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

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ABSTRACT

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Mombasa is the second largest city in Kenya and the largest international seaport in East Africa, with over 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 and caused damage to important infrastructure. Because 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 that have the potential to further increase the threats of flooding within the city. This geographic information system–based study provides a first quantitative estimate, both now and through the twenty-first 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 y extreme water level for the Mombasa district is estimated at 190,000 people and US$470 million in assets. About 60% of this exposure is concentrated in the Mombasa Island division of the city, where about 117,000 people (2005 estimate) live below 10 m elevation. By 2080, exposure could grow to over 380,000 people and US$15 billion in assets, assuming the well-known A1B sea-level and socioeconomic scenario. Future exposure is more sensitive to socioeconomic 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: *Mombasa, extreme water levels, storm surges, coastal flooding, population exposure, asset exposure.*

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 and 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 twenty-first 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 that contributes to changes in water levels or sediment availability (*e.g.,* subsidence due to groundwater extraction). Despite these threats, few coastal cities (*e.g.,* Cotonou, Benin [Dossou and Gléhouenou-Dossou, 2007], and Nile delta, Egypt [*e.g.,* El-Raey, 1997]) 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, 2007). The city has two major harbours (Kilindini Harbour and Old Port), comprising the largest seaport in Eastern Africa serving

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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 were to be 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% of tourists visiting Kenya visit the coast, making tourism an important part of the city's economy. At a national level, it contributes about 12% (in 2004) of the country's gross domestic product (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 affected about 60,000 people in the city. Coastal erosion also poses a problem in the coastal zone (Mwakumanya and Bdo, 2007). For instance, the Nyali and Bamburi sandy beaches experienced severe erosion at a rate of 2.5–20 cm/y over the last decade.

The coastal zone has significant low-lying land areas that 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 lead to high vulnerability (*e.g.,* due to intense back-to-back development leading to overconcentration in low-lying areas) (NEMA, 2009).

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% (about 4600 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 nonclimate causes are quite plausible. It is also anticipated that the city could face significant climate change–related health risks (*e.g.,* waterborne 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 socioeconomic 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 twenty-first 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.

STUDY AREA

City of Mombasa

The coastal city of Mombasa is located in southern Kenya (39.7°E, 4.1°S) (Figure 1). The geology of the Kenyan coast is dominated by the rifting and breakup of the Palaeozoic Gondwana continent and the development of the Indian Ocean (Embleton and Valencio, 1977; Horkel *et al*., 1984). Mombasa itself lies on a coastal plain that has a variable width ranging from 4 to 6 km (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; Oosterom, 1988). Tidal exchange in the creeks is considerable, with a maximum tidal range of 4.0 m at spring tide and 2.5 m at neap tide. There are also freshwater and sediment inputs from rivers. The waves outside the fringing reef may reach amplitudes ranging from 1 to 3 m during monsoons (Ruwa and Jaccarini, 1986). Offshore, the seafloor drops to below 200 m within less than 4 km of the shoreline (Abuodha, 1992).

Mombasa is one of the major tourist destinations in Africa and has the highest tourism facility and infrastructure concentrations in the coastal zone (Akama and Kieti, 2007). The city's history dates back to the sixteenth 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 in the tourism industry, attracting many tourists worldwide. The city's population has also more than doubled within the last two decades since 1980, with an average annual growth rate of about 3.4% (UNPD, 2007). This fast growth is attributed to natural and rural-urban migration and associated socioeconomic development, and it is projected to continue due to the high economic potential there.

For the purpose of this study, the city boundary is considered to be the Mombasa District, which is 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 3 y of census data (used in the analysis) and the 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 2450 people/km^2) lived in the Mombasa Island and the Kisauni-2 divisions, respectively.

According to the 250 m resolution Digital Elevation Model (DEM) used in the study (obtained from the World Resources

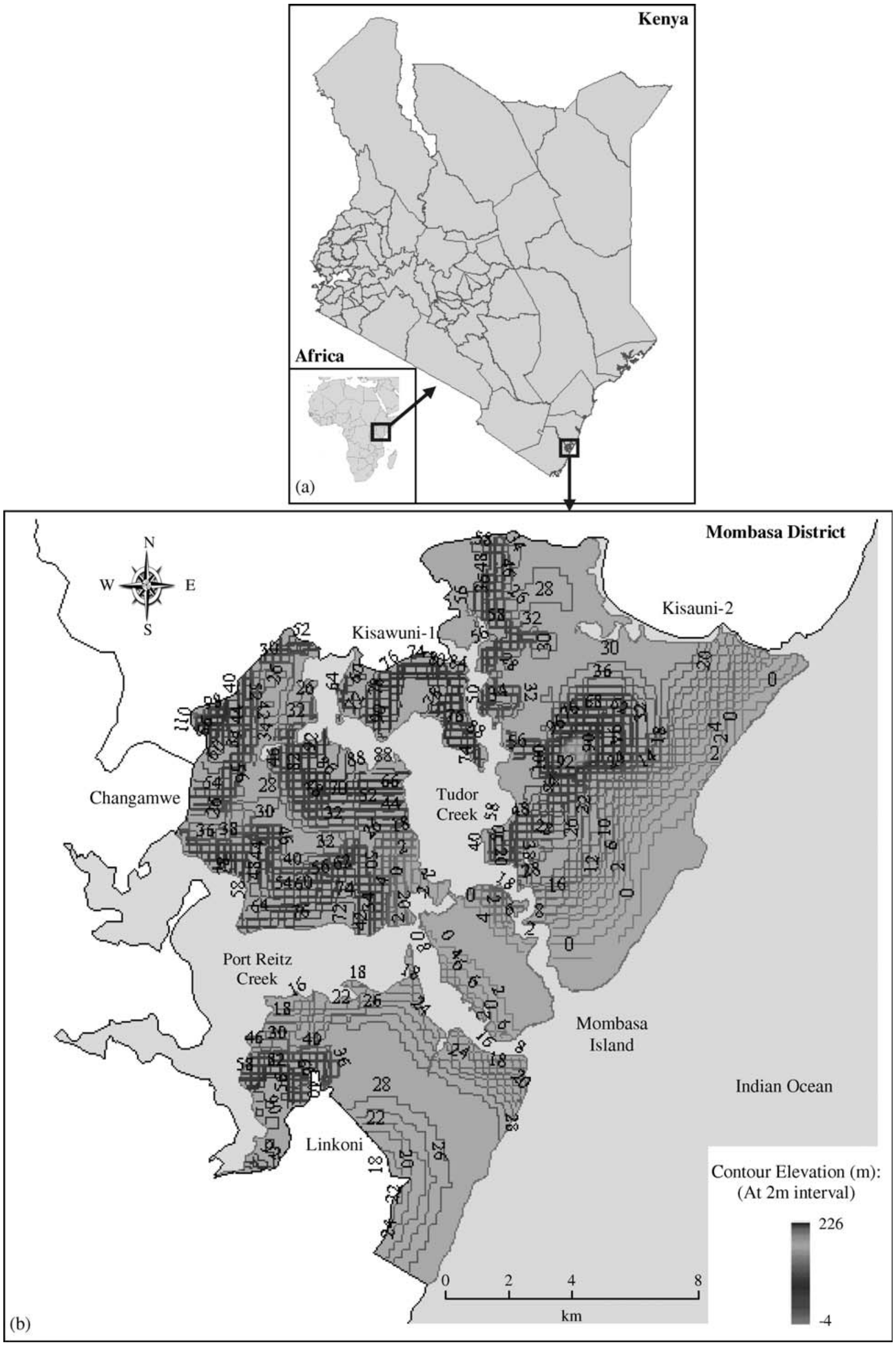

Figure 1. (a) Location of Mombasa, and (b) elevation distribution within Mombasa district (Source: World Resources Institute, 2007), and the five divisions.

Institute, 2007), 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 m of mean sea level) (Figure 1). In the other divisions, the land areas are generally at higher elevations (up to 226 m), and only limited areas could be affected by present or future extreme sea levels.

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 deep-water harbour on the southwest side of Mombasa Island, with extensive docks, shipyards, and sugar and petroleum refineries handling about

Table 1. *Population and land area distribution in the Mombasa District by division (source: GOK, 1979, 1989, 1999; World Resources Institute,* 2007*).*

				In 1999			
	Population (thousands)			Land Area (km^2)		Population Distribution	
Division Name	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**	**100**	**2858**

33.3 million tonnages of traffic, as reported in Hanson *et al.* (2009). The Old Mombasa Port, on the northeast 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% of the total land area and are mainly concentrated in the low-lying areas. According to the elevation data used in the analysis, more than 19% of the total land area of the district and about 32% of the urban areas (including the whole urban area of the Mombasa Island division) lie within the LLCZ.

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 that consists of 47.5 km^2 of wetlands, of which about 39 km^2 are mangroves (World

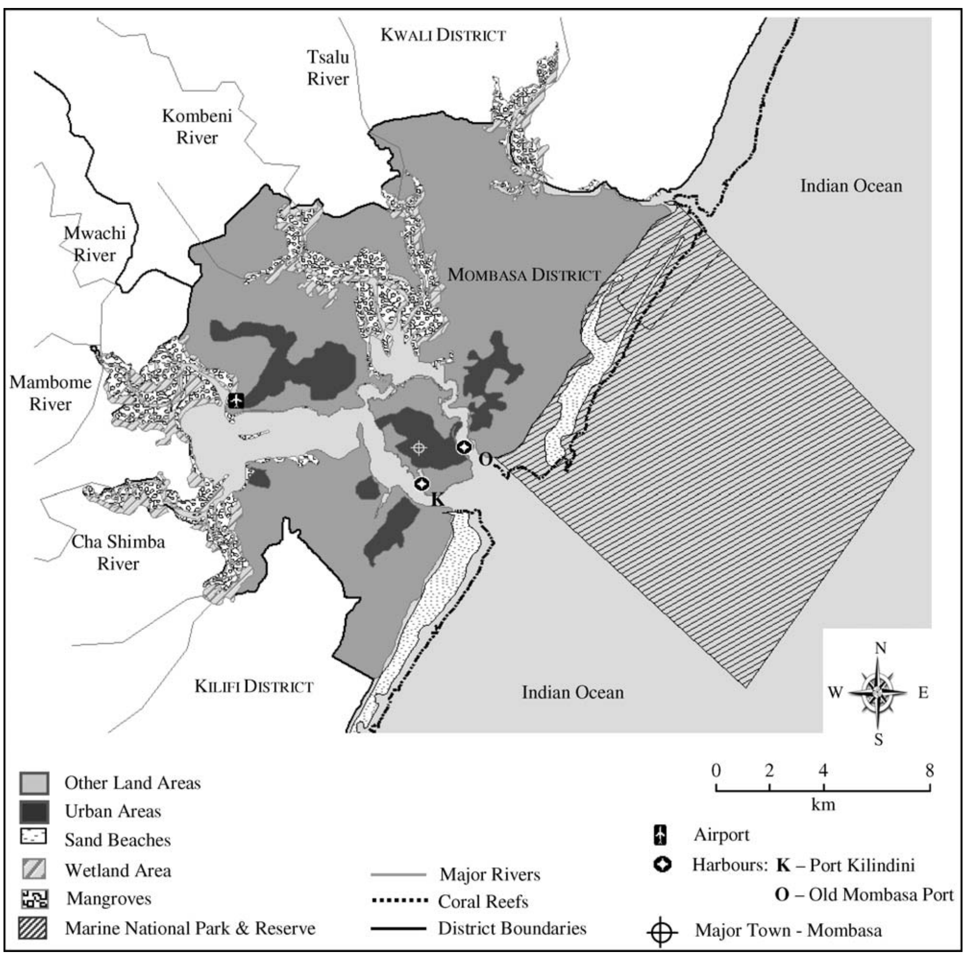

Figure 2. Major land-use and coastal characteristics/facilities in the Mombasa District.

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

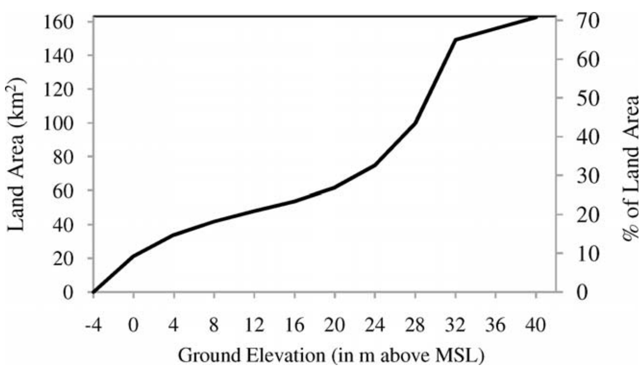

Figure 3. Distribution of land area against elevation in the Mombasa District (in 1999).

Resources Institute, 2007). The two major rivers of the Tudor creek, Kombeni and Tsalu (see Figure 2), drain a total area of 550 km^2. The Port Reitz creek, which formed as a result of drowning of former river valleys due to late Pleistocene/early Holocene sea-level rise (Caswell, 1956), receives its freshwater from three seasonal river systems, Cha Shimba, Mambome, and Mwachi (see Figure 2) (Kamau, 2002). The mangroves provide essential functions and services to the coastal ecosystem, but they 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, there lies a government-managed protected Marine National Park and Reserve, which cover about 10 and 200 km^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, 2009). 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.

Recent Sea-Level Change

The global mean sea-level rise was 1.7 mm/y during the twentieth century and 1.8 mm/y for the period 1961–2003 (Bindoff *et al*., 2007; Church and White, 2006). This has been modified with the satellite altimetry provided by *Topex/ Poseidon* to 3.1 mm/y over the period 1993–2008 (*e.g.,* Cazenave and Llovel, 2010). Based on models of thermal expansion and

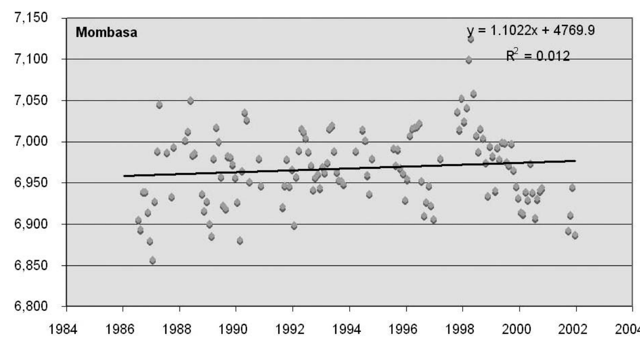

Figure 4. Monthly mean sea-level tide gauge measurements for Mombasa Station, Kenya (39°39′ E, 04°04′ S), from 1986 to 2002 (Source: Permanent Service for Mean Sea Level [PSMSL], 2009). (Note: all values are in mm.)

ice-sheet response to global warming, global mean sea-level rise is expected to accelerate in the twenty-first century (Church *et al*., 2001; Meehl *et al*., 2007). In Africa, sea-level measurements are limited, and continuous sea-level records are very short (generally less than 20 y). Moreover, with the major exceptions of stations in South Africa and the Indian Ocean islands, there are relatively few stations that provide recent data to the Permanent Service for Mean Sea Level (PSMSL) (Woodworth, Aman, and Aarup, 2007; Woodworth and Player, 2003). There are some data at Mombasa received by the PSMSL (Kibue, 2006; Magori, 2005). The monthly mean sea level data set available from tide gauge records covers the period 1986 to 2002, but no recent records are available. Considering the available data set, it shows no significant trend, although the best fit is 1.1 mm/y (Figure 4). It is important to note that estimates of trends of sea-level change obtained from tide gauge records of short durations (<50 y) could have a significant bias due to interannual to decadal water-level variability (Douglas, 2001). Hence, due to the limited long-term continuous records and lack of recent sea-level data in Mombasa, the global scenarios are directly applied in this analysis. However, it is important for the sea-level rise measurements at Mombasa to be continued, and as their duration increases, they will become more useful, both scientifically and for future risk assessment and coastal management purposes.

METHODOLOGY

The focus of this analysis is to provide a more quantitative and broader context to the potential impacts of coastal flooding on Mombasa due to extreme water levels, based on physical exposure and socioeconomic 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 twenty-first 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), because 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 that could be flooded in an extreme event. The analysis is conducted within the framework of the SRES scenarios, although post-AR4 insights are considered. (The SRES scenarios are the sea-level and socioeconomic scenarios based on the Special Report on Emission Scenarios [SRES] of the Intergovernmental Panel on Climate Change [IPCC]; IMAGE Team, 2002; Nakićenović and Swart, 2000).

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 was 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 and 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:

$$EWL = SLR + S100 + SUB_{\mathrm{Natural}}, \quad (1)$$

where *SLR* represents global mean sea-level rise scenarios, *S100* is the 1 : 100 y extreme water level (estimated as 3.62 m), and SUB_{Natural} is the total natural land subsidence (estimated as 0.42 mm/y).

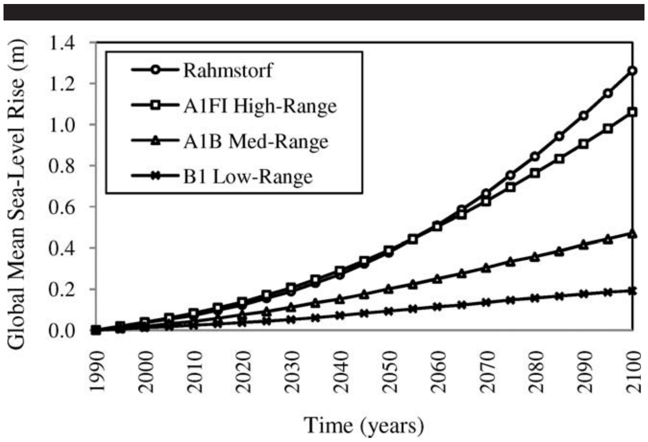

Figure 5. Global mean sea-level rise scenarios.

For the analysis, storm-surge heights and natural subsidence rates were directly adopted from the coastal segment in the DIVA database that includes Mombasa (Vafeidis *et al*., 2005, 2008) (DIVA is the Dynamic Interactive Vulnerability Assessment model developed in the EU 5th Framework DINAS-COAST project (DINAS-COAST Consortium, 2006). The water levels were 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), and 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 (Figure 5). Note that even higher scenarios than used here have been suggested (*e.g.,* Vermeer and Rahmstorf, 2009). The ranges of the SLR scenarios used here act as a sensitivity analysis to examine impacts on a range of uncertainty. Considering the historic global mean sea-level rise values for the period 1990–2010 (*e.g.,* from satellite altimetry) (see section 2), comparisons between these scenarios can be made to better understand which is the more likely future trend.

Future Socioeconomic Scenarios

The analysis of future impacts considers future socioeconomic changes based on scenarios of population, including urbanisation, and gross domestic product (GDP) of the district, following the A1 scenario (A1 is derived from the SRES of the IPCC; IMAGE Team, 2002; Nakićenović and Swart, 2000; Nicholls *et al*., 2008b). Future projections were 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 scenario is reasonably adopted (wherein growth corresponds to a direct extrapolation of the 2030 UN scenarios to 2080; in this scenario, all cities within the country are assumed to grow at the same rate). Table 3 gives the socioeconomic 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 socioeconomic scenario. It is also consistent with the declining fertility in Kenya as noted by United Nations Urbanisation Prospects (UNPD, 2007). Other socioeconomic

Table 3. *Population and GDP per capita of Mombasa through the twenty-first century under the A1 socioeconomic scenario with rapid urbanisation.*

	Year			
Projections	2005	2030	2050	2080
Population (thousands)	821	1262	1893	1767
GDP per capita (US$)	378.7	796.0	2023.5	8040.4

Table 4. *Population growth distribution scenarios.*

Population Growth (PG)	Scenario Description
Scenario 1	Assuming the population of the five divisions of Mombasa will grow uniformly based on the 2005 distribution (worst scenario).
Scenario 2	Assuming 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 scenario	A "no population growth" scenario, assuming the population in all the divisions is kept at 2005 levels.

scenarios such as the A2 socioeconomic scenario would give a continual growth to 2100, and a larger exposed population but a lower GDP.

The process of downscaling population projections into land use is based on available historic census data distribution over the district. The downscaled population distributions over the five divisions for the base year (*i.e.,* 2005) were estimated based on the growth trends of the percentage population distributions in the divisions from the available 3 y of historic census data (*i.e.,* 1979, 1989, and 1999) (see Table 1), and assuming a linear trend line projection over time up to 2005. This gives the percentage population distribution of the total population in 2005 (see Table 3) over the five divisions of the district. Next, snapshot projections of the population distributions over the divisions in 2030, 2050, and 2080 relative to the 2005 levels were estimated considering two population growth distribution scenarios along with a "no population growth" scenario (Table 4). These reflect the potential policy choices for managing the expanding future population and associated exposure.

Estimates of Population and Asset Exposure

The sea-level rise scenarios coupled with the A1 socioeconomic and the rapid urbanisation scenarios were then considered to estimate the future projected population exposure. This follows the methodology used by Hanson *et al.* (2009). The simulations to estimate exposed number of people and associated economic assets that are located below the 1 : 100 y return period for extreme water levels for each scenarios were performed based on a population distribution data (see Table 1) and 250-m-resolution elevation data obtained from the World Resources Institute (2007).

The population by elevation on a horizontal map of geographical cells was 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 1 : 100 y extreme water levels, a method commonly used in the insurance industry and applied by Nicholls *et al*. (2008a) was adopted to relate the value of assets to the population exposed to the same extreme water levels (Equation 2).

$$E_a = E_p \times GDP_{\text{percapita (PPP)}} \times 5, \qquad (2)$$

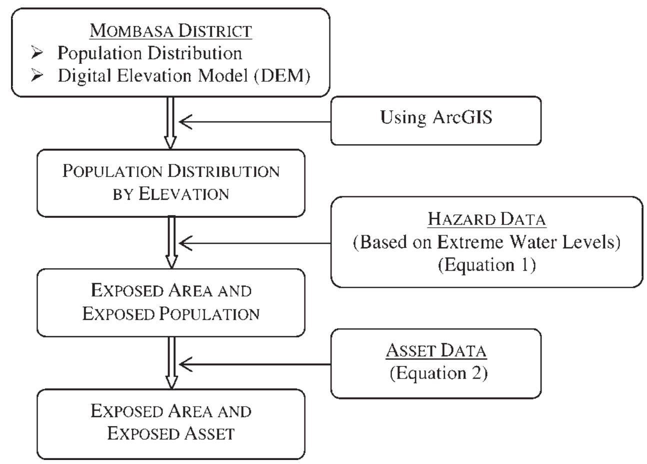

Figure 6. A simplified flowchart of the methodology (adapted from Nicholls *et al*., 2008a).

where E_a is exposed asset (monetary value), E_p is exposed population, and $GDP_{\text{percapita (PPP)}}$ is the national per capita gross domestic product (GDP) purchasing power parity (PPP).

Figure 6 summarises the methodology.

RESULTS AND DISCUSSION

Significant numbers of people and economic assets are estimated to be located within the low-lying coastal zone (LLCZ) in Mombasa. Table 5 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 m contours, respectively, and hence population and asset exposure is much lower. In addition, about 82% (*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 y return period is already significant. The informal shanty towns that 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 exacerbate the observed floods, such as in October 2006, unless drainage can be upgraded.

Based on the population growth (PG) scenarios used (see Table 4), a sensitivity analysis on future population and asset exposure is performed. Results show that by 2050 under the PG scenario 1, more than 480,000 people and assets worth over US$4.8 billion would be located within the LLCZ. For the PG scenario 2, the exposure within the LLCZ becomes 350,000 people and US$3.5 billion in assets. Furthermore, when the "no

Table 5. *Population distribution in 2005 (base year) against selected range of vertical ground elevations.*

	Total Number of People (thousands)					
		Divisions of Mombasa District				
Elevation Ranges (m)	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**

population growth" (NoPG) scenario is considered, about 205,000 people and US$2.1 billion in assets would be distributed within the LLCZ. Although the population declines beyond 2050, the asset exposure continues to grow significantly due to the projected increase in GDP per capita. Note that these costs are reported in 2005 US$ and are NOT discounted.

Table 6 shows the total number of people and economic assets exposed to 1 : 100 y return period extreme water levels under the ranges of sea-level rise and socioeconomic scenarios considered.

The results demonstrate that future population and asset exposure is more sensitive to socioeconomic 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 4), the exposure will increase by a factor of more than 1.4 compared to that assuming it stays at 2005 levels (*i.e.,* PG scenario 2 of Table 4) under all sea-level rise scenarios.

Due to the lack of data on current population, a linear growth in population and asset exposure between 2005 and 2030 is assumed, and it is estimated that as high as 190,000 people and economic assets worth over US$470 million are currently exposed to a 1 : 100 y extreme water level for the whole of Mombasa district under PG scenario 1. By 2080, exposure could reach over 392,000 people and about US$16 billion infrastructure assets for the Rahmstorf sea-level rise scenario (a 1.26 m rise in sea level by 2100) (Table 6). Under PG scenario 2, the current exposure becomes 180,000 people and US$430 million in assets. By 2080, the exposure is reduced by a factor of 1.4 to 285,000 people and US$11.5 billion in assets when compared

Table 6. *Population and asset exposed to 1 : 100 y return period extreme water levels under the three population growth scenarios and the different sea-level rise scenarios.*

		Population Exposed (thousands)			Asset Exposed (US$ billions)		
Year	Extreme Still-Water Levels (m)	PG Scenario 1	PG Scenario 2	NoPG Scenario	PG Scenario 1	PG Scenario 2	NoPG Scenario
No climate-induced sea-level rise 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
B1 low-range sea-level rise 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
A1B midrange sea-level rise 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
A1FI high-range sea-level rise 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
Rahmstorf sea-level rise 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

with the worst scenario (*i.e.,* PG scenario 1). For the NoPG scenario, the current exposure is estimated at 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 when compared with the worst scenario. Under the no-climate-induced sea-level rise scenario, as many as 393,000 people and economic assets worth US$4 billion are estimated to be exposed by 2050, highlighting the potential future risk even without climate-induced sea-level rise.

Figures 7 and 8 show the population and asset exposure distributions in the divisions under the population growth distribution scenarios considered (Table 4).

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 7 and 8). The area of exposure to extreme water levels in the division includes, in addition to the direct flood impacts on people and their assets, harbours, hospitals, schools, roads, bridges, ferry services, and other important infrastructure located within the low-lying areas. When PG scenario 2 is considered, while the exposure in Mombasa Island declines, it increases and becomes largest in the Kisauni-2 division. This is mainly related to the potentially rapid trend of the population growth in the division, which is also shown by the 3 previous years of census data (see Table 1). Hence, results demonstrate the sensitivity of the potential exposures of people and assets to socioeconomic scenarios.

For instance, by 2050 for the A1B midrange SLR scenario under 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 1 : 100 y return period extreme water levels. This represents more than 60% 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). When PG scenario 2 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 when compared with the worst scenario (PG scenario 1). However, under the NoPG scenario, the number of people and economic assets exposed in the Kisauni-2 division considerably drop down to 59,000 people and US$0.6 billion assets. This is a reduction by a factor of more than 2.5 when compared with 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 subnational level are limited (Brown, Kebede, and Nicholls, 2009; Desanker *et al*., 2001; Zinyowera *et al*., 1998). However, population growth and urbanization are factors that increase the number of people and assets exposed to flooding, and this will be an important factor during the twenty-first 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, 1999). For instance, for Mombasa under the A1B SLR and A1 SE scenarios, a 3.88 m 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, asset exposure will increase dramatically to more than US$15 billion.

CONCLUSIONS

This case study on the impacts of climate change and sea-level rise on the coastal city of Mombasa district presents 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, that the city is currently experiencing and that projected in the future under scenarios of rapid growth in population, urbanisation, and associated economic growth over the twenty-first century.

The GIS-based analysis results show that about 19% of the land area of the district lies within the low-lying coastal zone (LLCZ). Current estimates show that as high as 190,000 people and over US$470 million assets are already exposed to 1 : 100 y return period extreme water levels. By 2080, for the A1B midrange sea-level rise (a 43 cm rise in sea level by 2100) and the A1 socioeconomic 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% 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 socioeconomic 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 are considered. Exposure in the Kisauni-2 division could also be higher in the 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 on Mombasa Island could be due to a policy decision—this 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 that need to be considered when planning for the future. However, the lack of sufficient and good-quality

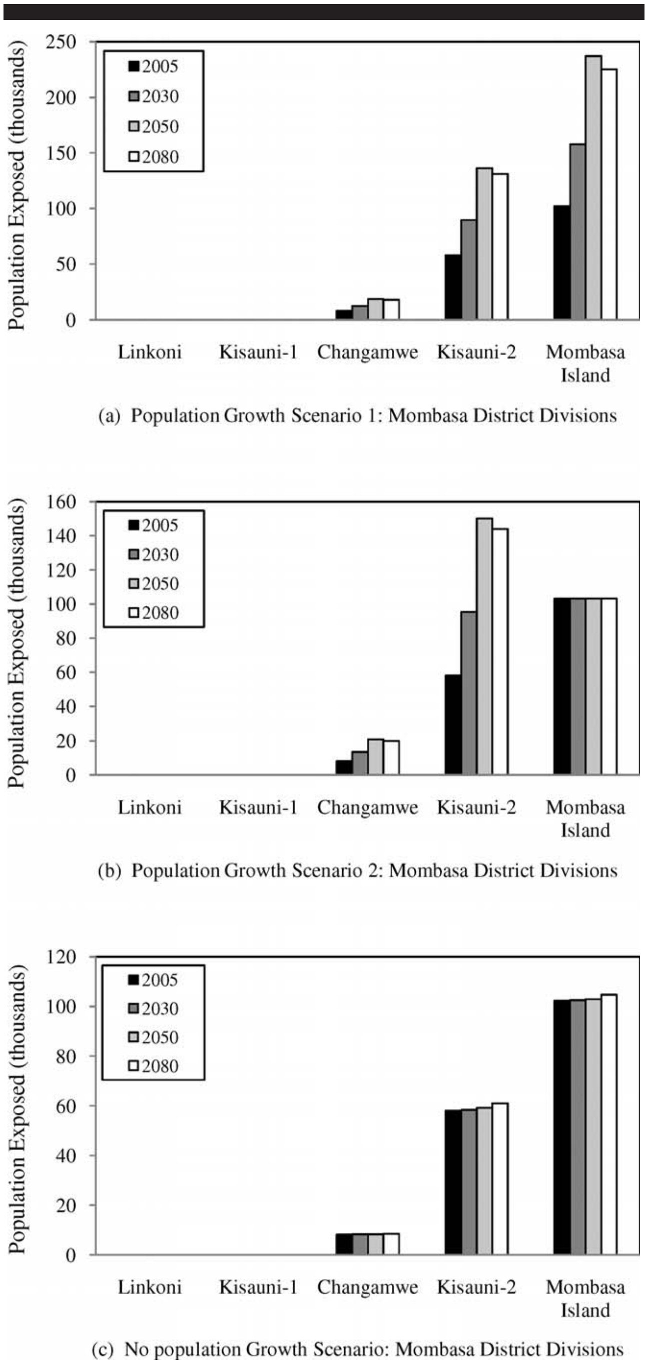

Figure 7. Exposed population in 2005, 2030, 2050, and 2080 under the A1B midrange SLR and the three population growth scenarios. Note different scales on *y*-axis.

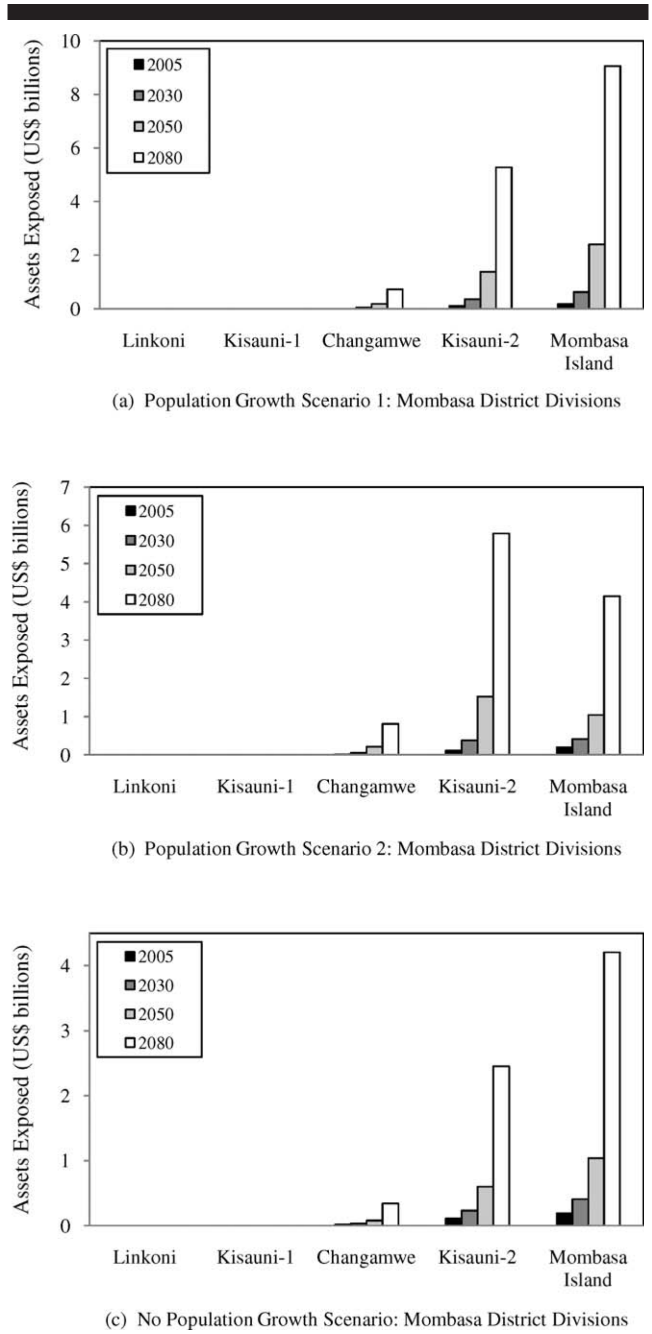

Figure 8. Exposed assets in 2005, 2030, 2050, and 2080 for the A1B midrange SLR and the three population growth scenarios. Note different scales on *y*-axis.

observational climate data (*e.g.,* sea-level measurements) significantly contributes to the lack of knowledge about 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 planning for the future. Hence, it is important for better data on Mombasa's coastal areas to be developed, such as collection and enhanced analysis of sea-level change measurements; as the duration of measurements get longer, they will become 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, since 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, and more on adaptation analysis. 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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