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ABSTRACT

Mombasa is the second largest city in Kenya and the largest international seaport in East Africa with more than 650,000 inhabitants. The city has a history of natural disasters associated with extreme climatic events, most recently the severe rain-induced flooding in October 2006, which affected about 60,000 people in the city and caused damage to important infrastructure. As the city is expected to continue to experience rapid growth, the future impacts of such events can only increase. Changes in sea level and storm surges are components of climate change which have the potential to further increasing the threats of flooding within the city.

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 potentially exposed to coastal flooding due to sea-level rise and storm surges in Mombasa. The current exposure to a 1:100 year extreme water level for the whole of Mombasa district is estimated at 190,000 people and US$470 million in assets. About 60 percent of this exposure is concentrated in the Mombasa Island division of the city where about 117,000 people (2005 estimate) live below 10m elevation. By 2080, the exposure could grow to over 380,000 people and US$15 billion in assets assuming the well-known A1B sea-level and socio-economic scenario. Future exposure is more sensitive to socio-economic than climate scenarios. However, there is significant scope within the city limits to steer future development to areas that are not threatened by sea-level rise. Hence, forward planning to focus population and asset growth in less vulnerable areas could be an important part of a strategic response to sea-level rise.

The methods used here could be applied more widely to other coastal cities in Africa and elsewhere to better understand present and future exposure and worst-case risks due to climate change and rising sea levels.

ADDITIONAL INDEX WORDS: *Extreme Water Levels, Storm Surges, Coastal Flooding, Population*

Exposure, Asset Exposure.

1. INTRODUCTION

The world is currently facing major challenges due to climate change and its variability (PARRY *et al.*, 2007). Sea-level rise and extreme water levels are important components of climate change for coastal areas. Coastal zones have high ecological value and economic importance, and typically are more densely populated than inland areas (MCGRANAHAN, BALK and ANDERSON, 2007; SMALL and NICHOLLS, 2003). The potential impacts are largest where populations and associated economic activities are highly concentrated such as in low-lying coastal cities. In the developing world, few if any coastal cities are prepared for the impacts of climate change, particularly sea-level rise and storm events (MCGRANAHAN, BALK and ANDERSON, 2007; NICHOLLS *et al.*, 2008a). They are typically undergoing fast and unplanned growth, have high population densities and overburdened infrastructure, 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 (BICKNELL, DODMAN and SATTERTHWAITE, 2009; NICHOLLS *et al.*, 2007). The magnitude of these sea level change impacts will vary from place-to-place depending on topography, geology, natural land movements and any human activity which contributes to changes in water levels or sediment availability (e.g. subsidence due to ground water extraction). Despite these threats, few coastal cities have been assessed in terms of possible coastal impacts.

The coastal city of Mombasa currently faces significant threats from direct and indirect impacts of climate change and its variability. Mombasa is Kenya's second largest city, after Nairobi, with a total population of more than 650,000 and an average population density of 2858 persons per square kilometre (1999 estimate) (World Resources Institute – *http://www.wri.org*). The city has two major harbours (Kilindini Harbour and Old Port), comprising the largest seaport in Eastern Africa serving not only Kenya, but also its landlocked East and Central African neighbours (such as Uganda, Rwanda, Burundi, Congo, Ethiopia and Southern Sudan) (MUSINGI, KITHIIA and WAMBUA, 1999). This significantly contributes to the region's economy, and if this international harbour was disrupted by extreme climate events, direct and indirect impacts would undoubtedly be felt across the region (AWUOR, ORINDI and ADWERA, 2008). In this regard, it has much in common with many other port cities around the world (NICHOLLS *et al.*, 2008a)

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 tourists. 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. At national level it contributes about 12 percent (2004 estimate) of the country's GDP (GOVERNMENT OF KENYA, 2006). Mombasa already has a history of extreme climatic events including floods that have caused damages nearly every year (AWUOR, ORINDI and ADWERA, 2008; UN-HABITAT, 2008). Most recently, the flooding due to intense precipitation in October 2006 has affected about 60,000 people in the city. Coastal erosion (where the sandy beaches along the coast experience erosion rate of 2.5 – 20 cm/year) also poses a problem in the coastal zone (MWAKUMANYA and BDO, 2007). The coastal zone has significant low-lying land areas which are vulnerable to increased flooding, landward saltwater intrusion, and shoreline erosion, including recently developed areas (OKEMWA, RUWA and MWANDOTTO, 1997). Tourist and port facilities and other industries could particularly be affected. Ecologically, loss of coral reefs, coastal and marine biodiversity, and fisheries is also possible. Informal and/or unplanned settlements in the coastal zone also negatively impact the environment (e.g. no/poor drainage system), and also leads to high vulnerability (e.g. due to intense back-to-back development leading to over-concentration in low-lying areas) (NEMA – *http://www.nema.go.ke*).

Concern about all these effects under the changing climate and rising sea levels is apparent. It has been predicted that a 30-cm rise in sea level could submerge 17 percent (about 4,600 hectares of land area) of the city, assuming no adaptation (AWUOR, ORINDI and ADWERA, 2008; UN-HABITAT, 2008). Hotels and other tourist facility providers are being forced to build seawalls and other defence structures. This is often anecdotally linked to climate change and rising sea levels, but detailed studies to understand these problems have not been carried out and non-climate causes are quite plausible. It is also anticipated that the city could face significant climate change related health risks (e.g. water-borne and diarrheal diseases such as cholera) (AWUOR, ORINDI and ADWERA, 2008). These effects are likely to disproportionately impact people who reside in informal/unplanned settlements within the low-lying areas due to their poor adaptive capacity. However, these judgements are not based on detailed quantitative analysis.

This paper therefore aims to provide a broader more quantitative context to the potential coastal flooding risks and anticipated impacts on Mombasa based on physical exposure and socio-economic vulnerability to climate extremes and sea-level rise. The study follows the approach of HANSON *et al*. (2009) and NICHOLLS *et al*. (2008a), and determines the number of people and value of assets exposed to extreme water levels over the 21st century under a range of scenarios. The paper is structured as follows: Section 2 gives a general description of the study area and sea level measurements in Mombasa. The methodology used is detailed in Section 3, and results are presented and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. STUDY AREA

2.1 City of Mombasa

The coastal city of Mombasa is located in southern Kenya (39.7^{o} East, 4.1^{o} South) (Figure 1). The geology of the Kenyan coast is dominated by the rifting and break-up of the Paleozoic Gondwana continent and the development of the Indian Ocean (EMBLETON and 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, ORINDI and ADWERA, 2008) and forms part of a fringing reef shoreline of Pleistocene Age with raised reef limestone along the coast (KAIRU, 1997). The coastal geomorphology consists of a mixture of sandy beaches, creeks, muddy tidal flats, coral reefs and rocky shores (ABUODHA, 1992; OESTEROM, 1988). Tidal exchange in the creeks is considerable with a maximum tidal range of 4.0 metre at spring tide and 2.5 metre at neap tide. There is also freshwater and sediment input from rivers. The waves outside the fringing reef may reach in amplitude ranging from 1 to 3 metres during monsoons (RUWA and JACCARINI, 1986). Offshore, the sea floor drops to below 200 metres within less than 4 kilometres of the shoreline (ABUODHA, 1992).

Mombasa is one of the major tourist destinations in Africa with the highest tourism facility and infrastructure concentrations in the coastal zone (AKAMA and KIETI, 2007). The city's history dates back to the 16th Century when it emerged as an important port (HOYLE, 2000). The international airport in Mombasa also represents an architectural symbol of the Kenya's growing investment on tourism industry, attracting many tourists worldwide. The population of the city has also increased by a factor of more than two-and-half from 350,000 in 1980 to 882,000 in 2007, and a growth rate of between 3.1% and 3.6% (UNPD, 2007). This fast growth is attributed to natural and rural-urban migration and associated socio-economic development, and is projected to continue due to the high economic potential.

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. The district has five divisions separated by tidal creeks and channels: Linkoni, Changamwe, Mombasa Island, Kisauni-1, and Kisauni-2 (Figure 1). They are connected by causeways, bridges, or ferries. Table 1 shows three years census data, and population and land area distribution between the divisions. In 1999, over 140,000 people (with a population density of more than 10,000 people/km^2) and over 240,000 people (with a population density of more than 2,450 people/km^2) lived on the Mombasa Island and the Kisauni-2 divisions, respectively.

According to the Digital Elevation Model (DEM) used in the study, about 94% of the Mombasa Island and 24% of the Kisauni-2 divisions lie within the Low-Lying Coastal Zone ('LLCZ' - defined here as the land area within 10 metres of mean sea level) (Figure 1). In the other divisions, the land areas are generally at higher elevations (up to 226m) and only limited areas could be affected by present or future extreme sea levels.

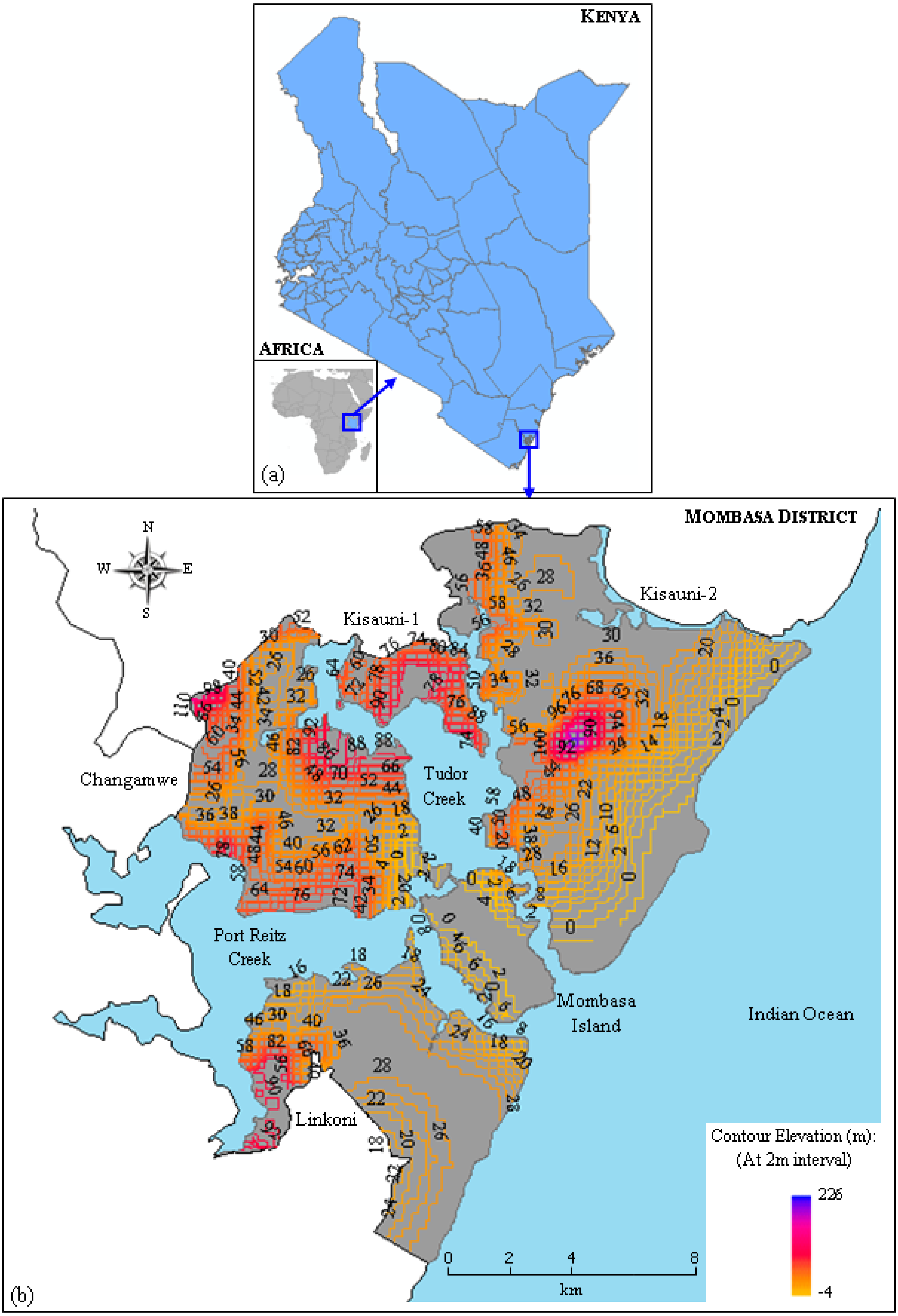


Figure 1: (a) Location of Mombasa, and (b) Elevation distribution within Mombasa district (Source: World Resources Institute – *http://www.wri.org*), and the five divisions.

Table 1: Population distribution in the Mombasa District by division (Source: GOK (1979, 1989 & 1999); World Resources Institute – *http://www.wri.org*).

DIVISION NAME	POPULATION (thousands)			In 1999			
				LAND AREA (km^2)		POPULATION	
	1979	1989	1999	Total	Urban	%	Population Density (people per km^2)
Changamwe	81.3	113.5	171.5	54.1	10.9	26.2	3173
Kisauni-1	1.7	3.3	5.4	10.6	-----	0.8	508
Kisauni-2	78.3	150.0	242.2	98.7	5.0	37.0	2454
Linkoni	39.7	67.2	93.3	51.3	4.6	14.3	1819
Mombasa Island	136.1	127.7	141.4	14.1	6.1	21.6	10023
MOMBASA DISTRICT	**337.1**	**461.7**	**653.8**	**228.8**	**26.6**		**2858**

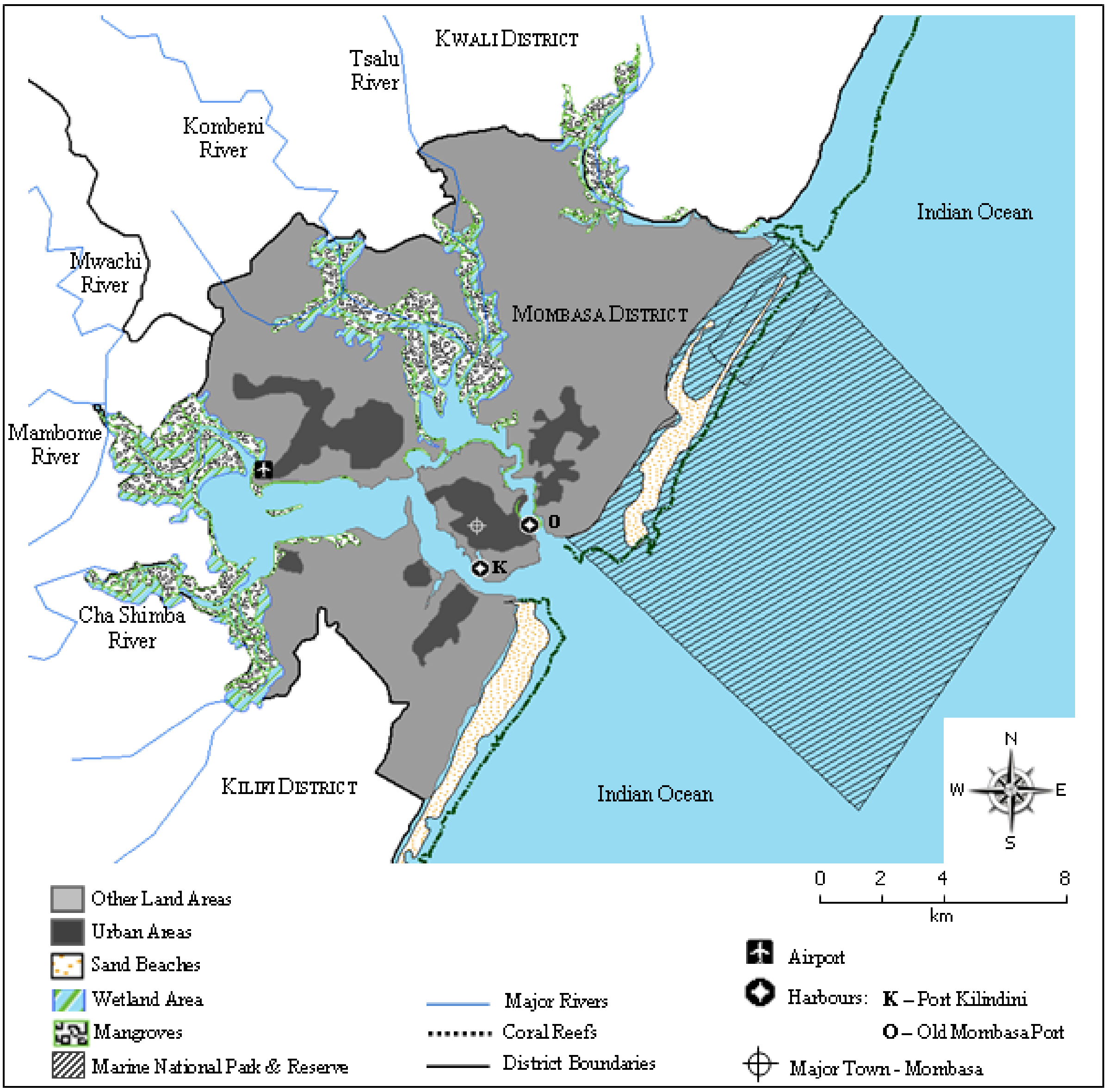


Figure 2: Major land use and coastal characteristics/facilities in the Mombasa District.

Figure 2 shows the major land use. Mombasa has both the international port - Kilindini Harbour (also called Port Kilindini) and the Moi International Airport serving as a gateway into the region. Kilindini is a modern deepwater harbour on the south-west side of the Mombasa Island, with extensive docks, shipyards, and sugar and petroleum refineries handling about 33.3 million tonnages traffic as reported in HANSON *et al*. (2009). The Old Mombasa Port, on the north-east side of the island, handles mainly dhows and other small coastal trading vessels. Mombasa is the country's and the region's principal seaport and is one of the most modern and busiest ports in Africa.

Table 2 and Figure 3 show the land and urban area distribution of the district against elevation. The urban areas represent about 12 percent of the total land area, and are mainly concentrated in the low-lying areas. According to the Digital Elevation Model (DEM) used in the study, more than 19 percent of the total land area of the district and about 32 percent of the urban areas (including the whole urban area of the Mombasa Island division) lie within the LLCZ.

Table 2: Urban and other land area distribution of Mombasa district against ground elevation (1999 estimate).

LAND AREA	ELEVATION RANGES (m)						TOTAL (District Wide)
	< 0	< 2	< 5	< 10	< 20	< 40	
Urban Area (km^2)	5.0	6.0	7.1	8.5	11.3	21.4	26.6
Total land area (km^2)	21.3	28.7	36.2	44.2	61.7	162.6	228.8

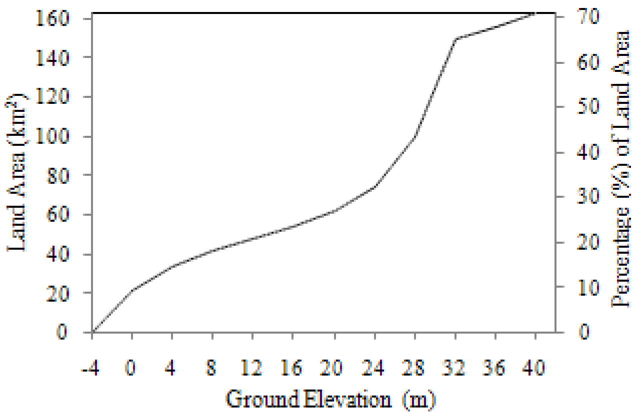


Figure 3: Distribution of land area against elevation in the Mombasa District.

The five divisions of the district are separated by two major creeks (Port Reitz - the southern inlet, and Tudor - the northern inlet (Figure 2)) and an estuary system which consists of 47.5km^2 of wetlands, of which about 39km^2 are mangroves (World Resources Institute – *http://www.wri.org*). The two major rivers (Kombeni and Tsalu, Figure 2) of the Tudor creek drain a total area of 550km^2. The Port Reitz creek, which is formed as a result of drowning of former river valleys due to late Pleistocene/early Holocene sea-level rise (CASEWELL, 1956), receives its freshwater from three seasonal river systems (Cha Shimba, Mambome and Mwachi, Figure 2) (KAMUA, 2002). The mangroves provide essential functions and services to the coastal ecosystem, but are threatened by human activities. Both direct destruction (e.g. as a source of fuelwood and timber production) and indirect effects (e.g. oil pollution) are leading to their deterioration and losses (ABUODHA and KAIRO, 2001).

Part of the coastal strip and seaward of the Kisauni-2 division is a government managed protected Marine National Park and Reserve – of about 10 and 200km^2, respectively (NGUGI, 2002) (Figure 2). 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, abundance of fish, coral cover and diversity of benthic communities, the park and the reserve also provide a significant tourist attraction.

2.2 Recent Sea-Level Change

The global rise in mean sea level was 1.7mm/year during the 20th Century (CHURCH and WHITE, 2006; BINDOFF *et al*., 2007). Based on models of thermal expansion and ice sheet response to global warming, global mean sea-level rise is expected to accelerate in the 21st Century (CHURCH *et al*., 2001; MEEHL *et al*., 2007). In Africa, sea level measurements are limited (WOODWORTH, AMAN and AARUP, 2007), but there is some data at Mombasa (KIBUE, 2006; MAGORI, 2005).

The available sea level dataset of monthly values received by the Permanent Service for Mean Sea Level (PSMSL RLR dataset) covers 1986 to 2002 and shows no significant trend, although the best fit is 1.1mm/year (Figure 4). This indicates that Mombasa is not experiencing a sea level trend substantially different to global mean trends, and applying global scenarios directly is meaningful for Mombasa. It is important to note that estimates of trends of sea level change obtained from records of short durations (< 50 years) could have a significant bias due to interannual-to-decadal water level variability (DOUGLAS, 2001). Hence, it is important that the sea-level rise measurements at Mombasa are continued: as their duration increases, so they will get more useful both scientifically and for coastal management purposes.

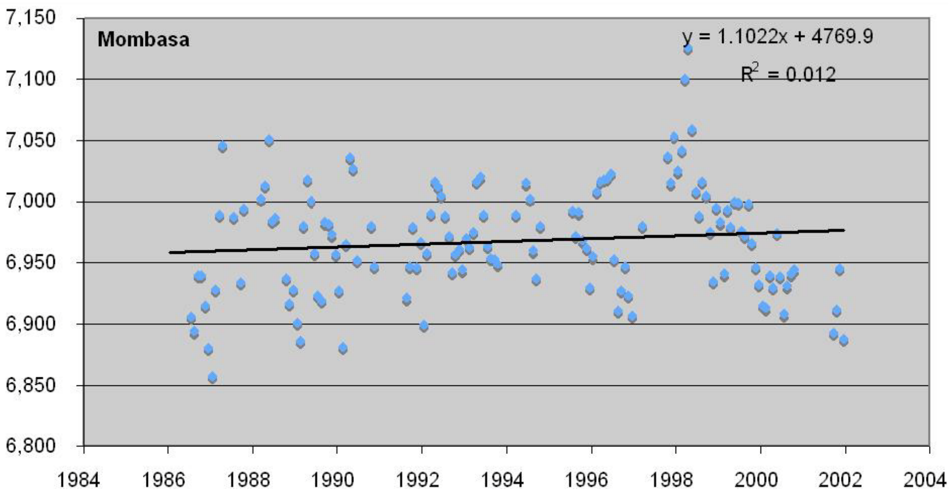


Figure 4: Monthly sea level measurements for Mombasa Station , Kenya (39°39'East, 04°04'South) from 1986 to 2002 (Source: Permanent Service for Mean Sea Level (PSMSL), *http://www.pol.ac.uk/psmsl*) (Note: all values are in mm).

3. METHODOLOGY

The focus of this analysis is to provide a more quantitative broader context to the potential impacts of coastal flooding due to extreme water levels on Mombasa based on physical exposure and socio-economic vulnerability. The study follows the approach of HANSON *et al*. (2009) and NICHOLLS *et al*. (2008a) to determine the number of people and value of assets exposed to extreme water levels over the 21st century under a range of scenarios. Particular focus is given to 'exposure' rather than 'residual risk' (which involves consideration of defences and other adaptation measures), as it represents the 'worst-case' impacts, recognising that even if defences (natural or artificial) are present they are subject to failure under the most extreme events. Exposure therefore indicates the potential worst-case magnitude for any future event, which needs to be considered when planning for the future. Due to lack of detailed information and accurate data on coastal defence system in Mombasa (if any), protection cannot be assessed here. The analysis however assesses exposure under a range of projected sea-level rise scenarios giving a good indication of the worst-case scenario in terms of the average population and value of assets which could be flooded in an extreme event. The analysis is conducted within the framework of the SRES[1] scenarios, although post-AR4 insights are considered.

3.1 Calculation of Extreme Water Levels

The methodology adopted in this study is based on that developed by MCGRANAHAN, BALK and ANDERSON (2007) and NICHOLLS *et al*. (2008a). 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.* (2008a) calculated extreme coastal water levels from a combination of storm surge, sea level, natural subsidence and human-induced subsidence. For Mombasa, changes in storminess and human-induced subsidence are not considered relevant. Mombasa is located near the Equator so does not experience the landfall of tropical storms today and this is not expected to change in the future. Hence, the storm surge regime is assumed to remain constant. Similarly, human-induced subsidence is not recognised as an issue in Mombasa, or suggested by the sea-level measurements (Figure 4), and given the absence of thick and extensive Holocene sediments, this is unlikely to change.

Hence, changes in Extreme Water Levels (*EWL*) are given by:

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

Where:

SLR = Global Mean Sea-Level Rise Scenarios

$S100$ = 1:100 year extreme water level (estimated as 3.62 m)

$SUB_{Natural}$ = Total natural land subsidence (estimated as 0.42 mm per year)

[1] The SRES scenarios are the sea-level and socio-economic scenarios based on the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IMAGE TEAM, 2002; NAKIĆENOVIĆ and SWART, 2000).

For the analysis, storm surge heights and natural subsidence rates are directly adopted from the coastal segment in the DIVA[2] database which includes Mombasa (VAFEIDIS *et al*., 2005; 2008). The water levels are calculated based on Equation 1 for current levels and four future projected global sea-level rise (SLR) scenarios which were selected to cover a wide range of possible change including scenarios above the range given by MEEHL *et al*. (2007) to reflect the post-AR4 literature on sea-level rise. These include: low (B1), medium (A1B), high (A1FI) (based on the grid of the Climate and Bio-sphere Group (CLIMBER) climate model as described by GANOPOLSKI and RAHMSTORF, 2001), and a further higher scenario termed 'Rahmstorf' (based on RAHMSTORF, 2007) for the years 2005, 2030, 2050 and 2080 (Table 3 and Figure 5). Note that even higher scenarios than used here have been suggested (e.g., VERMEER and RAHMSTORF, 2007). The ranges of the SLR scenarios used here are considered as a sensitivity analysis to examine impacts on a range of uncertainty. The estimated extreme still water levels are given in Table 4.

Table 3: Global mean sea-level rise scenarios: 1990 to 2100.

YEAR	SEA-LEVEL RISE SCENARIOS (m)				
	Rahmstorf	A1FI high-range	A1B mid-range	B1 low-range	No SLR
1990	0.00	0.00	0.00	0.00	0.00
2000	0.04	0.04	0.02	0.01	0.00
2005	0.05	0.06	0.03	0.02	0.00
2010	0.07	0.08	0.04	0.02	0.00
2020	0.12	0.13	0.07	0.03	0.00
2030	0.19	0.19	0.10	0.05	0.00
2040	0.27	0.26	0.14	0.06	0.00
2050	0.38	0.35	0.18	0.08	0.00
2060	0.51	0.46	0.23	0.10	0.00
2070	0.66	0.57	0.28	0.12	0.00
2080	0.84	0.70	0.32	0.14	0.00
2090	1.04	0.83	0.38	0.16	0.00
2100	1.26	0.97	0.43	0.17	0.00

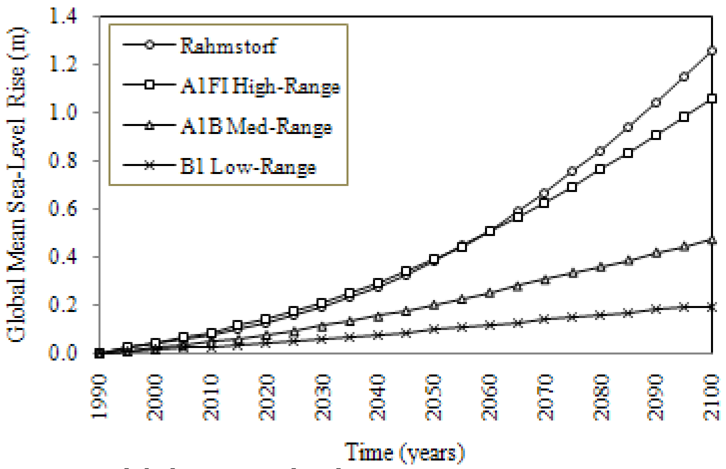


Figure 5: Global mean sea-level rise scenarios.

Table 4: Extreme still water levels for each scenario.

[2] DIVA is the Dynamic Interactive Vulnerability Assessment model developed in the EU 5th Framework Project DINAS-COAST (DINAS-COAST CONSORTIUM, 2006)

YEAR	SEA-LEVEL RISE SCENARIOS (m)				
	Rahmstorf	**A1FI high-range**	**A1B mid-range**	**B1 low-range**	**No SLR**
2005	3.70	3.71	3.67	3.65	3.63
2030	3.91	3.90	3.78	3.70	3.64
2050	4.16	4.11	3.88	3.75	3.65
2080	4.70	4.49	4.04	3.82	3.66

3.2 Future Socio-Economic Scenarios

The analysis of future impacts considers future socio-economic changes based on future scenarios of population, including urbanisation, and gross domestic product (GDP) of the district, following the A1 scenario [3]. Future projections are obtained from country level predictions, following the methodology of HANSON *et al*. (2009), which is downscaled for Mombasa based on 2005 population levels reported in UNPD (2007). Projected per capita GDP levels were taken from the same report. In addition, focussing on worst-case impacts, the rapid urbanization[4] scenario is reasonably adopted. Table 5 gives the socio-economic scenarios used for the base year (2005), and three projected time series of the years 2030, 2050 and 2080. Note that the population decreases beyond 2050, which is consistent with the A1 socio-economic scenario[5]. Other socio-economic scenarios such as the A2 socio-economic scenario would give a continual growth to 2100, and a larger exposed population but a lower GDP.

Table 5: Population and GDP per capita of Mombasa through the 21st Century under the A1 socio-economic scenario with rapid urbanisation.

PROJECTIONS	YEAR			
	2005	**2030**	**2050**	**2080**
Population (Thousands)	821	1262	1893	1767
GDP per capita (US$)	378.7	796.0	2023.5	8040.4

3.3 Estimates of Population and Asset Exposure

The sea-level rise scenarios considered are coupled with the A1 socio-economic and the rapid urbanisation scenarios for estimating the future projected population exposure. This follows the methodology used by HANSON *et al*. (2009). The population distributions over the five divisions for the base year (2005) are estimated based on the growth trend of the population distributions in the divisions for the three years (1979, 1989 and 1999) census data (see Table 1), assuming a linear trend line projection with time. For the years 2030, 2050 and 2080 predictions, two population growth distribution scenarios along with a 'no population growth' scenario are considered relative to the 2005

[3] A1 is derived from the Special Report on Emission Scenarios (SRES) of the IPCC (IMAGE TEAM, 2002; NAKIĆENOVIĆ and SWART, 2000; NICHOLLS *et al*., 2008b).

[4] 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.

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

levels reflecting the potential policy choices of how to manage the expanding future population and associated exposure (Table 6).

Table 6: Population growth distribution scenarios used in this study.

Population Growth (PG)	**Scenario Description**
1	Assume the population of the five divisions of Mombasa will grow uniformly based on the 2005 distribution (worst scenario),
2	Assume the population growth on Mombasa Island is zero (i.e. kept constant at 2005 levels) and the projected population growth occurs in the other four divisions of Mombasa.
NoPG	A 'no population growth' scenario – assume the population in all the divisions is kept at 2005 levels.

The simulations to estimate exposed number of people and associated economic assets that are located below the 1:100 year return period extreme water levels for each scenarios are performed based on a population distribution data (see Table 1) and a Digital Elevation Model (DEM) of 250m-resolution elevation data obtained from the World Resources Institute online database (*http://www.wri.org*).

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, which allows the total population distribution against elevation to be estimated. In estimating the infrastructure assets exposed to a 1:100 year extreme water levels, a method commonly used in the insurance industry and applied by NICHOLLS *et al*. (2008a) is adopted to relate the value of assets to the population exposed to the same extreme water levels (Equation 2).

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

Where,

E_a = Exposed asset (monetary value)

E_p = Exposed population

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

Figure 6 summarises the methodology.

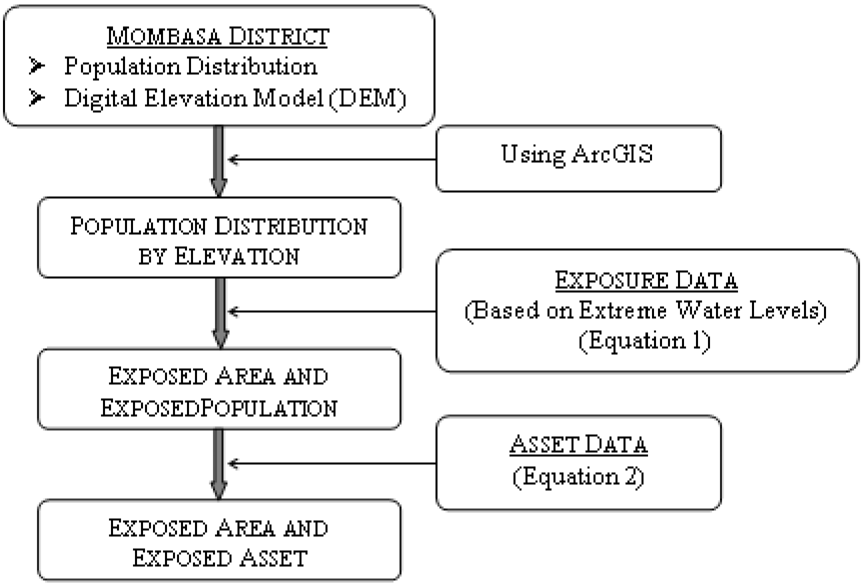


Figure 6: A simplified flowchart of the methodology (Adapted from NICHOLLS *et al.*, 2008a).

4. RESULTS AND DISCUSSION

Significant numbers of people and economic assets are estimated to be located within the Low-Lying Coastal Zone (LLCZ) Mombasa. Table 7 shows that more than 210,000 people (in 2005) are located within the LLCZ. This represents about 26% of the total population of Mombasa for the same year. About 55% of these are in the Mombasa Island division, followed by 39% in the Kisauni-2 division, and 5% in the Changamwe division. Elevations in the Linkoni and Kisauni-1 divisions are generally above the 8 and 40 metre contours, respectively, and hence population and asset exposure is much lower. In addition, about 82 percent (i.e., 67,000 people in 2005) of the total population who resided below mean sea level are concentrated on the Mombasa Island. By implication, the population and asset exposure to a coastal flood event of a 1:100 year return period is already significant. The informal shanty towns which have developed in recent years will be most exposed to high sea levels – but it is worth noting that to date reported floods are linked to high precipitation events and not extreme sea levels, so the DEM may overestimate the areas at lowest elevations. However, the low land elevations make drainage an issue and this contributes to flooding in the rainfall events. As sea-level rise degrades drainage, it contributes to exacerbating the observed floods, such as in October 2006, unless drainage can be upgraded.

Table 7: Population distribution in 2005 (base line) against selected range of vertical ground elevations.

ELEVATION RANGES (m)	**TOTAL NUMBER OF PEOPLE (Thousands)**					
	Mombasa District	**DIVISIONS OF MOMBASA DISTRICT**				
		Changamwe	Kisauni-1	Kisauni-2	Linkoni	Mombasa Island
< 0	81.3	3.9	0.0	10.7	0.0	66.7
< 2	127.2	6.8	0.0	31.6	0.0	88.8
< 5	180.2	8.7	0.0	64.8	0.0	106.7

< 10	212.3	10.7	0.0	82.6	2.5	116.5
< 20	254.9	15.0	0.0	111.7	7.3	120.9
< 40	581.8	89.8	0.0	255.8	112.0	124.2
TOTAL	**821.0**	**218.4**	**7.4**	**342.4**	**128.1**	**124.8**

Based on the population growth (PG) scenarios used (see Table 6), the sensitivity of future population and asset exposure is estimated. For instance by 2050 under the PG Scenario 1, more than 480,000 people and assets worth over US$4.8 billion will be exposed within the LLCZ (Figure 7). However, for the PG Scenario 2, the exposure falls to 350,000 people and US$3.5 billion in assets (Figure 8). Furthermore, when the 'no population growth' (NoPG) scenario is considered, the exposure drops further to 205,000 people and US$2.1 billion in assets (Figure 9). Although the population declines beyond 2050, the asset exposure continues to grow significantly due to the projected increase in GDP per capita (Figures 7, 8 and 9). Note that these costs are reported in 2005 US$ and are NOT discounted.

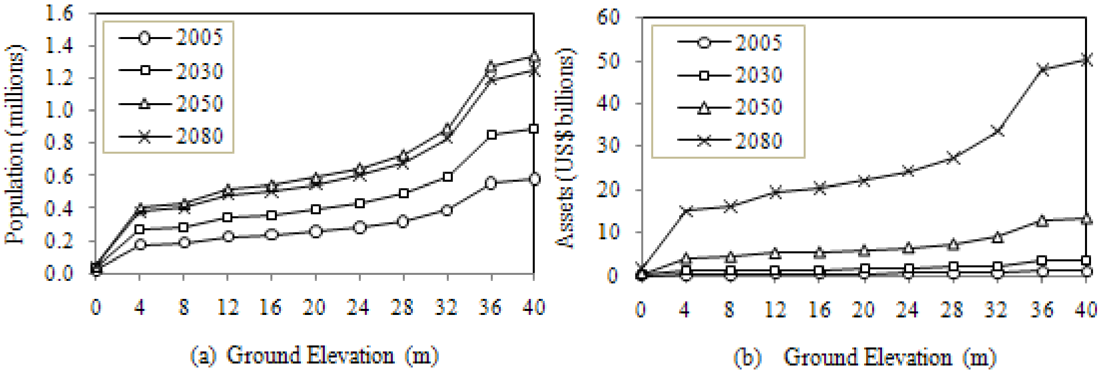


Figure 7: POPULATION GROWTH SCENARIO 1: (a) Population and (b) Asset distribution against vertical ground elevation for the years 2005, 2030, 2050, and 2080.

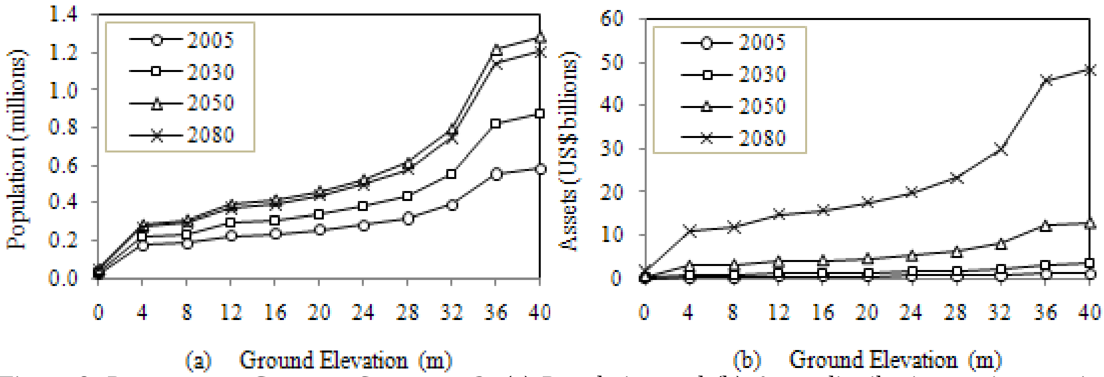


Figure 8: POPULATION GROWTH SCENARIO 2: (a) Population and (b) Asset distribution against vertical ground elevation for the years 2005, 2030, 2050, and 2080.

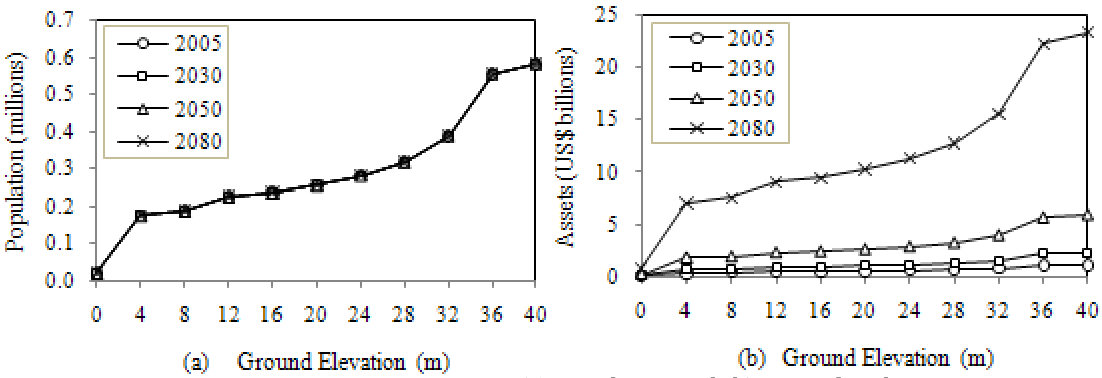


Figure 9: NO POPULATION GROWTH SCENARIO: (a) Population and (b) Asset distribution against vertical ground elevation for the years 2005, 2030, 2050, and 2080.

Tables 8 to 12 show the total number of people and economic assets exposed to a 1:100 year return period extreme water levels under the ranges of sea-level rise and socio-economic scenarios considered.

Table 8: Population and asset exposed to a 1:100 year return period extreme water levels under the three population growth scenarios for the no climate-induced sea-level rise and A1 socio-economic scenario with rapid urbanisation.

YEAR	**EXTREME STILL WATER LEVELS (m)**	**POPULATION EXPOSED (Thousands)**			**ASSETS EXPOSED (US$ Billions)**		
		PG Scenario 1	**PG Scenario 2**	**NoPG Scenario**	**PG Scenario 1**	**PG Scenario 2**	**NoPG Scenario**
2005	3.63	170.6	170.6	170.6	0.32	0.32	0.32
2030	3.64	262.4	214.1	170.7	1.04	0.85	0.68
2050	3.65	393.7	276.4	170.8	3.98	2.80	1.73
2080	3.66	367.8	264.2	170.9	14.78	10.62	6.87

Table 9: Population and asset exposed to a 1:100 year return period extreme water levels under the three population growth scenarios for the B1 low-range sea-level rise and A1 socio-economic scenario with rapid urbanisation.

YEAR	**EXTREME STILL WATER LEVELS (m)**	**POPULATION EXPOSED (Thousands)**			**ASSETS EXPOSED (US$ Billions)**		
		PG Scenario 1	**PG Scenario 2**	**NoPG Scenario**	**PG Scenario 1**	**PG Scenario 2**	**NoPG Scenario**
2005	3.65	170.8	170.8	170.8	0.32	0.32	0.32
2030	3.70	263.1	214.7	171.1	1.05	0.85	0.68
2050	3.75	394.9	277.3	171.3	4.00	2.81	1.73
2080	3.82	369.7	265.9	171.8	14.86	10.69	6.91

Table 10: Population and asset exposed to a 1:100 year return period extreme water levels under the three population growth scenarios for the A1B mid-range sea-level rise and A1 socio-economic scenarios with rapid urbanisation.

YEAR	**EXTREME STILL WATER LEVELS (m)**	**POPULATION EXPOSED (Thousands)**			**ASSETS EXPOSED (US$ Billions)**		
		PG Scenario 1	**PG Scenario 2**	**NoPG Scenario**	**PG Scenario 1**	**PG Scenario 2**	**NoPG Scenario**
2005	3.67	170.9	170.9	170.9	0.32	0.32	0.32
2030	3.78	263.6	215.2	171.5	1.05	0.86	0.68
2050	3.88	398.2	280.3	172.7	4.03	2.84	1.75
2080	4.04	380.0	274.3	176.5	15.28	11.03	7.10

Table 11: Population and asset exposed to a 1:100 year return period extreme water levels under the three population growth scenarios for the A1FI high-range sea-level rise and A1 socio-economic scenario with rapid urbanisation.

YEAR	**EXTREME STILL WATER LEVELS (m)**	**POPULATION EXPOSED (Thousands)**			**ASSETS EXPOSED (US$ Billions)**		
		PG Scenario 1	**PG Scenario 2**	**NoPG Scenario**	**PG Scenario 1**	**PG Scenario 2**	**NoPG Scenario**
2005	3.71	171.2	171.2	171.2	0.32	0.32	0.32
2030	3.90	265.7	217.2	172.9	1.06	0.86	0.69
2050	4.11	410.4	290.3	178.0	4.15	2.94	1.80
2080	4.49	389.9	283.2	181.1	15.67	11.39	7.28

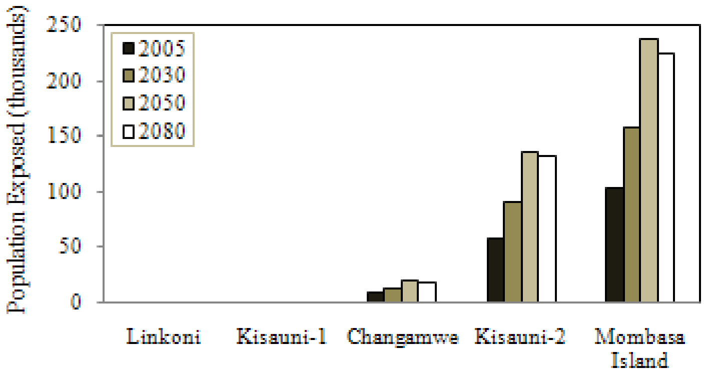
Table 12: Population and asset exposed to a 1:100 year return period extreme water levels under the three population growth scenarios for the Rahmstorf sea-level rise and A1 socio-economic scenario with rapid urbanisation.

YEAR	**EXTREME STILL WATER LEVELS (m)**	**POPULATION EXPOSED (Thousands)**			**ASSETS EXPOSED (US$ Billions)**		
		PG Scenario 1	**PG Scenario 2**	**NoPG Scenario**	**PG Scenario 1**	**PG Scenario 2**	**NoPG Scenario**
2005	3.70	171.1	171.1	171.1	0.32	0.32	0.32
2030	3.91	266.3	217.6	173.2	1.06	0.87	0.69
2050	4.16	412.8	292.7	179.0	4.18	2.96	1.81
2080	4.70	392.3	285.3	182.3	15.77	11.47	7.33

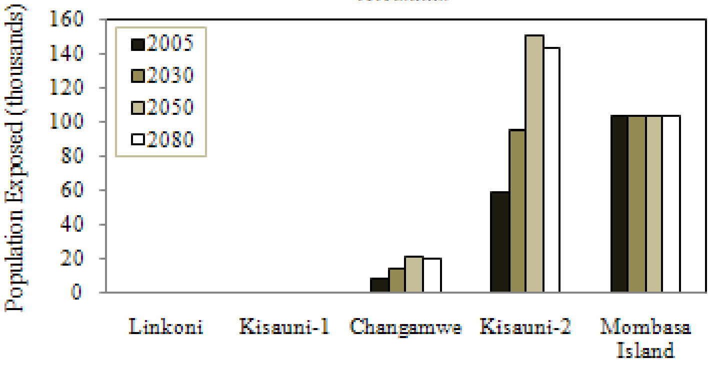
The results demonstrated that future population and asset exposure is more sensitive to socio-economic scenarios than climate scenarios. By 2050, if the population of Mombasa Island grows in the future in line with the other four divisions of the district (i.e., PG Scenario 1 of Table 6), the exposure will increase by a factor of more than 1.4 than assuming it stays at 2005 levels (i.e., PG Scenario 2 of Table 6) under all sea-level rise scenarios.

Assuming a linear growth in population and asset exposure between 2005 and 2030, as high as 190,000 people and economic assets worth over US$470 million are currently exposed to a 1:100 year extreme water level for the whole of Mombasa district under the PG Scenario 1. By 2080, exposure could reach up to over 392,000 people and about US$16 billion infrastructure assets for the Rahmstorf sea-level rise scenario (a 1.26m rise in sea level by 2100) (Table 12). Under the PG Scenario 2, the current exposure falls to 180,000 people and US$430 million in assets. By 2080, exposure is reduced by a factor of 1.4 to 285,000 people and US$11.5 billion in assets. For the 'no population growth' (NoPG) scenario, the current exposure falls further down to about 172,000 people and US$390 million in assets, and by 2080 it is reduced by a factor of more than 2 to 182,000 people and US$7.3 billion in assets. Under the no climate-induced sea-level rise scenario, as high as 393,000 people and economic assets worth US$4 billion is estimated to be exposed by 2050, highlighting the potential future risk even without climate-induced sea-level rise.

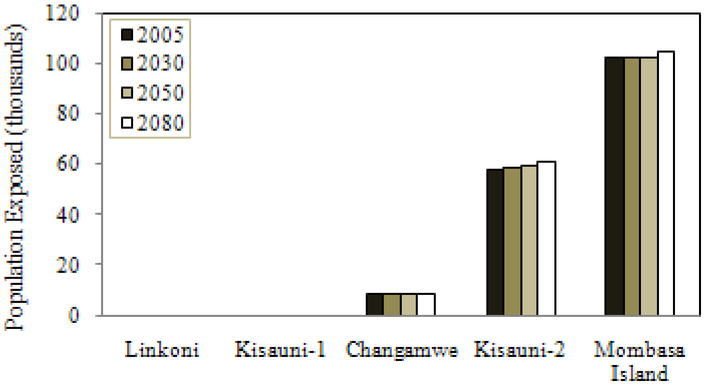
Figures 10 and 11 show the population and asset exposure distributions in the divisions under the population growth distribution scenarios considered (Table 6).



(a) Population Growth Scenario 1: Mombasa District Divisions

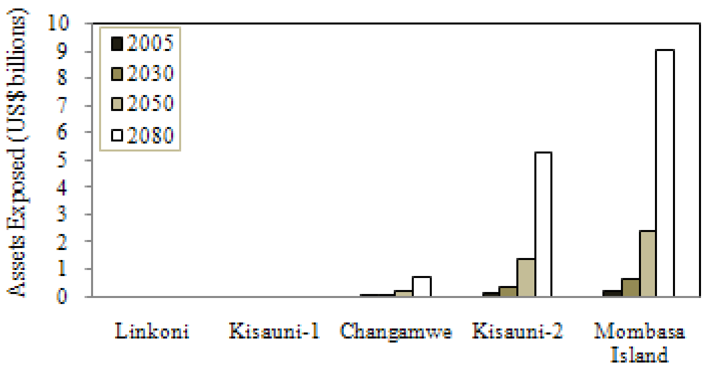


(b) Population Growth Scenario 2: Mombasa District Divisions

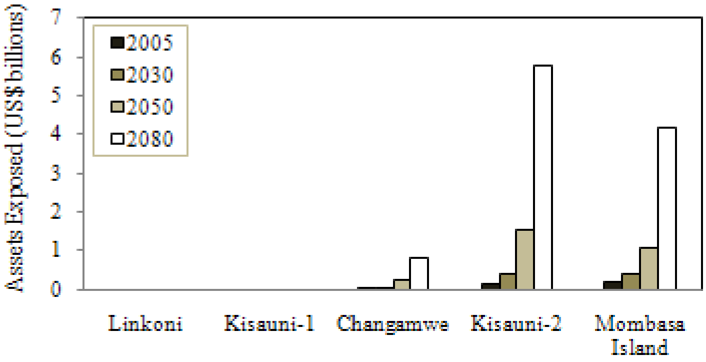


(c) No population Growth Scenario: Mombasa District Divisions

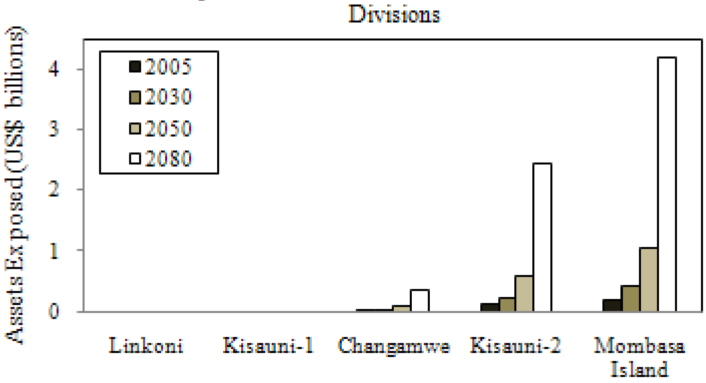
Figure 10: Exposed population in 2005, 2030, 2050, and 2080 under the A1B mid-range SLR and the three Population Growth scenarios. Note different scales on y-axis.



(a) Population Growth Scenario 1: Mombasa District Divisions



(b) Population Growth Scenario 2: Mombasa District Divisions



(c) No Population Growth Scenario: Mombasa District Divisions

Figure 11: Exposure of assets in 2005, 2030, 2050, and 2080 for the A1B mid-range SLR and the three Population Growth scenarios. Note different scales on y-axis.

The PG Scenario 1 shows that if the population continues to grow in all the divisions, future exposure will be highest in the Mombasa Island division due to the very low-lying nature of the division (Figures 10 and 11). The area of exposure to extreme water levels in the division includes, in addition to the direct flood impacts on people and their assets, both harbours, hospitals, schools, roads, bridges, ferry services and other important infrastructure located within the low-lying areas. However, when the PG Scenario 2 is considered, while the exposure in the Mombasa Island declines, it increases and becomes largest in the Kisauni-2 division. This is mainly related to the potential rapid trend of population growth in the division, as also shown by the three previous years' census data (see Table 1). These demonstrate the sensitivity of the potential exposures of people and assets to socio-economic scenarios.

For instance, by 2050 for the A1B mid-range SLR scenario with the PG Scenario 1, more than 235,000 people and economic assets worth over US$2.4 billion could be flooded in the Mombasa Island division due to a 1:100 year return period extreme water levels. This represents more than 60 percent of the population and asset exposure for the whole of Mombasa district. The Kisauni-2 division follows with more than 135,000 people and US$1.4 billion in asset (about 35% of the total). However, when the PG Scenario 2 scenario is considered, the exposure for the Mombasa Island division is reduced by a factor of 2.3 to 103,000 people and assets worth US$1 billion, while in the Kisauni-2 division exposure rises to over 150,000 people and more than US$1.5 billion economic assets. But, under the 'no population growth' (NoPG) scenario, the number of people and economic assets exposed in the Kisauni-2 division considerably drops down to 59,000 people and US$0.6 billion assets. This is a reduction by a factor of more than 2.5 from the highest scenario for the division (i.e., PG Scenario 2).

Knowledge about the impacts of climate change and sea-level rise and other coastal related issues on Africa in general on a continental, national and sub-national level are limited (BROWN, KEBEDE and NICHOLLS, 2009; DASANKER *et al*., 2001; ZINYOWERA *et al*., 1998). However, population growth and urbanization are factors which increase the number of people and assets exposed to flooding, and this will be an important factor during the 21st Century independent of other drivers as demonstrated here. Climate-induced sea-level rise and storm surges could also increase the exposure of many low-lying coastal cities in Africa (as well as increasing the risks of flooding (NICHOLLS 2004; NICHOLLS, HOOZEMANS and MARCHAND, M., 1999)). For instance, for Mombasa under the A1B SLR and A1 SE scenario, a 3.88 metre extreme still water level by 2050 would put approximately 400,000 people and infrastructure assets worth over US$4 billion at risk of flooding. 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 380,000 by 2080), but due to the high increase in the projected GDP per capita for 2080, assets exposure will increase dramatically to more than US$15 billion.

5. CONCLUSIONS

This case study on the impacts of climate change and sea-level rise on the coastal city of Mombasa district has made a first quantitative estimate of the number of people and associated economic assets exposed to coastal flooding due to extreme water levels. It provides a good indication of the potential exposure and hence the worst-case impacts 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 over the 21st Century.

The GIS-based analysis results showed that about 19 percent of the land area of the district lies within the Low-Lying Coastal Zone (LLCZ). Current estimates shows that as high as 190,000 people and over US$470 million assets are already exposed to a 1:100 year return period extreme water levels. By 2080, for the A1B mid-range sea-level rise (a 43 cm rise in sea level by 2100) and A1 socio-economic scenario with rapid urbanisation, more than 380,000 people and infrastructure assets worth more than US$15 billion will be exposed to coastal flooding due to sea-level rise and storm surges. About 60 percent of this exposure is concentrated on Mombasa Island where more than 250,000 people by 2080 are projected to settle within the LLCZ, if the population is allowed to grow. 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 population growth distribution scenarios investigated, which demonstrate that exposure will still increase even if no changes in extreme water levels were considered. Exposure in the Kisauni-2 division could also be higher in future due to the potential increase in population as shown by the growing trend of population distributions in the division. The lack of population growth in Mombasa Island could be due to a policy decision - it shows that steering development away from low-lying areas could reduce the growth in exposure. However, given that much of the exposure is within informal settlements, such a policy might be quite difficult to enforce.

In conclusion, unless appropriate adaptation and mitigation measures are put in place, with the changing climate and rising mean and extreme sea levels, the growing exposure in Mombasa is of concern, and appropriate adaptation is required to keep the risks at an acceptable level. Rising sea levels will also reduce gravity drainage and exacerbate flooding during intense precipitation events. This study suggests the magnitude of the impacts which need to be considered when planning for the future. However, the lack of sufficient and good quality observational climate data (e.g., sea level measurements) significantly contribute to the lack of knowledge of the potential impacts and consequences that Mombasa could face in years to come. This will, directly or indirectly influence the decision that authorities have to make in terms of what they should be doing to plan for the future. Hence, it is important that better data on Mombasa's coastal areas is developed, such as sea level change measurements are collected and analysed as sufficiently good as possible, and as the duration of measurements get longer they will get more useful for a better understanding of current and future climate change and its variability, and to make an optimum use in predicting potential future impacts.

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 and mangroves. Other flood mechanisms may become important such as intense precipitation events, as in 2006, as these will also affect the overall sustainability of the rapidly growing coastal city of Mombasa.

In terms of further work, Mombasa should be assessed in more detail using higher quality, more detailed data on elevation, population and assets, and defences both in terms of natural features and artificial measures. Equally, these methods could be applied more widely to other African coastal cities to develop a better indication of present and future exposure, and potential risks to support decision makers when planning for the future.

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