.

Perhaps approaches used in India, Bangladesh, New Zealand and USA to adapt to the flood risk of their low-lying coastal cities (Mascarenhas 2004; Nicholls et al. 2007; Healy and Soomere, 2008 and Boatman et al, 2008) should be adopted and used to accommodate vulnerable settlements in both the Western, the Eastern and the Central coast in the short-term (0-10 years) to medium-term (10-20 years). Examples of these approaches include, coastal buffer zones, building houses on stilts, early storm warning systems and elevated storm shelters among others, which enable areas to be occupied for longer before eventual retreat. However, strict land-use planning and education should be used to discourage growing trends of human development along the coast, which could exacerbate the vulnerability due to increased risk to life and property. The IPCC 2007; 2014) identified that one way of increasing adaptive capacity is by introducing the consideration of climate change development planning, by including adaptation measures in land-use planning and infrastructure design and measures to reduce vulnerability in existing disaster zones.

It is important to highlight the need to educate coastal communities about coastal vulnerability, land use planning and the possible implications of settling on coastal lands which are at high risk of flood and erosion. Settlers in vulnerable areas especially, those living at the east coast should be educated about the potential impacts of climate

change on their life, properties and local economy. They should be involved in the decision-making processes on the planning, the development and implementation of adaptation policies. Accommodation measures can help to manage risks in the short to medium term and such measures should be implemented immediately since some coastal communities are already experiencing the effect of rising sea levels (GNA 2012; Citifmonline 2015).

Furthermore, there is the need to improve co-ordination and promote integrated shoreline management plans. A national coastal management forum or action group should be formed to promote sustainable coastal management policies. The national forum should involve the four coastal regions (Volta, Greater Accra, Central and Western Regions), the coastal districts and the central government (ministries, departments and agencies whose work relates to the coast). These governmental institutions, NGOs, private organisations and individuals who are involved in coastal and marine activities could come together and pursue an agenda of mutual benefit, like Standing Conference on Problems Associated with the Coastline (SCOPAC) in the UK (SCOPAC 2001; Stojanovic and Barker 2008; and Inder 1996). This forum could improve capacity building toward holistic coastal adaptation and integrated coastal zone management and organised consistent updated coverage of the entire coast. The proposed national forum could then collaborate to initiate preparation of holistic climate change adaptation plans for the entire coastline.

5. Conclusions

The paper has conducted a sea level rise vulnerability assessment of the entire Ghana's coastline for the first time. It has identified that about 50% of the coastline of Ghana is vulnerable to sea level rise. The paper has presented for the first time, district level coastal vulnerability assessment in Ghana. This makes the outcome very relevant for effective planning and management of the entire coastline of Ghana, because coastal districts are responsible for managing their coastal frontage, based upon the laws of Ghana. It has been identified that the outcome of the assessment for Accra coast (Figure 6 and Table 3) is consistent with previous studies and that the CVI methodology could deliver consistent outcomes from different users if the same variables were applied for the same coastline. There is the need for improved co-ordination among coastal districts and other stakeholders to promote integrated and sustainable coastal management policies as there is no artificial district boundaries with coastal processes that shape the coastline.

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Table 1: Ranking of coastal vulnerability index variables for the Coast of Ghana

Variable	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
Geomorphology	Rocky coasts	Medium cliffs	Low cliffs	Estuary, Lagoon	Deltas, Sandy beaches, mangroves
Coastal Geology	Pegmatite, Biotitetonalite	Amphibolite, Gneiss, Quartzite	Limestone, Sandstone, Mudstone, Conglomerate	Alluvial Sand, Silt, Clay	Alluvial Sand, Silt, Clay
Coastal Elevation	>30	>20 and <=30	>10 and <=20	>5 and <=10	>=0 and <=5
Shoreline erosion/accretion (m/yr)	>2.0	1.0 to 2.0	-1.0 to 1.0	-2.0 to 1.0	<-2.0
Sea-level rise (mm/yr)	3.0 to 3.4	3.0 to 3.4	3.0 to 3.4	3.0 to 3.4	3.0 to 3.4
Subsidence (mm/yr)	$\leq$ -1	$\leq$ -1	$\leq$ -1	$\leq$ -1	$\leq$ -1

Mean tide range (m)	1.0 to 2.0	1.0 to 2.0	1.0 to 2.0	1.0 to 2.0	1.0 to 2.0
Mean wave height	1.05 to1.25	1.05 to 1.25	1.05 to 1.25	1.05 to 1.25	1.05 to 1.25

Table 1

Table 2: Formulae for computing Coastal Vulnerability Index (CVI) (Source: Gorntiz

Product mean:	$$CVI_1 = \frac{(X_1 * X_2 * X_3 * X_4 * \ldots X_n)}{n},$$
Modified product mean:	$$CVI_2 = \frac{[X_1 * X_2 * {}^1\!/_2 (X_3 + X_4) * X_5 * {}^1\!/_2 (X_6 + X_7)]}{n - 2},$$
Average sum of squares:	$$CVI_3 = \frac{(X_1^2 + X_2^2 + X_3^2 + X_4^2 + \ldots X_n^2)}{n},$$
Modified product mean (2):	$$CVI_4 = \frac{(X_1 * X_2 * X_3 * X_4 * \ldots X_n)}{5^{(n-4)}},$$
Square root of product mean:	$CVI_5 = [CVI_1]^{1/2}$, and
Sum of products:	$CVI_6 = 4x_1 + 4x_2 + 2(x_3 + x_4) + 4x_5 + 2(x_6 + x_7).$
Where: n = variables present	x_1 = mean elevation
x_2 = local subsidence trend	x_3 = geology
x_4 = geomorphology	x_5 = mean shoreline displacement

Table 2

Table 3 Comparison and verification of coastal vulnerability of Accra coast

Appeaning-Addo, (2013) Location	Appeaning-Addo, (2013) Vulnerability Results	This paper Location	This paper Vulnerability results
Western Accra coast	High	District 11 (Fig.3)	High
Central Accra coast	Moderate	District 12 (Fig.3)	Moderate
Eastern Accra coast	Low	District 13 (Fig.3)	Moderate

Table 3
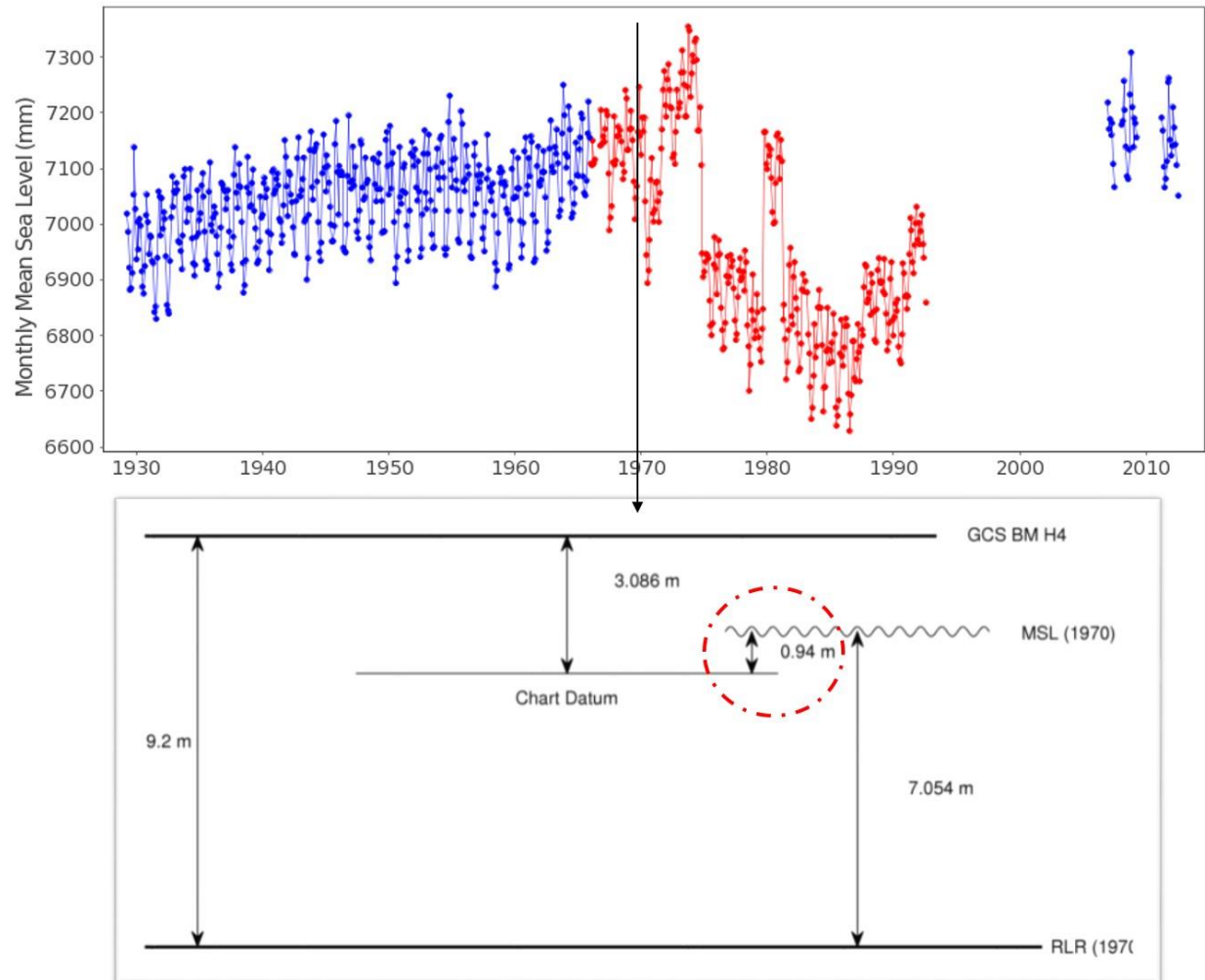
Figure 1: Analysis of sea level record from Takoradi port, Ghana (After Permanent Service for Mean Sea Level 2013)
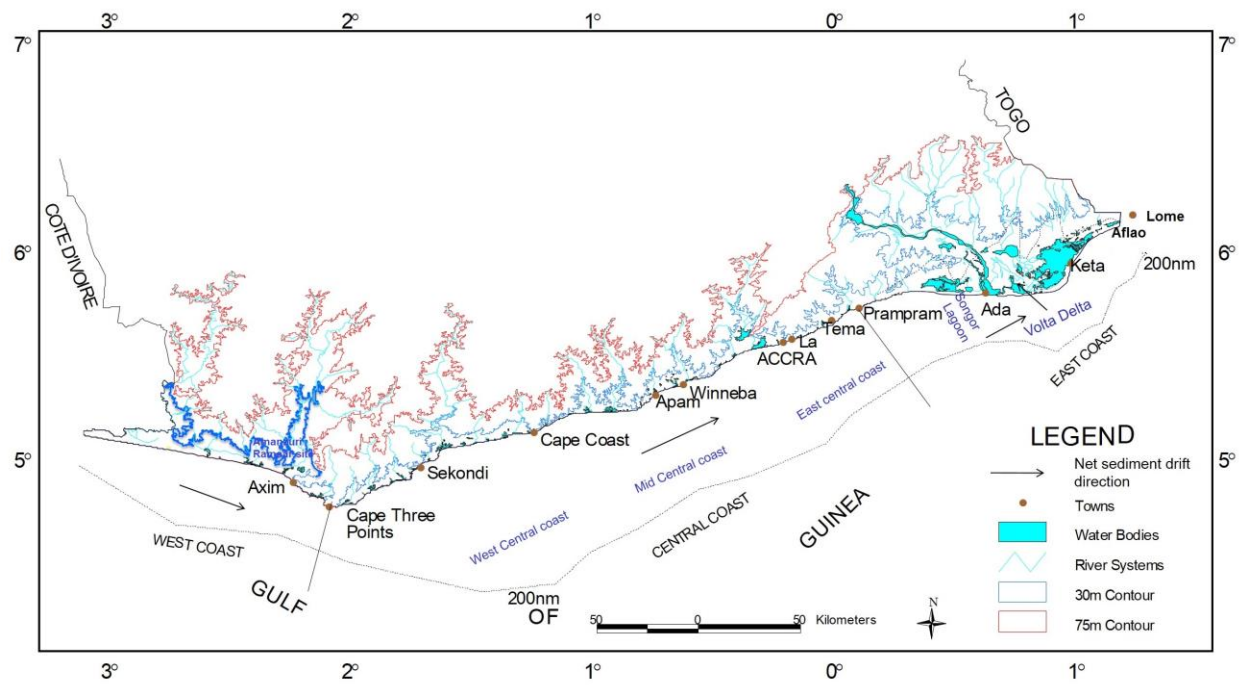
Figure 2: The Coastal Area of Ghana (After Armah and Amlalo, 1998)
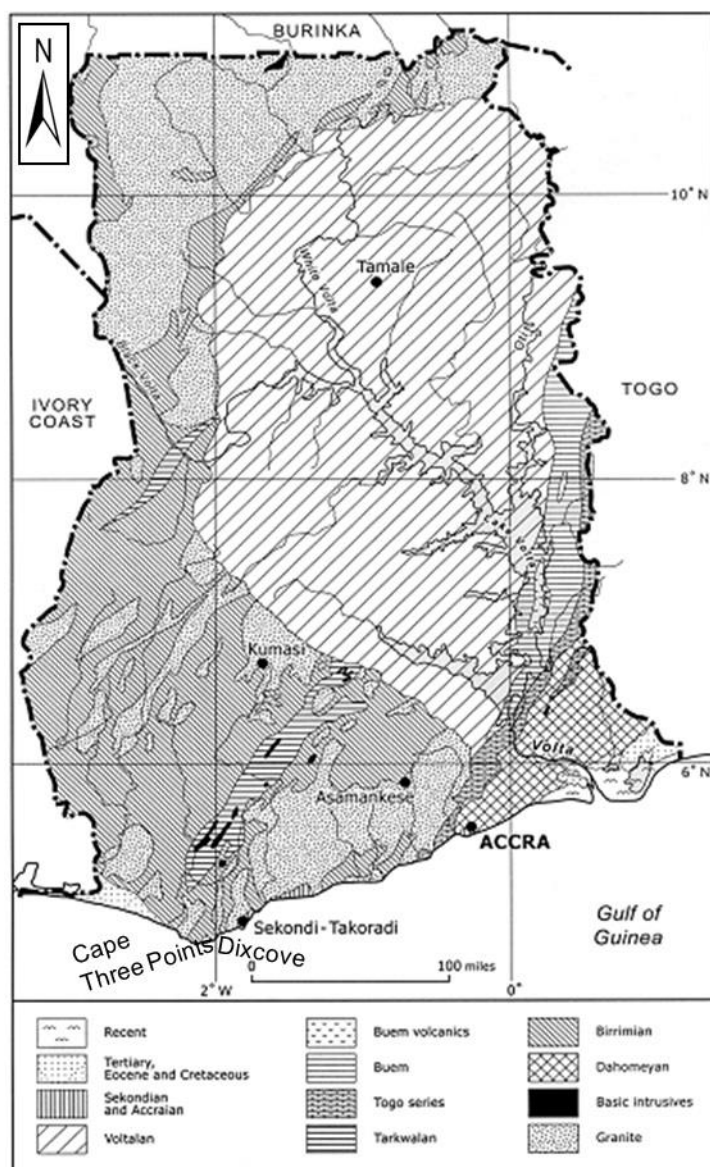
Figure 3: Coastal Geology of Ghana (Boateng 1970)
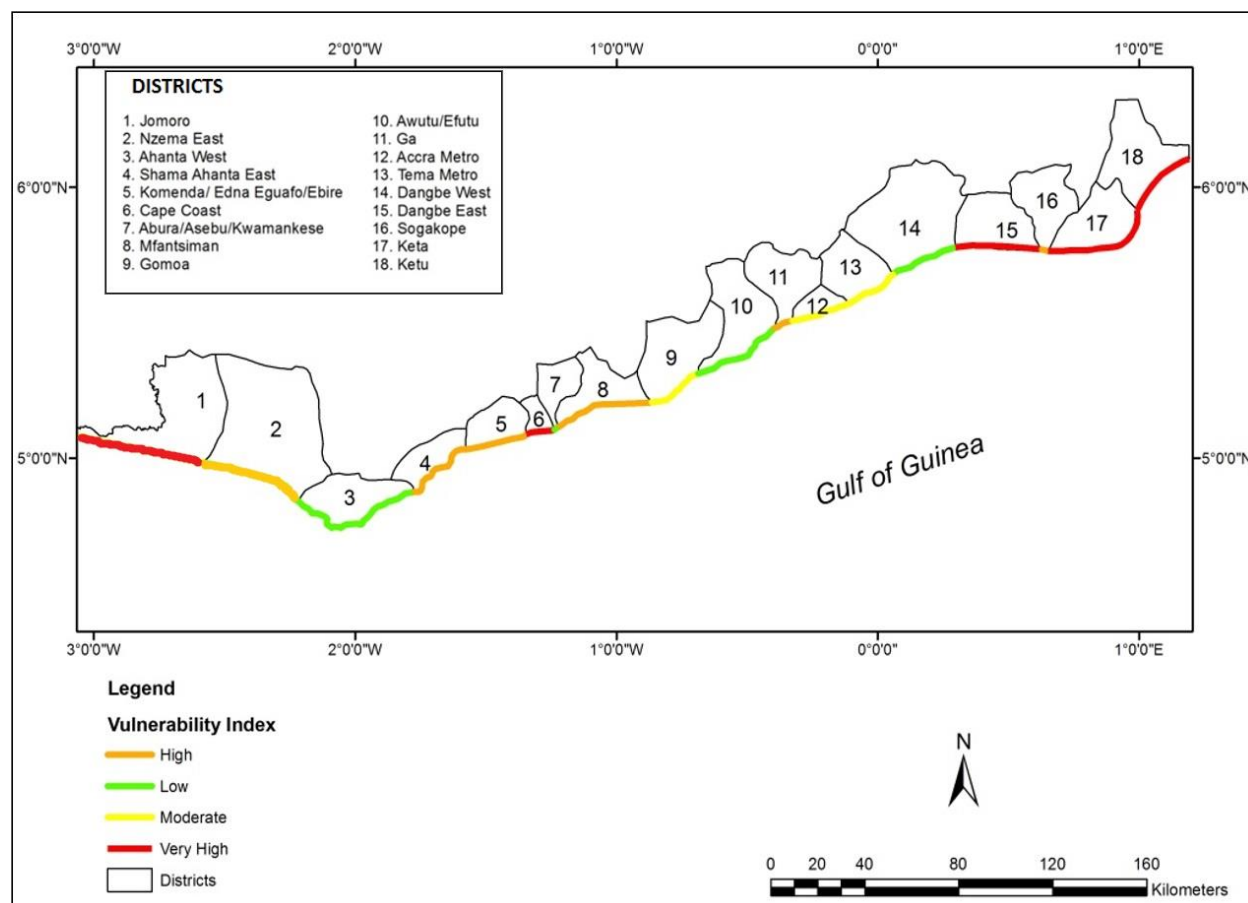
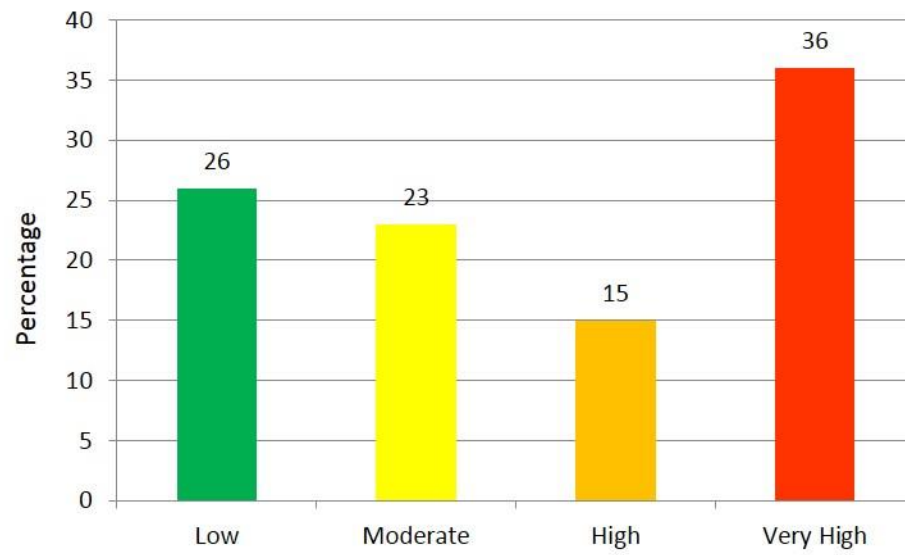Figure 4 Ghana's coast showing various degree of vulnerability and related coastal districts

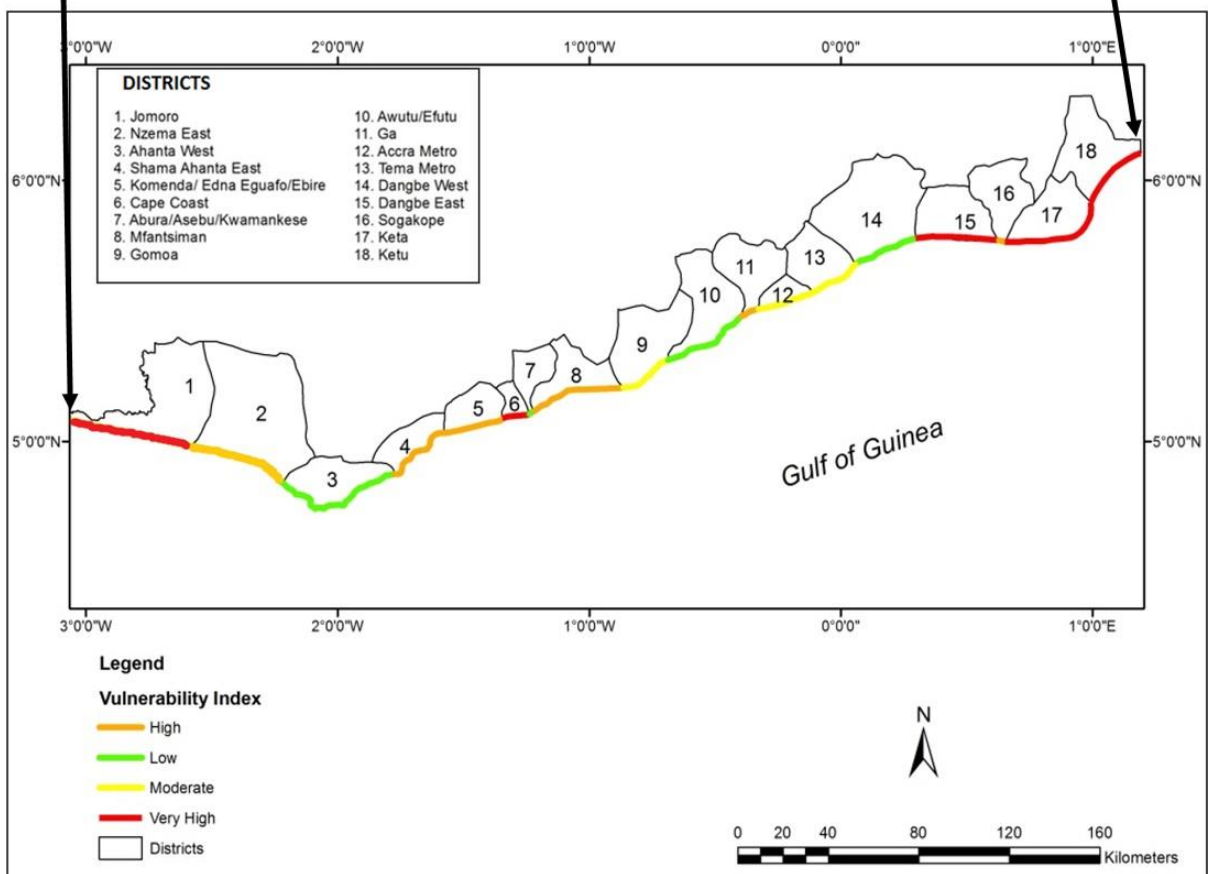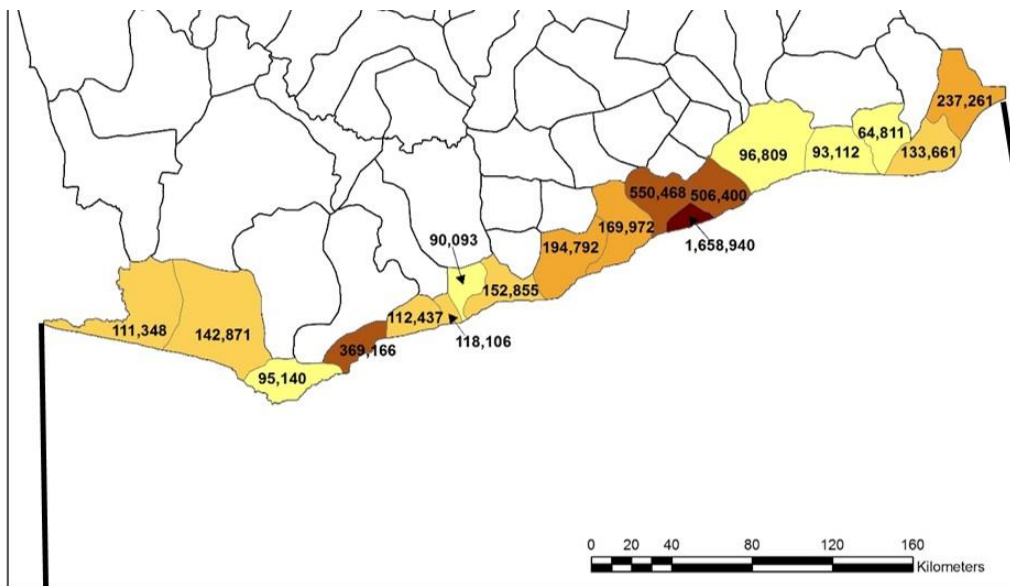Figure 5 Vulnerability levels of Ghana's coast in percentages

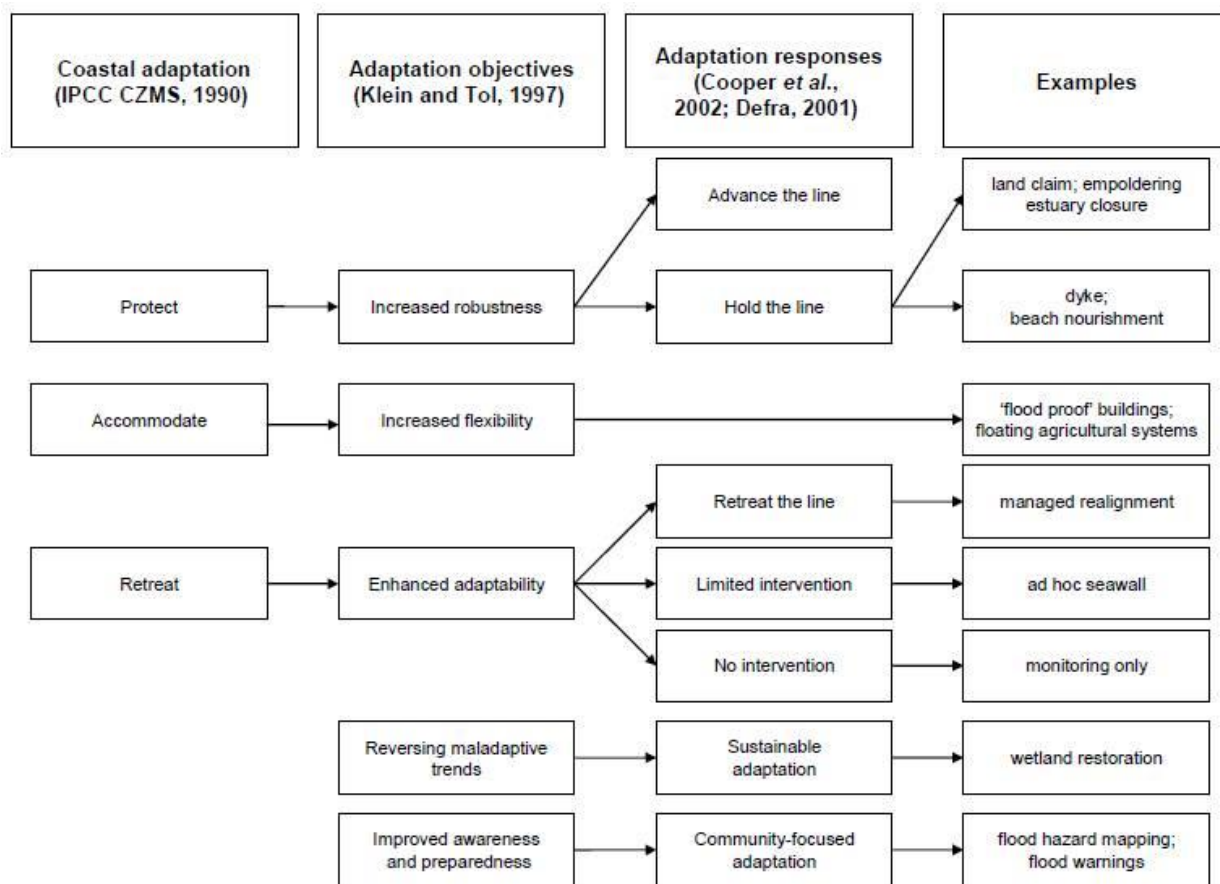Figure 6 Levels of Coastline Vulnerability and related towns and population

Figure 7 Adaptation policies in the coastal zone (Nicholls et al. 2007)

Figure 8 Example of large lagoons fronted by barrier beach with settlement at

Mfantsiman and Ekumfi (District 8) and Elmina (District 5)