Assessing the Vulnerability of an Industrial City to Predicted Sea Level Rise using SRTM and GPS Observations: The Case of Yanbu, Saudi Arabia

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Abstract
This study examines the different scenarios of sea level rise and its consequences on a coastal industrial city. Analyses of these scenarios were carried out using Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) with high resolution remote sensing data (for visualization) within Geospatial Information System (GIS) environment. The SRTM data was validated by GPS observations. A minimum scenario of SLR of 1m by the year 2100 was adopted in assesing the vulnerability of the study area. The extracted layers of vulnerable areas were overlaid on the demographic and land use data of the city to estimate the likely impact on land use and population of the area. The study shows a root mean square error (RMSE) value of 2.07 for SRTM values corresponding to GPS observations that are less than or equal to 3m. The results show that the industrial city is vulnerable to predicted sea level rise.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" (McCarthy et al., 2001). It is "related or equated to concepts such as resilience, marginality, susceptibility, adaptability, fragility, and risk" (Liverman, 1990). Fussel (2007) added exposure, sensitivity, coping capacity, criticality, and robustness to the list. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. Vulnerability therefore, "can be used in different policy contexts, referring to different systems exposed to different hazards" (Fussel, 2007). One of the important issues related to climate change and vulnerability is the rising sea levels. Sea level rise (SLR) is the changes in the level of the surface of the sea with respect to the land, taken to be the mean level between high and low tide, and used as a standard base for measuring heights and depths. Experts on the sea level rise triggered by climate change have long known that it will proceed faster in some places than others and it is a continuous process. This will cause coastal flooding, inundation and other environmental problems. The impacts of which would disrupt the physical, cultural and socio-economic systems in the coastal region.

It therefore, poses one of the major environmental challenges and major concerns of today. This has made the United Nation General Assembly to adopt the establishment of Intergovernmental Panel on Climate Change (IPCC) under the United Nations Environmental Programme (UNEP) and the World Metrological Organization (WMO) as the leading international body for the assessment of climate change and its attendant sea level rise. In the light of this, various countries also set up National action plan on climate change and collaborate with IPCC in other to cater for the the challenges posed by the phenomena (Aleem and Aina, 2012). One of the challenges of climate change and sea level rise is coastal erosion and inundation. Coastal erosion is the wearing away of the coast by waves or other agents, which shape the coast, because the power of wave has a significant influence on the coast. Such influence is aided by sea level rise. This will definitely affect the socio-economic activities of the coastal and densely populated region of the world. In order to study the impacts of climate change and SLR on societies, different climate modeling groups have developed scenarios of SLR given expected rise in temperature. The key issues in the simulation of the scenarios are modeled considering the parameters like: combinations of demographic change, social and economic development, and broad technological developments (Aleem and Aina,

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2012). The scenarios are used to predict the sea level rise to year 2100. Geospatial technologies such as Digital Elevation Model (DEM) have been used by several authors to study, analyse, assess and predict the vulnerability of global and local communities to different scenarios of sea level rise. Warrick et al., (1996) made projections of thermal expansion and of loss of mass from glaciers and ice-sheets for the 21st century based on IPCC scenarios using two alternative simple climate models. Several other authors (for example, Onyenechere (2010), Babu et al., (2012) and Aleem and Aina (2012)) have based their prediction on these scenarios. A Digital Elevation Model refers to a quantitative model of a part of the earth's surface in digital form (Burrough and McDonnell, 1998). A DEM consists of a two-dimensional array of numbers that represents the spatial distribution of elevations on a regular grid; they are particularly useful in regions that are devoid of detailed topographic maps (Forkuor and Maathuis, 2012). DEMs (Digital Elevation Models) can be divided into two; Digital Terrain Models (DTM) and Digital Surface Models (DSM). "DTMs represent the terrain's elevation, whereas DSMs represents the surface elevation of objects in the landscape" (Van de Sande et al., 2012). Though ASTER GDEM and STRM DEM datasets are Digital Surface Models, they are used as Digital Terrain Models. There are several methods of generating DEM, depending on the area of coverage, accuracy, cost, topography and availability of equipment. The available methods include but not limited to following:

- Traditional land surveying methods of mapping to produce topographic map. Contour from such map can be used to generate DEM.
- Photogrammetric techniques - DEM can be derived from contours that are extracted with photogrammetric techniques from aerial stereo photographs but currently digital photogrammetric software is being used.
- Satellite Methods - Programs are now available in MATLAB and similar programming languages for the extraction of DEMs. SPOT, a remote sensing satellite, was the first satellite to provide stereoscopic images that allowed the extraction of DEMs (Nikolakopoulos and Chrysoulakis, 2006). Advances in space technology have now resulted in many more satellites such as SRTM, ASTER, IKONOS, Quickbird and so on.
- Google Elevation Data - Google elevation data is available to the public but the permission from Google limits the usage to applications within the Google earth and Google map environment.

The use of satellite images for DEM generation has considerable merits over the traditional methods because DEMs cover large and inaccessible areas and are equally available online. It can "nowadays be easily produced (near) real-time and within a relatively short time and at remarkable cheaper costs" (Forkuor and Maathuis, 2012). Example of the satellites global DEM, available online is SRTM. Shuttle Radar Topographic Mission (SRTM), undertaken by National Aeronautics and Space Administrations (NASA) and US National Geospatial-Intelligence Agency (NGA), collected interferometry radar data which has been used by the Jet Propulsion Laboratory (JPL) to generate a near-global (80% of earth's land mass) DEM. SRTM has been the first mission using space-borne Interferometric Synthetic Aperture Radar (InSAR). "An extensive global assessment revealed that the data meets and exceeds the mission's 16m (90 percent) absolute height accuracy, often by a factor of two" (Rodríguez et al., 2006). Since its release in 2005, the user community has embraced the availability of SRTM data, using the data in many operational and research settings. DEM from SRTM has been used for various studies by several authors in different parts of the world. The SRTM mission has been a breakthrough in remote sensing of topography (Van Zyl, 2001), producing the most complete, highest resolution DEM of the world (Farr et al., 2007). The mission has assisted studies such as LeFavour and Alsdorf (2005), Wang et al., (2005), Menze et al., (2006), Simard et al., (2006), Lane et al., (1994) and Bishop et al., (2001) in delineating areas susceptible to inundation and deriving hydrologic and hydraulic parameters. A vital limitation to the use of SRTM in inundation studies, especially in sea level rise modeling, is its accuracy. An RMSE of 1.07m had been reported by Schumann et al., (2008) in a low-lying area while Forkuor and Maathuis (2012) reported RMSEs of 5.70m and 16.08m from two different sites. The level of accuracy of SRTM could lead to an underestimation of areas prone to inundation since surfaces can be depicted as 1m or more, higher than their elevations. Thus, SRTM DEM might need some corrections for topographical modeling (Czubski et al., 2013). The use of GPS or LiDAR data could lead to an improvement in the accuracy of an estimated inundation area. However, LiDAR data are still not publically available for some regions and it is highly costly and time-consuming to model a large area by GPS. A way to improve SRTM based inundation estimation is to use some sample GPS data to validate SRTM elevations. In this paper, SRTM and GPS observations have been adopted to study the vulnerability to predicted sea level rise in Yanbu industrial city of Saudi Arabia.

1.1 Aim and objectives

The main aim of this paper is to use DEM from SRTM data for assessing vulnerability to coastal flooding and inundation due to predicted sea level rise. The specific objectives of this paper are:

- to obtain scenarios of global sea level rise from literature.
- to validate the SRTM data with GPS observations.
- to assess the vulnerability of Yanbu industrial city to coastal flooding and inundation using the scenarios.
- to assess the impact of inundation on land use and population

1.2 The Study Area

The study was carried out in Yanbu industrial city, popularly known as Yanbu Al-Sina'iya in Arabic, which literarily means Industrial Yanbu in Madina Province of Saudi Arabia (Figure 1). The city, which was established around 1975, is located on the Coast of Red Sea about 350km North of Jeddah, one of the major ports in the Kingdom. The city is located on: Latitude $23^0 59' 57.840''$N (23.9994) and longitude $38^0 13' 39.000''$E (38.2275). Yanbu is an important petroleum shipping terminal and is home to three oil refineries, a plastic factory and several other petrochemical plants. It is the country's second port (after Jeddah) and serves as the main port for the holy city of Medina. Yanbu existing area is about 185 km^2. RC Yanbu expansion area is about 420 km^2. Its residents are mainly expatriates and Saudis working in the industries. The population of the area is growing, Saudis in particular, while the Non-Saudi share of the population is reducing at the rate 1% per annum (RCJY, 2012). Yanbu industrial city can be regarded as a Low Elevation Coastal Zone (LECZ), which is defined by Mcgranahan (2007) as "the contiguous area along the coast that is less than 10 meters above sea level", where large percentage of the world population resides. Unlike, other coastal cities, which are densely populated, the population of Yanbu industrial city is moderate because, it is controlled by the Royal Commission for Jubail and Yanbu – a government agency established under Royal Decree. The building and allocation of residential quarters lies with the Commission, which is a good control measure on the population of the city.

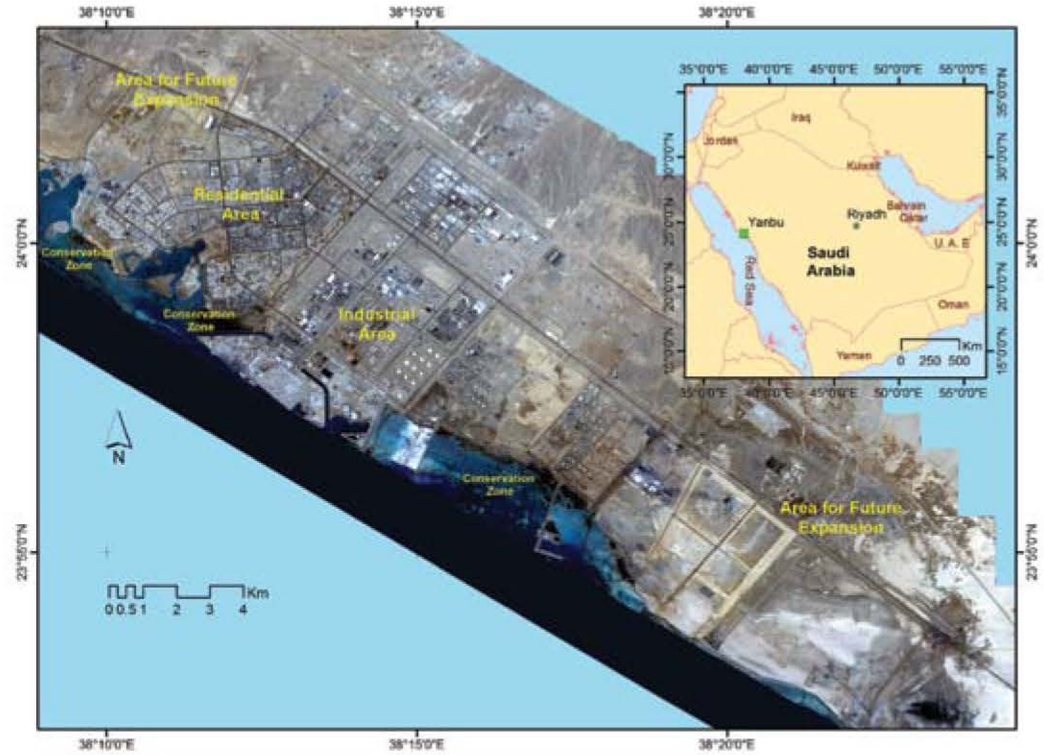

Figure 1: Land use pattern of Yanbu industrial city

1.2.1 Population and land use of Yanbu industrial city

The population of Yanbu industrial city is 91479 according to 2010 Kingdom of Saudi Arabia census. The net budget of Royal Commission at Yanbu is about 2.4 billion SAR while the expenditure for the period exceeded the budget totaling 2.6 billion SAR for the year 2012. This is quite a huge sum of money. There is a need for adequate protection of the investments located within this city to forestall loss of these assets and lives of the capable human resources (including expatriates) to sea level rise; since "settlements in coastal lowlands are especially vulnerable to risks resulting from climate change" (Mcgranahan, 2007). The flooding will affect the land use pattern of the city whenever it occurs. Land use of Yanbu industrial city comprises of 4,240 hectares of community and residential area, 381 hectares of waterfront and about 2100 hectares of buffer /open space. This work aimed at studying the effect of sea level rise on the land use pattern and population of Yanbu industrial city using the freely available online DEM from SRTM.

2. Materials and Method

2.1 Materials

SRTM DEM data was downloaded from the Consortium for Spatial Information (CSI) web portal (http://srtm.csi.cgiar.org/) (International Centre for Tropical Agriculture (CIAT), 2004). CSI DEM data (Void-filled seamless data) of 3 arc-second (90-m resolution) which is available for the study area was originally processed (by changing the projection to Universal Traverse Mercator (UTM- Zone 37) and cell size to 90m) using ArcGIS software (Figure 2). The demographic data was obtained from Socioeconomic Data and Applications Center (SEDAC) (Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); the World Bank; and Centro Internacional de Agricultura Tropical (CIAT), 2005). The data contain estimated population count of Saudi Arabia in grid format for year 2000.

2.2 Method

Generally, studies of inundation due to sea level rise adopt a minimum scenario of 1m SLR; but studies like Van de Sande et al. (2012), have included storm surge in their sea level rise analyses. Also, the RMSE of SRTM DEM compared with LiDAR or GPS data have been found to be around 1m to 5m (Sun et al., 2003; Tachikawa et al., 2011; Van de Sande et al., 2012 and Schumann et al., 2008). Thus, this study adopted scenarios of 1m, 2m, 3m and 5m, to cover the expected SLR of 1m, tidal range (around 1m in the study area (Saudi Aramco, 2012)) and the difference between SRTM and GPS or LiDAR data as implemented by Li et al. (2009) and Dasgupta et al. (2009). GPS observations were carried out at different points in the study area in order to validate the SRTM data. Since GPS data has been reported to have centimeter RMSE like total station and terrestrial laser scanner (El-Ashmawy, 2014), it can be used for validation. Points with heights equal to or less than 3m (91 points) were selected for comparison with the SRTM data. The "bathtub" approach (Gesch, 2009; Hadley et al., 2010; Van de Sande, 2011; Oswald and Treat, 2013), which assumes that an area is inundated if its elevation is equal to or less than the expected sea level rise, was adopted for this study. A simple implementation of the approach (without consideration of hydrological connectivity) might overestimate inundation area by including areas with elevations lower than the projected elevation but are not connected to an ocean/sea (Gesch, 2009 and Oswald and Treat, 2013). A better way of implementing the approach is to consider hydrological connectivity and filter out the unconnected areas. The two ways of implementing the "bathtub" approach were carried out in this paper to highlight the differences in their results. ArcGIS (version 10.1) software was used to carry out the analyses by extracting the areas that could be vulnerable to inundation based on the different scenarios (1m, 2m, 3m and 5m). Hydrological connectivity was considered by using the Region Group Tool (eight-side rule) in ArcGIS (NOAA, 2012 and Oswald and Treat, 2013). The output of Region Group analysis was a raster layer with all connected cells merged into groups (including their "Count"). NOAA (2012) suggested that extracting the "Count" with the maximum value might filter out the unconnected groups. One might need to supervise the process to avoid filtering out groups with low values that are connected and groups with high values that are unconnected. The results of the extracted areas were overlaid on land use and demographic data to compute the effect of inundation on land use and population. The population data for 2014 was estimated from the SEDAC data based on 5% annual population growth as stated in the economic plan of Yanbu industrial city (RCJY, 2012).

3. Results and Discussion

3.1 Results

The results of the analysis are shown in Figure 2 and Figure 3 below. Figure 2 shows the elevation of the area ranges between 0 and 67m above sea level and the GPS observation points. Figure 3 shows the areas that will be inundated by the projected elevations of 1m, 2m, 3m and 5m (considering hydrological connectivity). Table 1 shows the estimate of the land use to be affected by different scenarios of SLR (without hydrological connectivity), while Table 2 shows the estimate of the population to be affected by different scenarios of SLR (without hydrological connectivity).

The estimates that are based on hydrological connectivity are presented in Table 3 and Table 4. The SRTM and GPS observations comparison result shows that the root mean square of SRTM is 2.07 if the GPS observations are taken as reference points. The correlation coefficient between the two data sets is 0.59. It means 1m sea level rise scenario is equivalent to about 3m SRTM value.

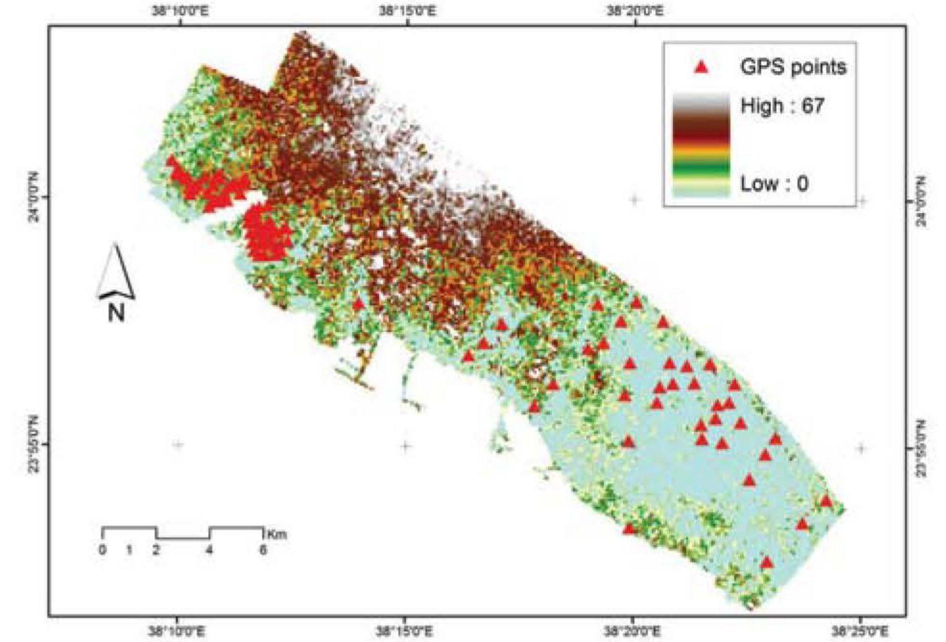

Figure 2: The SRTM DEM of Yanbu industrial city

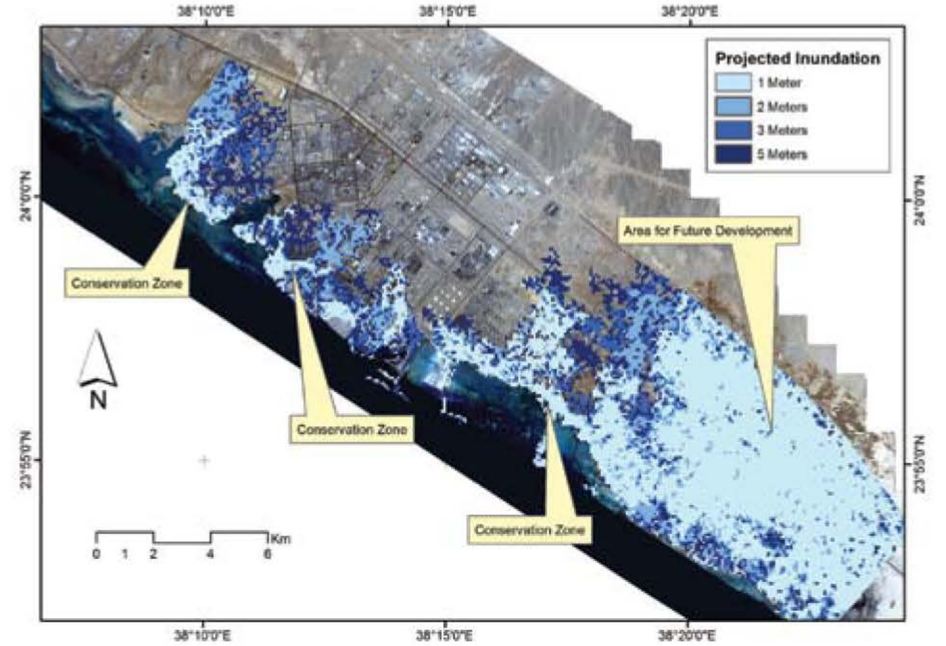

Figure 3: Areas projected to be affected by sea level rise in Yanbu industrial city (with hydrological connectivity)

Table 1: Estimates of affected land use patterns by different scenarios of SLR (without hydrological connectivity)

Scenarios of SLR (without hydrological connection)	Residential (Hectares)	Industrial (Hectares)	Area For Future Development (Hectares)	Total Area (Hectares)
1m	50.706	271.188	421.524	743.418
2m	72.819	341.091	482.193	896.103
3m	99.63	397.872	518.805	1016.31
5m	158.598	504.468	558.09	1221.16

Table 2: Estimates of affected population by different scenarios of SLR (without hydrological connectivity)

Scenarios of SLR (without hydrological connection)	Estimated Area to be affected (Hectares)	Year 2000 Population	Estimated Population for 2014
1m	743.418	17000	33700
2m	896.103	18000	35600
3m	1016.307	20000	39600
5m	1221.156	22000	43600

Table 3: Estimates of affected land use patterns by different scenarios of SLR (with hydrological connectivity)

Scenarios of SLR (with hydrological connection)	Residential (Hectares)	Industrial (Hectares)	Area For Future Development (Hectares)	Total Area (Hectares)
1m	34.02	222.588	396.171	652.779
2m	60.021	297.432	465.912	823.365
3m	89.667	354.942	503.415	948.024
5m	153.495	448.740	536.787	1139.022

Table 4: Estimates of affected population by different scenarios of SLR (with hydrological connectivity)

Scenarios of SLR (with hydrological connection)	Estimated Area to be affected (Hectares)	Year 2000 Population	Estimated Population for 2014
1m	652.779	8500	17000
2m	823.365	10500	20800
3m	948.024	12700	25100
5m	1139.022	14500	28700

3.2 Discussion

According to the different scenarios, the impacts of sea level rise were predicted for Yanbu industrial city. A sea level rise of 1 m (Figure 3) could potentially flood a total area of 652.779 hectares (a reduction of about 90 hectares from the area computed without hydrological connectivity), which represents all the land below 1m elevation. The whole area for future expansion would be affected. A sea level rise of 2m (Figure 3) could potentially flood a total area of 823.365 hectares, which represents all the land below 2m elevation. A sea level rise of 3m (Figure 3) could potentially flood a total area of 948.024 hectares, which represents all the land below 3m elevation. A sea level rise of 5m (Figure 3) could potentially flood a total area of 1139.022 hectaress, which represents all the land below 5m elevation. There is about 70 hectares or more difference between areas computed with hydrological connection and without hydrological connection. The greatest impacts will be in the area designated for future development, which covers more than half of the areas to be affected by 1m to 3m inundation. Other land uses will also be affected even at 1m inundation. For example, all the three conservation zones, residential and industrial areas are at risk of 1m inundation. The conservation zones contain mangroves and coral reefs which are very important to the ecosystem, especially in a desert where such are very scarce to come by. The major road that links Yanbu with other cities like Madinah and Jeddah might also be inundated and rendered impassable. About 17000 people will be affected when the sea level rises by 1m and this figure can rise to about 28700 at a projected elevation of 5m bearing the quality of the SRTM data. There might be some uncertainties associated with the estimated vulnerable population based on the GRUMP data as suggested by Mondal and Tatem (2012), since the population estimate might differ from recent and accurate census data. It is also observed that population counts are allocated to grid cells located within the factories in the study area. These factories might not have any population at all (unless during the working hours) and uncertainty might be introduced into the vulnerable population estimates by this factor.

4. Conclusion and Recommendations

4.1 Conclusion

DEM data from SRTM was used in a GIS environment to analyse the vulnerability of coastal flooding and inundation due to the impacts of sea level rise. Scenarios of sea level rise for 1m, 2m, 3m and 5m were used for the analyses. The study indicates that SRTM DEM data is suitable for depicting areas prone to inundation due to sea level rise in the study area. Though DEM datasets such as LiDAR with higher vertical accuracy and spatial resolution would give better estimations (Gesch, 2009 and Nettleman III et al., 2012), SRTM can still be considered if LiDAR datasets are unavailable or inaccessible. Considering the current rates of global sea level rise which is about 1.8 mm/year (Church et al., 2004), and 2.5 mm/year as indicated by Cazenave et al. (2008); the sea level should rise only between 0.18– 0.25 m by the end of this century (Hereher, 2010). This might not pose a major threat to Yanbu Industrial city but the predicted 1m rise by the year 2100 is a major challenge, especially now that the IPCC scenarios are being reviewed to take into consideration recent melting of Polar ice and other factors.

4.2 Recommendations

The authors recommend as follows:

1. Coastal defences such as raised coastal sand dunes, coastal ridges and elevated coastal strips should be built along the coast to act as the first barrier that help protect inland areas, particularly existing low-lying lands, from inundation and sea surges.
2. Since a rise in sea level by 1m will affect most of the areas for future expansion, we therefore recommend that sand filling and other preventive measures should be carried out before the construction works are commenced.

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