Impacts of Climate Change and Sea-Level Rise: A Case Study of Mombasa, Kenya

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Summary

The coastal city of Mombasa is the second largest city in Kenya after Nairobi. It is the largest international seaport in the Eastern Africa and has more than 650,000 inhabitants. The city has a long history of frequent natural disasters associated with extreme climatic events, most recently the severe flooding in October 2006. This event, caused by intense precipitation, affected approximately 60,000 people in the city and caused damage to important infrastructure. With socio-economic projections indicating that the city will experience rapid population growth and urbanisation, the future impacts of such events can only increase.

Located in the coastal zone and with an estimated 17 percent of land lying below the 10 metre contour, changes in sea level and storm surges are components of climate change which have the potential to further increase the threat of flooding within the city. However, a literature survey shows that very little study, apart from the recent paper by Awuor *et al.* (2008), has been carried out on impacts of sea level and storm surge, particularly in regard to quantitatively assessing the potential impacts that Mombasa could face over the 21st century.

This GIS-based study provides a first quantitative estimate, both now and through the 21st century, of the number of people and associated economic assets exposed to coastal flooding due to sea level rise and storm surges. It gives a good indication of the potential impacts that the city might experience and indicates the magnitude of impacts which need to be considered in planning decisions. Results show that the current exposure to the 1:100 storm surge levels for the Mombasa district as a whole is estimated at more than 210,000 people and over US$ 500 million in assets. By 2080, under the A1B sea-level rise scenario (43 cm rise in sea level by 2100) and the A1 socio-economic scenario with rapid urbanisation, this increases to more than 426,000 people and infrastructure costing approximately US$ 17 billion.

The analysis shows that the projected socio-economic change and the location of population growth play a significant role in the overall increase in population and asset exposure to extreme water levels. About 75 percent of this exposure is concentrated in the Island city of Mombasa where approximately 426,000 people (2080 estimate) are projected to live within the low-lying coastal zone (within 10m of mean sea level). This continues into the future if the projected population growth is distributed across the city. However, if the population of Mombasa Island remains constant at 2005 levels, exposure is reduced by up to one third, with a total of 272,000 people and assets worth to US$ 1.1 billion exposed across the city by 2080. It should be noted that 54% of these reduced totals is still located on Mombasa Island highlighting its vulnerability to extreme water levels.

This study shows that significant numbers of people in Mombasa are, and will continue to be, vulnerable to flooding due to extreme water levels during this century. However, forward planning to address projected population growth can reduce exposure levels to a significant degree. Appropriate adaptation measures, such as the construction of defences, can be expected to reduce the flooding risk but this was not considered as part of this study. This work has also highlighted that only limited accurate and long-term sea-level rise measurement data exists in the area and the monitoring of both sea level and extreme coastal events need to be continued to enable more detailed studies to be carried out.

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1. Introduction

The world is currently facing a major challenge due to climate change and its variability (Parry *et al.*, 2007). Sea-level rise and extreme water levels are important components of the impacts of climate change causing major threats to human beings around the world particularly in low-lying coastal areas and beyond. The potential impacts worsen when populations and their associated economic activities are highly concentrated such as in cities. Many of the cities in the developing world are located on such low-lying ocean coasts and very few of them are prepared for the impacts of climate change, particularly sea-level rise and storm events (McGranahan *et al.*, 2007; Nicholls *et al.*, 2007b). Many are typically undergoing fast and unplanned growth, have high population densities and overburdened infrastructures, all of which will influence the extent of any potential impacts they might face due to the changes in extreme water levels during the 21st century. A rise in sea level, for example, can have significant impacts in low-lying coastal areas through flooding, erosion, increased frequency of storm surges, and saltwater intrusion (Nicholls *et al.*, 2007a; Bicknell *et al.*, 2009). The magnitude of these sea-level change impacts will vary from place to place according to topography, geology and natural land movements and any human activity which contributes to changes in water level or sediment availability, for example subsidence due to ground water extraction. However, the literature survey shows that the knowledge about the impacts of climate change and sea-level rise and other coastal related issues on Africa on a continental scale and at country level are very limited, little has been done to assess these issues (Zinyowera *et al.*, 1998; Dasanker *et al.*, 2001; Brown *et al.*, 2009).

Kenya's major coastal city, Mombasa, currently faces significant threats from direct and indirect impacts of climate change and its variability. It is Kenya's second largest city with a total population of about 650,000 and an average population density of 2879 persons per square kilometre (1999 estimate) (World Resources Institute – *http://www.wri.org*) and has two major harbours (Kilindini harbour and Old port). It is the largest seaport in Eastern Africa serving not only Kenya, but also most East and Central landlocked African countries (such as Uganda, Rwanda, Burundi, Congo and Southern Sudan), significantly contributing to the region's economy. Hence, direct and indirect impacts of climate change and sea-level rise would be felt further inland in the landlocked countries, if the international harbour in Mombasa was affected by changes in sea level and storm surge (Awuor *et al.*, 2008). In this regard, it has much in common with many other world port cities (Nicholls *et al.*, 2007b)

The city of Mombasa is also known for its beaches and important terrestrial and marine-based habitats (e.g. Mohamed *et al* 2009) which attract large numbers of people. The Kenyan Tourist Board (KTB) reports about 65 percent of tourists visiting Kenya visit the coast making tourism an important part of the city's economy. On a national basis it contributes about 12 percent (2004 estimate) of the country's GDP (Government of Kenya, 2006). However, the city has a long history of extreme climatic events including the recent flooding due to intense precipitation in October 2006 which affected about 60,000 people in the Mombasa province (Awuor *et al.*, 2008). The coastal area has significant low-lying land areas which are vulnerable to increased flooding, landward saltwater intrusion, and shoreline erosion. Recent rapid population growth and infrastructure development in the coastal area are at risk from these processes (Okemwa *et al* 1997). Tourist and port facilities, agriculture and other industries could particularly be affected, negatively impacting the national economy as the city's activities and investments are the major contributor to the nation's prosperity. Ecologically, loss of coral reefs, coastal and marine biodiversity and fisheries is also possible. Concern about these effects is apparent. It has been estimated that, a 30 centimetres rise in sea level could cause 17 percent (about 4,600 hectares of land area) of the city to be submerged, making large areas uninhabitable (Awuor *et al*., 2008). More anecdotally, it has been reported that unless urgent adaptation and mitigation measures are put in place, in just 20 years a significant sections of Mombasa could be submerged by the sea (African Press International (API) – http://africanpress.wordpress.com). Iit also anticipated that the city could face significant climate change related health risks (e.g. water-borne and diarrheal diseases such as cholera). These effects are likely to disproportionately impact people who reside in informal, unplanned settlements within the low-lying areas of the city as they are poorly prepared to adapt. However, these judgements are not based on detailed quantitative analysis.

In addition, there are already signs of coastal erosion problems - hotels and other tourist facility providers are being forced to build seawalls and other defence structures to deal with increased wave impacts. This is often linked to climate and rising sea levels in discussions, but detailed studies have not been carried out. Although these impacts are likely to rise in the future, a literature survey shows that very little has been done so far to assess these issues, apart from a recent paper by Awuor *et al*. (2008).

This paper therefore aims to provide a broader more quantitative context to the potential risks and anticipated impacts of extreme water levels on the City of Mombasa. Based on determining the number of people and assets exposed to extreme water levels over the 21st century, it follows the approach of Nicholls *et al* (2007b). Exposure, rather than risk levels, has been investigated as it represents the 'worst-case' future, recognising that even if defences (natural or artificial) are present they are subject to failure. It therefore indicates the potential magnitude for any future event which needs to be considered when planning for the future. Due to the lack of information and accurate data on the defence system (if any) of the coastal system in the city of Mombasa, protection cannot be considered here. However, the analysis assesses exposure under a range of projected sea levels giving a indication of the residual risk on a basis of worst case scenario in terms of the average population and asset which could be flooded per year.

2. Study Area

2.1 City of Mombasa

The coastal city of Mombasa (see Figure 1) is located at the southern tip of the country (39.7oE, 4.1oS). The geology of the Kenyan coast of the coast is dominated by the rifting and break-up of the Paleozoic Gondwana continent and the development of the Indian Ocean (Embleton & Valencio, 1977; Horkel et al., 1984). Mombasa itself lies on a coastal plain which has a variable width ranging from 4 to 6 kilometres (Awuor et al., 2008) and forms part of a fringing reef shoreline. The coastal geomorphology consists mainly of sandy beaches, creeks, muddy tidal flats and rocky shores and is influenced by climate, wave, tidal regime, sedimentation and river discharge (Oesterom, 1988; Aguodha, 1992). Offshore, the sea floor drops to below 200 metres within less than 4 kilometres of the shoreline (Abuodha, 1992). In addition, factors such as its low altitude, high average temperature and high humidity contribute to Mombasa's high vulnerability to climate change (Awuor *et al*., 2008).

For the purpose of this study, the city boundary is considered to be the Mombasa District bordered by the two larger (in terms of land area) Districts of Kilifi and Kwale. Mombasa district is divided into five areas namely: Linkoni, Changamwe, Mombasa Island, Kisauni-1, and Kisauni-2 (Figure 1) divisions which are interconnected by causeways, bridges, or ferries. Table 1 shows the population density in each division, which is estimated based on the assumption that the total number of people in each division is evenly distributed throughout each area. The topography (Figure 1) of the district shows that the Island City of Mombasa lies below 10 metres above mean sea level, with about 55 percent of its land below mean sea level according to the DEM used in this study. The remaining land areas are at much higher elevations and only limited areas would be affected by changes in extreme water levels.

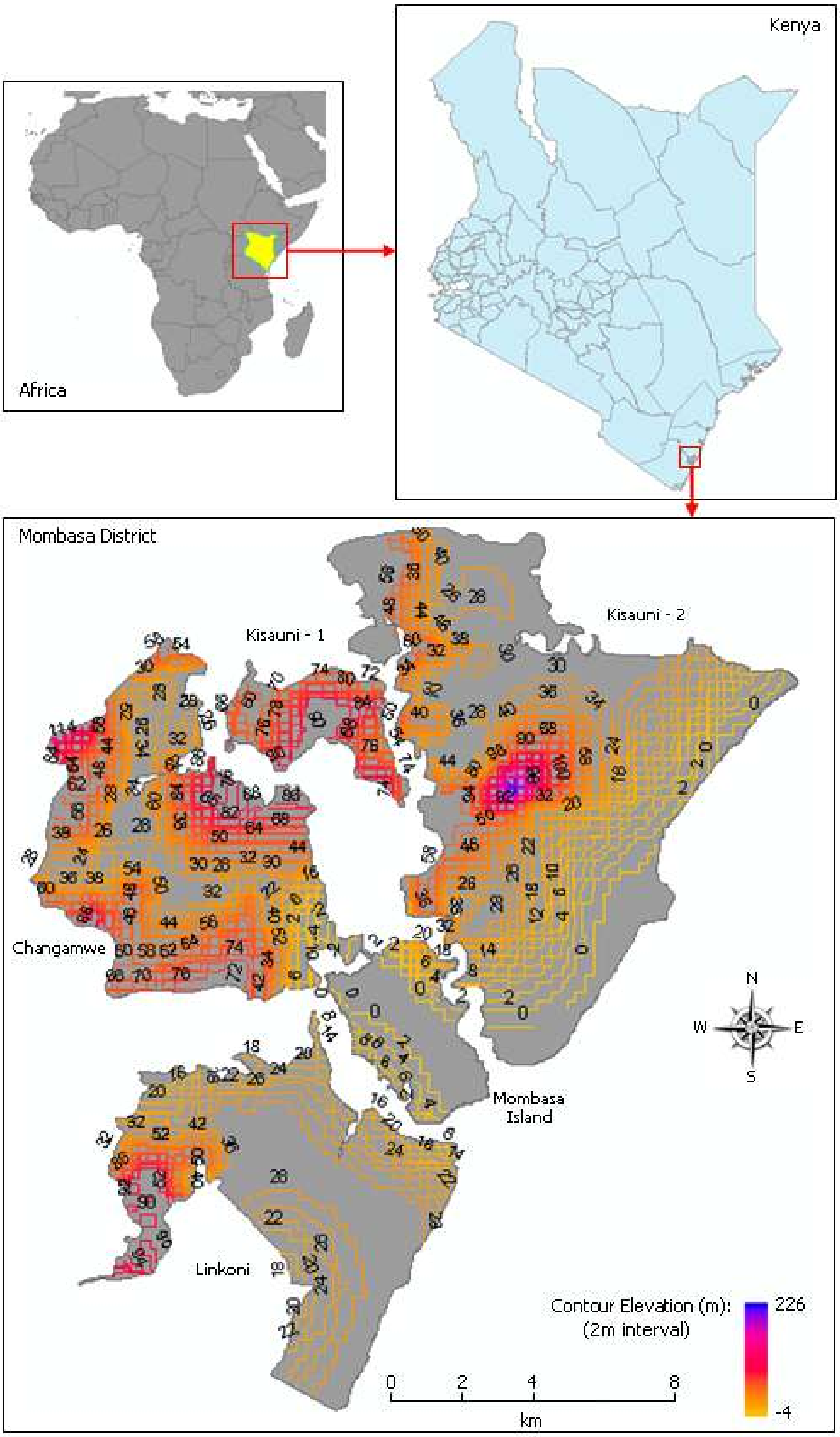

Figure 1: Study area with elevation distribution of the land: - The City of Mombasa is considered being the Mombasa District with its five divisions: Linkoni, Changamwe, Mombasa Island, Kisauni-1, and Kisauni-2

Table 1: Population distribution (1999) of the Mombasa District in the five divisions (Source: World Resources Institute – *http://www.wri.org*)

Division	Division Name	Population (1999)		Area (km^2)	Population density (per km^2)
		Population (Thousands)	Percentage (%)		
1	Linkoni	93.34	14.3	50.42	1851.23
2	Changamwe	171.52	26.2	53.38	3213.15
3	Mombasa Island	141.42	21.6	13.76	10277.62
4	Kisauni-1	5.37	0.8	10.16	528.15
5	Kisauni-2	242.16	37.0	99.39	2436.46
Total	Mombasa District	653.80	100	227.11	2878.78

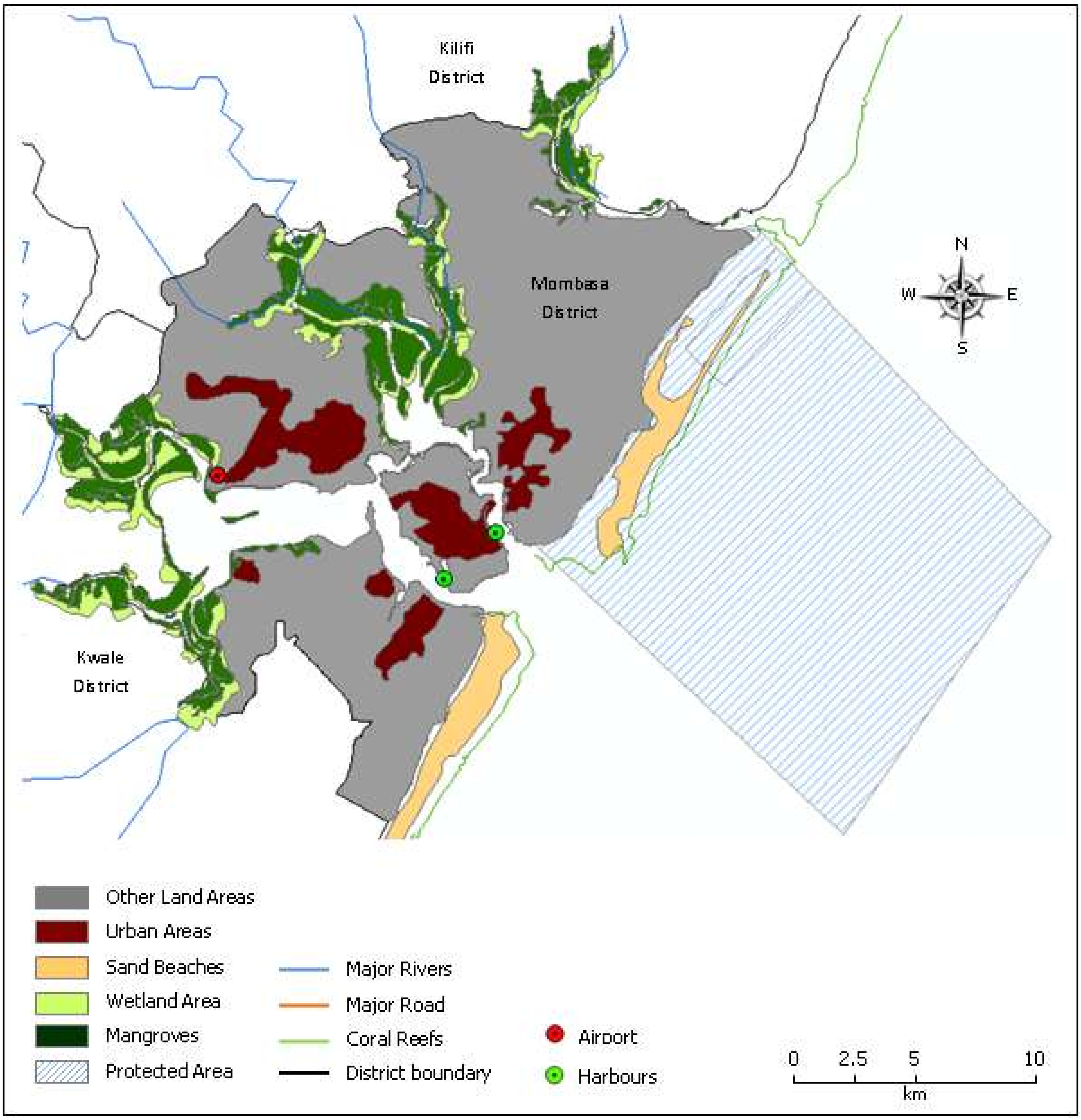

Figure 2: Major land use distribution and coastal description of the Mombasa District

Figure 2 shows the major land use categories of the district. Mombasa has both an international port (Kilindini harbour, also called Port Kilindini) and one of Kenya's international airports (Moi International Airport - Mombasa) serving as a gateway into the region. The Kilindini, a modern deepwater harbour on the south-west side of the Mombasa Island, has extensive docks, shipyards, and sugar and petroleum refineries. The Old Mombasa Port, on the north-east side of the island, handles mainly dhows and other small coastal trading vessels. Shipping transport is one of the main sources of foreign exchange for Kenya. Out of the several ports along the coastline of Kenya, Mombasa is the country's principal seaport and is one of the most modern and busiest ports in Africa. The port is linked with other world's major ports with over 20 sailings per week.

The major urban agglomerations are concentrated in low-lying areas and small part of the district with a maximum population density of more than 10,000 people per square kilometre living on Mombasa Island (See Table 1, Figures 1 and 2), on which over 140,000 people (1999 estimate) live within the low-lying (below 10 metres above mean sea level) area (about 14 square kilometres) of the island city. About 24 percent (approximately 58,000 people, 1999 estimate) are living on a small area of the low-lying (below 10 metre above mean sea level) part of the southern area of Kisauni-2 (Figures 2) with a population density of over 2,400 persons per square kilometre. Table 2 and Figure 3 shows the land area distribution of the district with elevation. More than 17 percent of the land area of the district lies within 10 metres of mean sea level.

The five sub-divisions of the district are separated by the two major creeks (Port Reitz, the southern inlet and Tudor, the northern inlet (Figure 2)) and estuary system which consists about a total of approximately 47.5 square kilometres wetland area with approximately 19.5 square kilometres mangrove forest areas (World Resources Institute – http://www.wri.org). The two major rivers (Kombeni and Tsalu) of the Tudor creek drain a total area of 550 square kilometres with a 0.9 cubic metres per second inter-monsoon freshwater water discharge (cited in Mohamed *et al.*, 2009). The Port Reitz creek, which is formed due to drowning of former river valleys due to sea-level rise (Casewell, 1956), receives its freshwater from three seasonal river systems (Cha Shimba, Mambome, and Mwachi) (Kamua, 2002). As an important intertidal ecosystem, the mangrove forests provide essential function and services to the coastal ecosystem. However, due to socio-economic human activities (associated with water quality problems, lack of sufficient freshwater, and deforestation) the mangrove forests are experiencing a major threat leading to their deterioration, and hence their ability to protect the coast.

Table 2: Urban and other land area distribution of the District per elevation

Land Area	**Elevation (m)**						
	< 0.00	< 2.00	< 3.64	< 4.50	< 10	< 20	Total (District wide)
Urban Area (km^2)	4.09	5.01	5.60	6.09	7.02	12.27	26.65
Other (km^2)	14.81	22.12	26.57	28.97	39.35	56.71	227.11

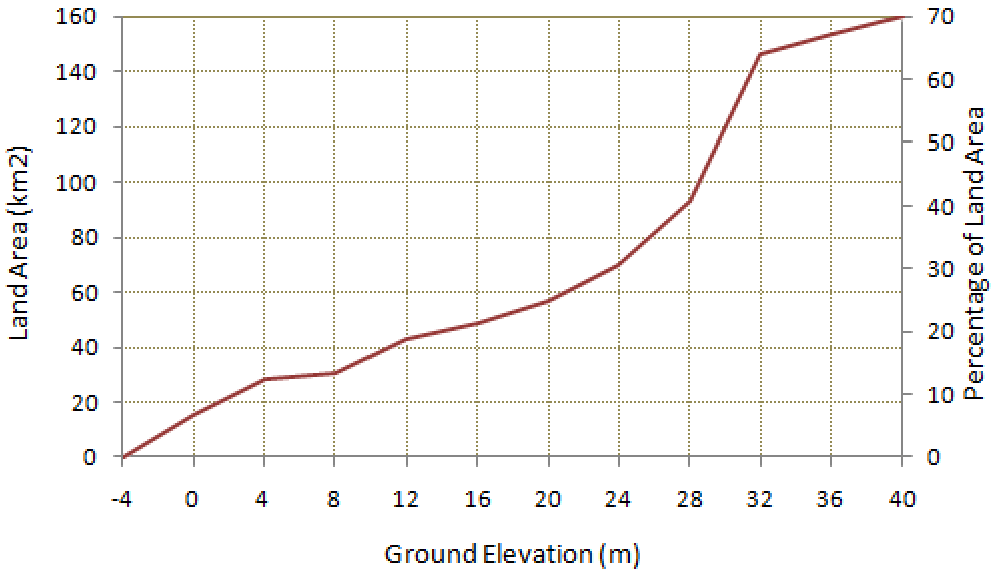

Figure 3: Land area distribution with elevation of the Mombasa District (with total land area of 227.11km^2)

Part of the coastal strip and seaward of the Kisauni-2 area is a government managed protected Marine National Park and Reserve – around 10 and 200 square kilometres, respectively. These were established in 1986 and enclose the beach, a lagoon, and the coral reef (World Database on Protected Areas – http://www.wdpa.org). Apart from its high ecological value in the marine environment with increased biodiversity and abundance of fish, coral cover and diversity of benthic communities, the park and the reserve also play a significant role as a tourist attraction.

2.2 Sea-Level Measurements in Mombasa

Time series measurements of sea-level rise are crucial as they provide information on the highly variable nature of the boundary between land and sea. The analysis of the available longer time series of sea level data from stations around the world showed that there is a rise in mean sea level globally of 1.7mm/year over the 20th Century (Meehl *et al.*, 2007). In addition, long term sea level data will also provide important information for navigation and harbour planning, beach protection and development and overall marine and other scientific research. A tide gauge was installed in Mombasa (Latitude: 04° 04´S Longitude: 039° 039'E) in 1986. The available sea level dataset received by the Permanent Service for Mean Sea Level (PSMSL RLR dataset) from Mombasa station covers the duration of 1986 – 2004 and shows no significant trend although the best fit is 1.1mm/year (Figure 4). This shows that Mombasa is not experiencing a sea-level trend substantially different to global mean trends, and applying global scenarios directly is meaningful. It is important to note that estimates of trends of sea level change obtained from records of short durations as 10 or 20 years could have a significant bias due to interannual-to-decadal water level variability (Douglas, 2001). Hence, it is very important that there sea-level rise measurements are continued, and as the duration of measurements get longer they will get more useful.

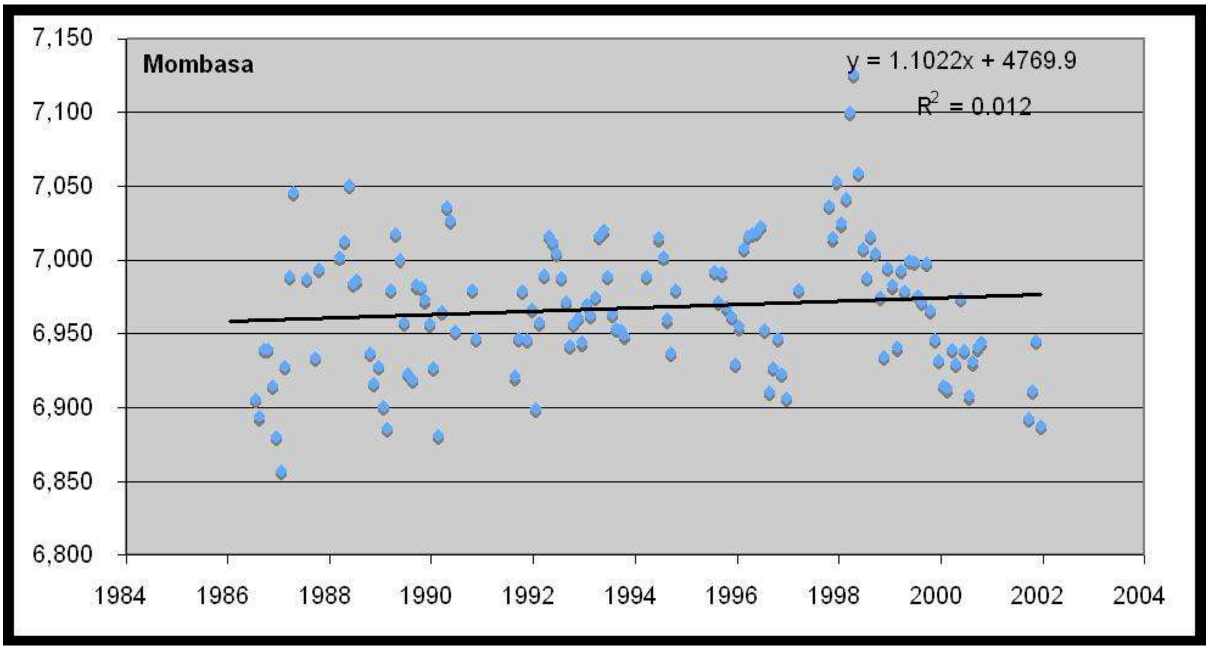

Figure 4: Monthly sea-level measurements (1986 – 2004) from Mombasa Station, Kenya (Source: Permanent Service for Mean Sea Level (PSMSL), http://www.pol.ac.uk/psmsl) (Note: values are in mm)

3. Methodology

3.1 Calculation of extreme water levels

The methodology adopted in this study is based on that developed by McGranahan *et al.*, (2007) and Nicholls *et al.*, (2007b). An elevation-based Geographic Information Systems (GIS) analysis is used to assess the number of people and associated economic assets exposed to extreme water levels. Nicholls *et al* (2007b) calculated extreme coastal water levels from a combination of storm surge, sea level, natural subsidence and human-induced subsidence. In the case of Mombasa, changes in storminess and human-induced subsidence are not considered. Mombasa as it is located near the Equator is not expected to experience the landfall of tropical storms in the future and the storm surge regime is considered to remain constant. Similarly, human-induced subsidence is currently not reported as an issue in Mombasa and based on the sea-level measurements shown in Figure 4 and given its geology, this is unlikely to change. The equation from Nicholls *et al* (2007) was therefore adapted to:

$EWL = SLR + S100 + SUB_{Total}$ ……………..……………………….………………………. (Eq. 1)

Where:

EWL = Extreme Water Levels

SLR = Global mean sea level rise scenarios

$S100$ = 1 in 100 year extreme water levels/storm surge (= 3.624 metres for the Kenyan coastal strip along the coast of the Mombasa district – taken from the DIVA database) – without cyclones

SUB_{Total} = Total land subsidence = $SUB_{Natural} + SUB_{Anthropogenic}$

> $SUB_{Natural}$ = Total natural land subsidence (= 0.42 millimetres per year for the Kenyan coastal strip along the coast of the Mombasa district – taken from the DIVA database, (Peltier, 2001)).
>
> $SUB_{Anthropogenic}$ = Total human-induced land subsidence (considered to be zero)

For the analysis, storm surge heights and natural subsidence rates are directly adopted from the DIVA database (Vafeidis *et al*., 2005). The water levels are calculated based on Equation 1 for current levels and four projected global sea-level rise (SLR) scenarios: low (B1), medium (A1B), high (A1FI) and the Rahmstorf for the years 2005, 2030, 2050 and 2080. The range of SLR scenarios considered in this study is used to examine the impacts on a range of uncertainty. Table 3 and Figure 5 shows the global sea-level rise scenarios on which this study is based, according to the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change, IPCC (Nakićenović and Swart, 2000; IMAGE Team, 2002). The extreme still water levels are given as:

Table 3: Global sea-level rise scenarios used in the study: 1990 to 2100

	Rahmstorf (m)	A1FI high-range (m)	A1B mid-range (m)	B1 low-range (m)
1990	0.00	0.00	0.00	0.00
2000	0.04	0.04	0.02	0.01
2005	0.05	0.06	0.03	0.02
2010	0.07	0.08	0.04	0.02
2020	0.12	0.13	0.07	0.03
2030	0.19	0.19	0.10	0.05
2040	0.27	0.26	0.14	0.06
2050	0.38	0.35	0.18	0.08
2060	0.51	0.46	0.23	0.10
2070	0.66	0.57	0.28	0.12
2080	0.84	0.70	0.32	0.14
2090	1.04	0.83	0.38	0.16
2100	1.26	0.97	0.43	0.17

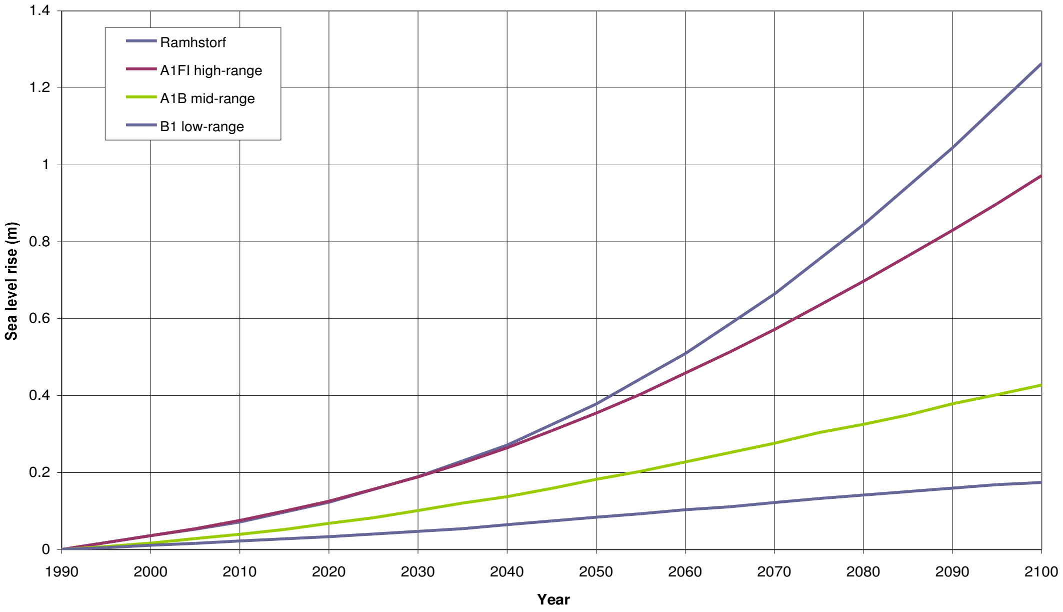

Figure 5: Sea-level rise scenario used in this study

Based on the Equation 1, Table 4 shows the extreme water levels estimated under the four sea-level rise scenarios are given for the time slices considered in the study.

Table 4: Extreme still water levels for each scenario used in the analysis (taken from the DIVA database)

Year	B1 low-range (m)	A1B mid-range (m)	A1FI high-range (m)	Rahmtorf (m)
2005	3.65	3.66	3.67	3.67
2030	3.69	3.74	3.83	3.83
2050	3.73	3.83	4.00	4.03
2080	3.80	3.98	4.36	4.50

The sea-level rise scenarios are coupled with the A1 socio-economic and rapid urbanisation[1] scenario for estimating the future projected population exposure. This follows the methodology used by Hanson *et al.*, (20090 which took country level data and downscaled it to city level based on 2005 population levels reported in World Urbanisation Prospects (2007);. Projected per capita GDP levels were taken from the same report. Table 5 shows the actual counts for 2005 and projected estimates for 2030, 2050 and 2080. Note that, projections show that the population decreases beyond 2050, which is consistent with the A1 socio-economic scenario used[2] in this study. Other socio-economic scenarios may give other trends.

Table 5: Population and GDP per capita of Mombasa for 2000 and future predictions (in 2030, 2050, and 2080) under the A1 socio-economic scenario with rapid urbanisation

Projections	**2005**	**2030**	**2050**	**2080**
Population (Thousands)	821	1262	1893	1767

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[1] A rapid urbanisation growth which corresponds to the direct extrapolation of the 2030 UN scenarios to 2080 is used here. In this scenario, all cities within the country are assumed to grow at the same rate.

[2] It is also consistent with the declining fertility in Kenya as noted by United Nations Urbanisation Prospects (UNUP, 2007).

GDP per capita (US$)	378.7	796.0	2023.5	8040.4

3.2 Estimates of Exposure

The simulations to estimate the exposed number of people and associated economic assets that are located below the 1 in 100 year return period extreme water levels for each scenarios are performed based on the national population distribution data (1999 estimate) and a Digital Elevation Model (DEM) 250m resolution elevation data obtained from the World Resources Institute online database (*http://www.wri.org*). Estimates of the population for the district and its distribution over the five Mombasa districts are extracted from the national dataset. The population by elevation on a horizontal map of geographical cells is then estimated by mapping the population distribution for each division of the district onto the DEM (extracted, again from the national dataset), which allows the total population distributions against elevation to be estimated.

Note that these exposure estimates are the potential impacts on population and assets of the 1 in 100 year return period extreme water level events *in the absence* of sea flood defences. In estimating the infrastructure assets exposed to the 1 in 100 extreme water levels, a method used in Nicholls *et al.* (2007b) is adopted here to relate assets to the population exposed to the same extreme water levels (Equation 2). This rule is widely used to estimate asset exposure.

$E_a = E_p \text{ x } GDP_{percapita\ (PPP)} \text{ x } 5$ ………………………………..........………………………. (Eq. 2)

Where,

E_a = Exposed assets

E_p = Exposed population

$GDP_{percapita\ (PPP)}$ = the nation’s per capita Gross Domestic Product (GDP) Purchasing Power Parity (PPP).

3.3 Future socio-economic scenarios

The analysis for future impact projections considers the future socio-economic changes based on future population projections and changes in urbanisation and GDP of the Mombasa district following the country’s growth trend. Future projections are obtained from the country level predictions, following the methodology of Hanson *et al.*, 2009, which is downscaled based on the 2005 values for the City of Mombasa. In addition, focussing on worst-case impacts, rapid urbanization scenario is adopted here. The population distributions over the five divisions are obtained from the World Resources Institute online database (*http://www.wri.org*) for the 1999 estimate and assumed the same for the 2005.

Two population growth distribution scenarios for the 2030, 2050 and 2080 predictions are considered relative to the 2005 estimate as: (1) assuming the population of all the five divisions of the district grow uniformly based on the 2005s proportion, and (2) assuming the population growth on Mombasa Island to be zero (assuming fully populated) and the projected population growth will occur only over the other four divisions of the district (See Appendix).

4. Results and Discussion

Significant number of people and economic assets are located within the low-lying coastal zone of the district below an elevation of 10 metre above mean sea level (Table 6 and Figures 6 and 7). Table 6 shows that more than 199,000 people (1999 estimate) are within 10 metre of mean sea level, out of which 66.8%, 29.0%, 3.9% and 0.3% are located on the Mombasa Island, Kisauni-2, Changamwe and Linkoni, respectively. Elevations in Kisauni-1 are generally above the 40 metre contour.. Results also show that more than 81 percent (over 77,000 people in 1999) of the total population residing below mean sea level are concentrated on the Island City of Mombasa. By implication, the exposure risk of population and asset for a flood event under a 1 in 100 year return period extreme water levels will be significant.

Table 6: Population distribution against selected range of vertical ground elevations (1999 estimates)

Elevation Ranges (m)	Total Number of People (Thousands)					
	Mombasa District	Linkoni	Changamwe	Island	Kisauni-1	Kisauni-2
< 0.00	95.5	0.0	3.1	77.4	0.0	15.0
< 2.00	133.7	0.0	3.9	103.9	0.0	25.9
< 3.64	154.0	0.0	4.2	115.9	0.0	33.9
< 4.50	163.2	0.0	4.6	120.3	0.0	38.4
< 10.00	199.2	0.6	7.7	133.0	0.0	57.8
< 20.00	244.0	10.4	11.6	139.4	0.0	82.6
< 40.00	490.4	82.5	78.3	141.2	0.0	188.2
Total Population	653.8	93.3	171.5	141.2	5.4	242.2

Based on the two population distribution scenarios considered in this study, the sensitivity of the future exposure of population and assents are predicted. For instance by 2050, under the worst scenario (Scenario-1), it is projected that more than 577,000 people (and associated assets worth more than US$ 5.8 billion) will be exposed within the low-lying coastal zone (within 10m of mean sea level). This represents more than 30% of the total population of Mombasa for the same year (Figure 6). Although the population declines beyond 2050, the assets exposure in 2080 will be significantly high due to the high projected GDP per capita of the district for the given year (Figures 6 and 7).

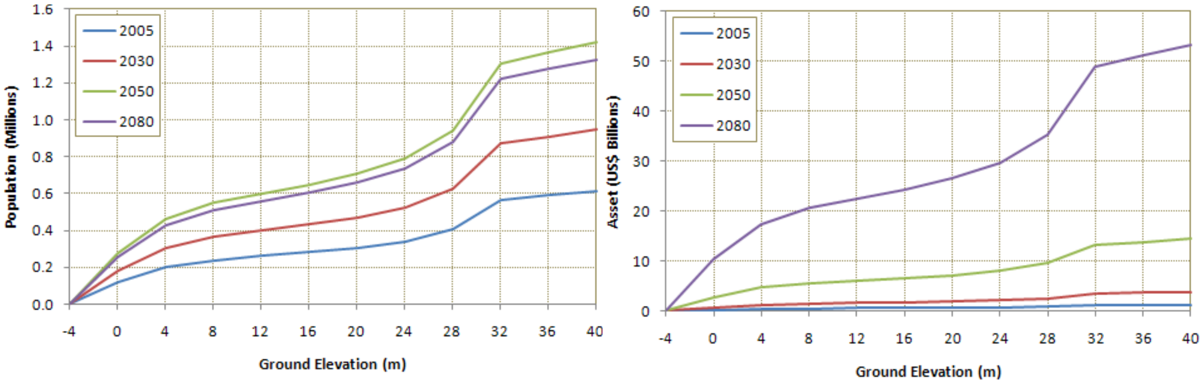

Figure 6: Scenario – 1: Projected Population and Assets distribution against vertical ground elevation of the district for the years 2030, 2050, and 2080 relative to the 2005 distribution – assuming Mombasa Island also grows as with the other four divisions of the district (See Appendix).

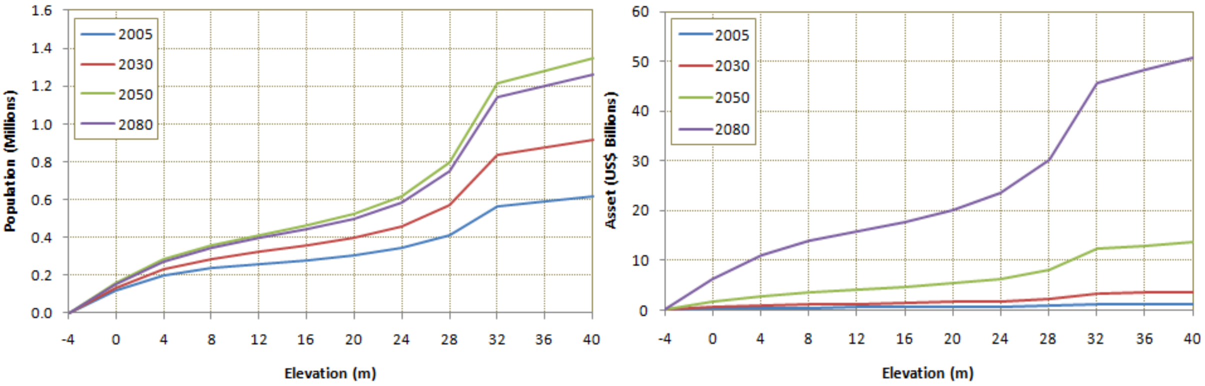

Figure 7: Scenario – 2: Projected Population and Assets distribution against vertical ground elevation of the district for the years 2030, 2050, and 2080 relative to the 2005 distribution – assuming Mombasa Island stays the same after the 2005 estimate, the growth occurs only in the other four divisions (See Appendix).

Table 7 – 10 show the total number of people and associated infrastructure assets exposed to a 1 in 100 year return period extreme water levels under low, medium and high sea-level rise scenarios coupled with the A1 socio-economic scenario and the two population distribution scenarios considered in this study. The two population growth distribution scenarios considered in the study show the sensitivity of future population and asset exposure predictions based on where people are going to settle in the future. If the population of Mombasa Island grows in the future in line with the other four divisions of the district, the population exposure will increase by over 1.5 times more than assuming it stays the same after 2005.

Table 7: Number of people and infrastructure assets exposed to a 1 in 100 year return period extreme water levels under the 2 scenarios of population growth and B1 low-range sea-level rise and A1 socio-economic scenario with rapid urbanisation

Year	Extreme Still Water Levels (m)	Exposed Population (Thousands)		Exposed Asset (US$ Billions)	
		Scenario - 1	Scenario - 2	Scenario - 1	Scenario - 2
2005	3.65	193.54	193.54	0.37	0.37
2030	3.69	297.93	226.78	1.19	0.90
2050	3.73	447.56	274.39	4.53	2.78
2080	3.80	418.87	265.97	16.84	10.69

Table 8: Number of people and infrastructure assets exposed to a 1 in 100 year return period extreme water levels under the 2 scenarios of population growth and A1B mid-range sea-level rise and A1 socio-economic scenarios with rapid urbanisation

Year	Extreme Still Water Levels (m)	Exposed Population (Thousands)		Exposed Asset (US$ Billions)	
		Scenario - 1	Scenario - 2	Scenario - 1	Scenario - 2
2005	3.66	193.61	193.61	0.37	0.37
2030	3.74	298.41	227.22	1.19	0.90
2050	3.83	449.48	276.09	4.55	2.79
2080	3.98	426.03	271.72	17.13	10.92

Table 9: Number of people and infrastructure assets exposed to a 1 in 100 year return period extreme water levels under the 2 scenarios of population growth and A1FI high-range sea-level rise and A1 socio-economic scenario with rapid urbanisation

Year	Extreme Still Water Levels (m)	Exposed Population (Thousands)		Exposed Asset (US$ Billions)	
		Scenario - 1	Scenario - 2	Scenario - 1	Scenario - 2
2005	3.67	193.68	193.68	0.37	0.37
2030	3.83	299.55	228.33	1.19	0.91
2050	4.00	460.90	284.82	4.66	2.88
2080	4.36	439.64	283.22	17.67	11.39

Table 10: Number of people and infrastructure assets exposed to a 1 in 100 year return period extreme water levels under the 2 scenarios of population growth and Rahmstorf sea-level rise and A1 socio-economic scenario with rapid urbanisation

Year	Extreme Still Water Levels (m)	Exposed Population (Thousands)		Exposed Asset (US$ Billions)	
		Scenario - 1	Scenario - 2	Scenario - 1	Scenario - 2
2005	3.67	193.68	193.68	0.37	0.37
2030	3.83	299.55	228.33	1.19	0.91
2050	4.03	462.53	286.24	4.68	2.90
2080	4.50	441.39	284.59	17.74	11.44

All the tables show that, significant number of people live within the low-lying areas of Mombasa. The highest exposure can be found on the Island City of Mombasa is with a total population of more than 140,000 (1999 estimate), as over 90% of its land is below 10 metre above mean sea level. The other three divisions are relatively at a much higher elevation. The two population growth distribution scenarios considered in the study show the sensitivity of future population and asset exposure predictions based on where people are going to settle in the future. If the population of Mombasa Island grows in the future in line with the other four divisions of the district (Scenario 1), the population exposure will increase by over 1.5 times more than assuming it stays the same after 2005 (Scenario 2)..

Assuming a linear growth in population and asset exposure between 2005 and 2030, the current exposures of the district is estimated at more than 210,000 people and an asset of over US$ 500 million. By 2080, under the worst scenario (Rahmstorf sea-level rise (84 cm rise in sea level) scenario combined with A1 socio-economic scenario and rapid urbanisation), approximately 285,000 people and over US$ 11 billion infrastructure asset throughout the district will be exposed to a 1 in 100 year storm surges assuming the Mombasa Island will not grow after the 2005 estimate. When Mombasa Island also assumed to grow in line with the other four divisions of the district, the exposure will increase by more than one and half times to over 440,000 people and an asset of approximately US$ 18 billion. The distribution of exposure of this population and asset are shown in Figure 6 and 7, based on the number of people living and associated infrastructure located within a given contour elevation.

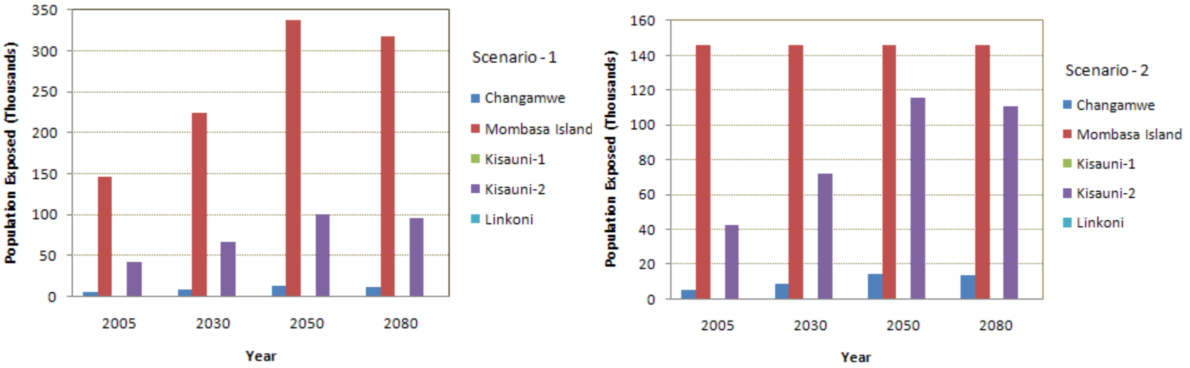

Figure 8: Population exposed to a 1 in 100 extreme still water levels in 2005, 2030, 2050, and 2080 under the A1B mid-range SLR and A1 SE scenarios coupled with a rapid urbanisation

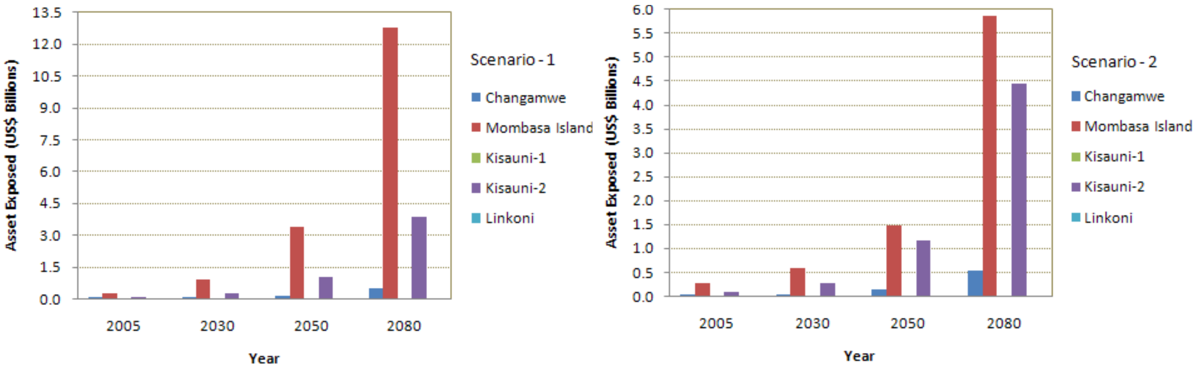

Figure 9: Economic asset exposed to a 1 in 100 extreme still water levels in 2005, 2030, 2050, and 2080 for the A1B mid-range SLR and A1 SE scenarios coupled with a rapid urbanisation

Figure 8 and 9 shows that Mombasa Island will significantly be impacted due to its high population density and associated economic assets located within the small but low-lying area in the district. By 2050 under the worst scenario (assuming the population on the island city also grows uniformly as with the other areas), more than 335,000 people and associated infrastructure which cost over US$ 3.4 billion will be flooded due to the 1 in 100 year return period extreme water levels under the A1B mid-range SLR and A1 SE scenarios. This represents more than 75 percent of the population and asset exposures of the whole district. This area of exposure to extreme water levels includes, in addition to the direct flood impacts on people and their assets, both harbours located on the east and west side of the island, hospitals, schools, roads, bridges, ferry services and other infrastructures located within the low-lying areas.

With population growth and urbanization considered to be a major factor to increase the number of people and asset exposed to flooding, climate-induced sea-level rise and storm surges will also significantly increase the exposure. For the A1B sea-level rise and A1 socio-economic scenario, a 3.83 metre extreme still water level would put approximately 450,000 people and infrastructure asset value more than US$ 4.5 billion at risk of flooding by 2050. However, it is observed that the population is projected to decline beyond 2050 showing a negative contribution to population exposure to extreme water levels (to 425,000 by 2080) but due to the high increase in the projected GDP per capita for 2080, the asset exposure will increase dramatically to more than US$ 17 billion (Table 8).

5. Conclusions

This case study on the impacts of climate change and sea-level rise on the coastal city of Mombasa has made a quantitative estimate of the number of people and associated economic asset exposed to coastal flooding due to extreme water levels. It provides a good indication of the potential impacts of climate change and sea-level rise on Mombasa due to extreme sea levels as the city is currently experiencing and is projected in the future to have a rapid growth in population, urbanisation and associated economic growth with time, e.g. by 2080. In this study it is assumed that human-induced subsidence and changes in tropical storms are not considered to be significant issues for Mombasa.

The GIS-based analysis results showed that more than 17 percent of the land area of the district lies within a low-lying area of the coastal zone (within 10 metre of mean sea level). Current estimates shows that more than 210,000 people and over US$ 500 million assets are exposed to a 1 in 100 year return period storm surges. By 2080, for the A1B mid-range sea-level rise (43 cm rise in sea level in 2100) and A1 socio-economic scenario with rapid urbanisation, more than 425,000 people, and infrastructure worth approximately US$ 17 billion will be exposed to coastal flooding due to sea-level rise and storm surges. About 75 percent of this exposure is concentrated in on Mombasa Island where approximately 360,000 people (2080 estimate) will settle within 10 metre contour elevation of mean sea-level, if the population is allowed to increase. Future socio-economic changes in terms of rapid population growth and urbanisation and associated economic growth in the city play a significant role in the overall increase of exposure of population and assets. This is highlighted by the two population growth scenarios for Mombasa Island which were investigated and show that exposure will still increase even if no changes in extreme water levels were predicted..

In conclusion, unless adaptation and mitigation measure are employed, with the changing climate and its severe consequences (such as rising sea levels and storm surges), significant portions of the city of Mombasa could be highly impacted leaving a large number of people and assets within the exposed areas at a higher risk of coastal flooding. This study suggests the magnitude of the impacts which need to be considered when planning for the future. However, the lack of accurate and long term sea-level measurement data could play a role in underestimating predictions of the potential impacts. Hence, it is very important that sea-level rise measurements are being made, and as the duration of measurements get longer they will get more useful for a better understanding of sea-level change. Furthermore, detailed work on Mombasa could assess flood risks (i.e. consideration of the influence of defences) as well as exposure. The full range of climate change risks could also be considered, such as the effects on corals (Nicholls *et al.*, 2007), and other flood mechanisms may become important such as intense precipitation events, as in 2006 as these will also affect the overall sustainability of this rapidly growing city.

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7. Appendices

Table A1: Scenario 1 - Future population and population density projections and their percentage distribution over the five divisions of the district – assuming that the population growth beyond 2005 would occur uniformly over all the five divisions of the district

			Linkoni	Changamwe	Island	Kisauni-1	Kisauni-2	Total
Area (km^2)			50.42	53.38	13.76	10.16	99.39	227.11
2005Actual Counts		Population Distributions (%)	14.30	26.20	21.60	0.80	37.00	100.00
		Population (Thousands)	117.21	215.31	177.59	6.74	304.09	821.00
		Population density (per km^2)	2,324.63	4,033.50	12,905.89	663.19	2,059.54	3,614.99
SCENARIO – 1: - Assuming all the five division will grow based on their proportion in the 2005s count								
Future Population Projections	Population Distributions (%)		14.30	26.20	21.60	0.80	37.00	100.00
	2030	Population (Thousands)	180.17	331.07	272.98	10.36	467.43	1,262.00
		Population density (per km^2)	3,572.32	6,202.15	19,838.30	1,019.49	4,702.98	5,556.78
	2050	Population (Thousands)	270.25	496.61	409.46	15.54	701.14	1,893.00
		Population density (per km^2)	5,359.98	9,303.24	29,757.41	1,529.23	7,054.47	8,335.17
	2080	Population (Thousands)	252.26	463.55	382.21	14.50	654.48	1,767.00
		Population density (per km^2)	5,003.21	8,684.00	27,776.74	1,427.36	6,584.92	7,780.37

Table A2: Scenario 2 - Future population and population density projections and their percentage distribution over the five divisions of the district – assuming that the population in the Mombasa Island remain the same and future growth would uniformly occur only in the other four divisions of the district

			Linkoni	Changamwe	Island	Kisauni-1	Kisauni-2	Total
Area (km^2)			50.42	53.38	13.76	10.16	99.39	227.11
2005Actual Counts		Population Distributions (%)	14.30	26.20	21.60	0.80	37.00	100.00
		Population (Thousands)	117.21	215.31	177.59	6.74	304.09	821.00
		Population density (per km^2)	2,324.63	4,033.50	12,905.89	663.19	2,059.54	3,614.99
SCENARIO – 2: - Assuming Mombasa Island stays the same and the growth will be distributed in the other four divisions of the district								
Future Population Projections	Population Distributions (%)		18.20	33.50	0.00	1.00	47.00	100.00
	2030	Population (Thousands)	197.54	363.00	177.59	11.36	512.51	1,262.00
		Population density (per km^2)	3,917.97	6,800.36	12,905.89	1117.81	5116.58	5,556.78
	2050	Population (Thousands)	312.49	574.23	177.59	17.97	810.73	1,893.00
		Population density (per km^2)	6,197.74	10,757.34	12,905.89	1,768.21	8,157.09	8,335.17
	2080	Population (Thousands)	289.54	532.05	177.59	16.65	751.18	1,767.00
		Population density (per km^2)	5,742.52	9,967.20	12,905.89	1,638.29	7,557.93	7,780.37