Pol. J. Environ. Stud. Vol. 21, No. 1 (2012), 209-217

Original Research

Investigation of Coastal Inundation Due to a Rise in Sea Level (Temporary and Permanent)

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Received: 31 May 2010
Accepted: 24 March 2011

Abstract

Population along coastal areas currently shows about three times average growth compared to other parts of the world. On the other hand, coastal flooding is a real threat to lives and property, and it is difficult to manage. Studies indicate that greenhouse gas emissions affect climate change and sea level rise (SLR). It is difficult to determine the exact value of the SLR and floodplain area because of the long-term effects, complexity, and source of uncertainties. This study attempts to calculate the SLR for the coast of Iran in the form of future scenarios. By using geographic information system (GIS) and digital elevation models, we predicted water level and flood depth. The high water level, which includes wind setup, wave setup, run up and permanent SLR, was investigated during the 21st century. These factors are calculated for the coast of Iran (Bandar Abbas) in five future scenarios based on the GIS rules. In the other view, increasing in coastal flood hazards, population growth and land use change means that the people, property, and environment along the coastal area will be exposed to greater inundation where improvements in coastal protection are absent or slow to improve. The results show that the ratio of whole flood plain area from S0 (present scenario) to S4 (worse scenario) is 3.5, but this ratio, in the case of residential flood plain, increases to 34. This means the residential area is more affected than other land uses. This study can help coastal managers make land use change plans for flood risk management as adequate methods.

Keywords: climate change, sea level rise, geographic information system, integrated coastal zone management

Introduction

Sea-level rise is one of the most important concerns about the potentially adverse effects of climate change [1-4]. While the potential of sea-level rise during the 21st century have not been reduced, the implications of a rise of sea level remain an important element in determining the overall response to climate change. Therefore, there is a complex relationship between climate and sea-level rise scenarios.

Human impacts on climate change have increased in the 21st century. Meanwhile, the population growth in coastal areas is increasing [5]. Studies and estimates show that in 1990 approximately 21 and 37 percent of the world's population were living within 30 and 100 km of a coastal area, respectively [6]. In addition, a coastal population growth rate of two to three times the average world population growth is predicted in 2030. This means that about 50 percent of the world's population will live in coastal areas 100 km away from the coast until 2030 [7]. Therefore, the main global economy will be concentrated in these areas [8]. Consequently, coastal areas play an important role in gross domestic product (GDP) [9].

SLR will have significant impacts on a number of marine and terrestrial ecosystems, many of which are

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already threatened by human activities [10]. Coastal wetlands are particularly at risk where coastal flood barriers and human settlement prevent their migration inland. Nicholls and Lowe assessed the sensitivity of the coastal system to flooding under different climate scenarios using the HadCM3 model and found that coastal wetlands are lost in all scenarios [11]. The impact of SLR on groundwater, future hurricanes, and flood risk and coastal defences has been studied [12-15].

Nicholls and Small infer growth from demographic momentum and migration to coastal urban areas based on dense coastal populations. The relationship between sea level rise and population is discussed in greater detail [16]. The result of spatial distribution of population relative to coastal elevation shows that many people will be affected by floods in future decades [7]. On the other hand, a rise in sea level makes four main impacts in coastal areas:

(1) inundate and displace wetlands and lowlands
(2) erode shorelines
(3) exacerbate storm flooding and damage
(4) increase the salinity of estuaries and threaten freshwater aquifers [9].

In addition, SLR has significant effects on aquifers and underground water quality and quantity in coastal areas. For example, with an SLR of 50 cm, the aquifer decreases 9 km in the Nile delta [17] and 0.4 km in the Bay of Bengal [18].

For that reason, it is important to investigate the coastal future climate change and sea level rise despite uncertainties. In the second IPCC assessment from 1990 to 2100, the rate of SLR was estimated between 23 and 96 cm [19]. The latest rate of sea level rise (SLR) is predicted to be between 9 and 88 cm [20]. The studies show large differences in storm intensity and frequency in future decades. “A slight increase in the annual number of named storms over the past 50 years presents no statistically significant trend in tropical storms, hurricanes, or major hurricanes in the Gulf of Mexico” [21]. Most climatic studies focus on the change in mean sea level and not other climate factors [22, 23]. Meteorological effects as well as oceanography and geological processes affect SLR and make it impossible to evaluate them clearly [24, 25]. Even with climate stabilization in the coming decades, the weather conditions and SLR will continue after 2100. In addition, local changes and changes in sea level affect the behavior of storms.

Consequently, coastal flooding is heavily influenced by environmental and geographical factors such as elevation above mean sea level, distance from the shoreline, and the effectiveness of artificial coastal defenses or natural barriers such as wetlands, dunes, coral reefs, or mangroves, which can dissipate the energy of hazards such as storm surges. However, the application of scenarios is necessary under uncertainties. This study tries to find a new approach for determination of future coastal flooding and its impacts on people, property, and the environment. This method focuses on population growth and land use change in coastal areas and using GIS tools and digital evaluation models (DEM). The application of GIS technology and DEM in urban communities has been performed by [26-29].

The Case Study Area

The study area is part of the city of Bandarabbas (Fig. 1), located on the Persian Gulf north of the Hormos Strait. The area is 27,316 square kilometers. According to the housing census in 2006, the population of the city of Bandarabbas was 515,577 people. The distance of Bandarabbas to Tehran is 1,333 km.

Material and Methods

Coastal flooding is the result of infrequent extreme sea levels. The intensity and range of SLR that effect people,

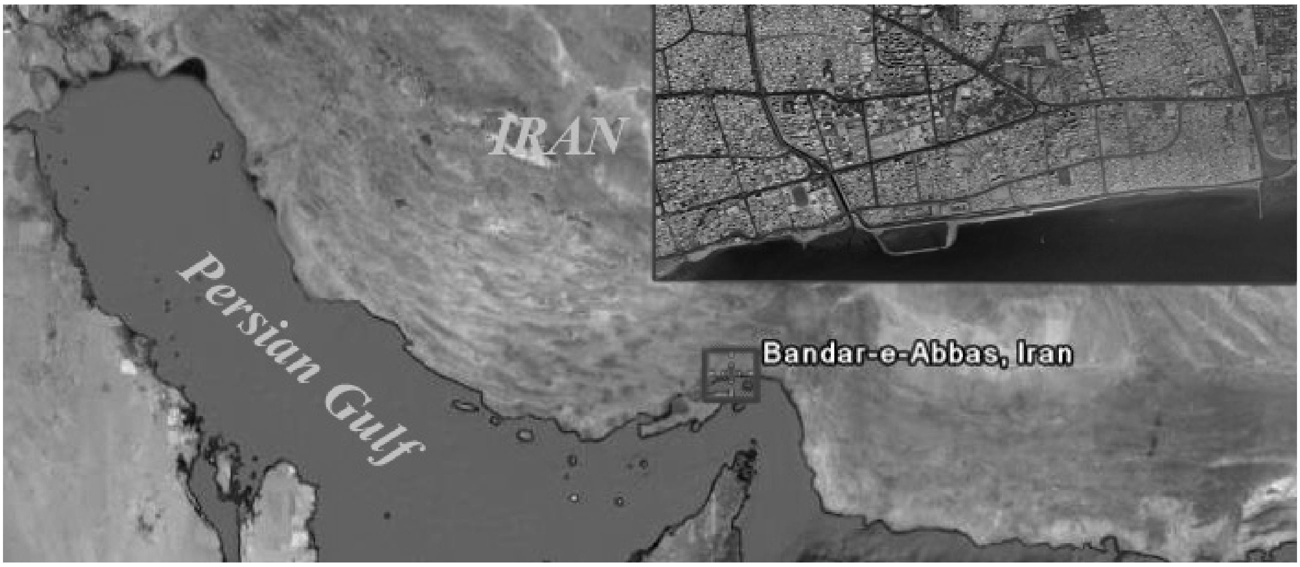

Fig. 1. Case study area (the Persian Gulf, Bandarabbas).

property, and the environment in coastal areas depend on the following factors:

- Dimensions of SLR
- The effect of SLR on storm surge
- Effect of hydrodynamic factors such as wind and waves
- The interaction of SLR with other climate factors, such as changes in storm intensity and frequency
- Response of coastal geomorphology to SLR, which depends on coastal ecosystems and human activities
- Population exposure to risk of SLR
- Ability of people and related systems to respond to SLR

The sea level rise has two significant parts. The first part is permanent due to climate change, melting ice, and the increase in the earth's temperature in this century. The second part is due to the wind set up, wave setup, run up, and maximum tide. Due to many uncertainties in both parts, the best method to define the future flood is application of scenarios. Total flood depth is calculated under future scenarios. The methodology emphasized on GIS[1] and DEM[2] models are population and land use.

Permanent Sea Level Rise

Climate change will be more serious by 2100, when global average sea level will have risen above present-day levels by between 20 and 59 cm. The World Meteorological Organization (WMO) and the United Nations Environment Program founded an intergovernmental panel on climate change in 2000. The different climate scenarios mentioned by the IPCC are presented in Table 1 [30]. For worse scenarios the highest level could be 88 cm [19].

Temporary Sea Level Rise

The following equations were used to determine wind set up, wave setup, and run up based on coastal engineering manuals. Then a program was developed in MATLAB software to solve these equations.

For the wind setup, equation 1 was used [31].

$$\frac{x}{l} = (1 - \frac{h+\eta(x)}{h_o}) - ALn(\frac{\frac{h+\eta(x)}{h_o} - A}{1-A}) \tag{1}$$

...where h is water depth in various parts, h_o is maximum water depth, l is maximum distance from sea to shore, x is distance in various parts of fixed slope, $\eta(x)$ is wind setup and $A= n\tau_{wx}\ l/\rho gh02$, a ratio of shear to hydrostatic forces, ρ is the mass density of water, g is gravity, and n is a friction factor of sea bottom that is greater than 1. Typical values for n=1.15 to 1.3 (Shore Protection Manual, 1977), $\tau_{wx}=|\tau_w|\cos\theta$ is onshore wind shear stress, $\tau_w=\rho k\mathbf{W}|\mathbf{W}|$ k is a friction factor of order 10-6, and W is the wind speed vector at a reference elevation of 10 m.

Table 1. SLR Scenarios (cm).

	Range	Average	Considered Value*
B_1	18-38	28	20 (min)
B_2	20-43	31.5	35 (moderate)
A_2	23-51	37	46 (moderate)
A_1F_1	26-59	42.5	59 (max)

*Values considered in this study

For the wave setup, equation 2 was used [32].

$$\bar{\eta}_{\max} = \bar{\eta}_s + \frac{d\bar{\eta}}{dx}\Delta x \tag{2}$$

...where $\bar{\eta}$max is the maximum setup at the mean shoreline, $\bar{\eta}_s$ is setup at the still-water shoreline, and Δx is the shoreward displacement of the shoreline. The parameters of equation 2 are represented below.

$$\bar{\eta}_s = \bar{\eta}_b + \left[\frac{1}{1+\frac{8}{3\gamma_b^2}}\right]h_b \tag{3}$$

$$\frac{d\bar{\eta}}{dx} = \frac{1}{1+\frac{8}{3\gamma_b^2}}\tan\beta \tag{4}$$

...where tanβ, is sea bed slope, γ_b is breaker depth index, and $\bar{\eta}_b$ is the maximum lowering of the water level, set down that occurs near the break point and is given by equation 5.

$$\bar{\eta}_b = -\frac{1}{8}\frac{H^2\frac{2\pi}{L}}{\sinh\left(\frac{4\pi}{L}d\right)} \tag{5}$$

...where H is wave height, L is wave length, and d is total water depth.

For the run up, equation 6 was used [32].

$$R_{2\%}/H_o=1.86\xi^{00.71} \tag{6}$$

...where $R_{2\%}$ is the run up exceeded by 2 percent of the run up crests, H_o is the significant deepwater wave height, L_o is wave length, and ξ_o is the surf similarity parameter given by equation 7.

$$\xi_o = \tan\beta\ (H_o/L_o)^{-1/2} \tag{7}$$

...where the subscript '$_o$' denotes the deepwater condition.

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[1] Geographic Information System

[2] Digital Elevation Model

Table 2. Top projection scenarios of sea level (cm).

	MHHW (cm)	Temporary Rise		Permanent SLR	Total (cm)
		Parameters	(Cm)		
S0	82	Wave and Wind (rp 50)	177	0	259
S1	82	Wave and Wind (rp 100)	238	20	340
S2	82	Wave and Wind (rp 100)	238	46	366
S3	82	Wave and Tropical Storm (rp 100)	392	59	533
S4	82	Wave and Tropical Storm (rp 100)	392	88	562

Results and Discussion

In this study, the total water level is calculated based on astronomical tide, wave setup, and wind setup for the case study area. The basic wave parameters were found using the Iran Wave Atlas (IWA) program and extracted from extreme value analysis (EVA) for return periods of 5, 20, and 50 years. For extracting the 100-year return period, linear regression was calculated. A twelve-year hindcast of wave conditions in the Oman Sea, the Persian Gulf, and the Caspian Sea was recently carried out by the Iranian National Centre for Oceanography (INCO) with collaboration of the Danish Hydraulic Institute (DHI). The project was introduced by the Port and Maritime Organization (PMO) and titled Iranian Seas Wave Modeling (ISWM). The ISWM study included a comprehensive assessment of available wind and wave data within Iranian waters and used the Danish Hydraulic Institute's MIKE21 3rd generation Spectral Wave model (M21SW) driven by winds from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational nowcast data. After a review of existing wave data sources, it was determined that, despite some inaccuracies and rather short duration (12 years), the ISWM dataset at present provides the most consistent and state-of-the-art wave climate data for Iranian coastlines.

ISWM results are accessible through Iran Wave Atlas (IWA) software, which also provides various statistical analyses of the data. IWA outputs wave information on a rectangular grid with grid size of 0.125º near Iranian coasts and 0.25º in the offshore. Wave data for areas close to the shore in the Caspian Sea, Persian Gulf, Hormoz Strait, and Oman Sea were provided by PMO at a total of 284 points.

The permanent SLR was added to the temporary SLR. The combination of five stages for temporary SLR (based on different return periods) and five stages for permanent SLR (based on IPCC studies) was considered that their total is expressed in Table 2.

Finally, each class is considered as a whole scenario in this study and has been named from S0 to S4. In each scenario, based on rising rates, flood depth is divided in the 2 to 5 range. Flood area and the range of flood depth in each scenario are shown in Figs. 2 to 6.

To display the maps, the following has been used.

- Analytical floodplain maps, which are outlines of the area that could potentially be flooded in a 1:100-year return period flood

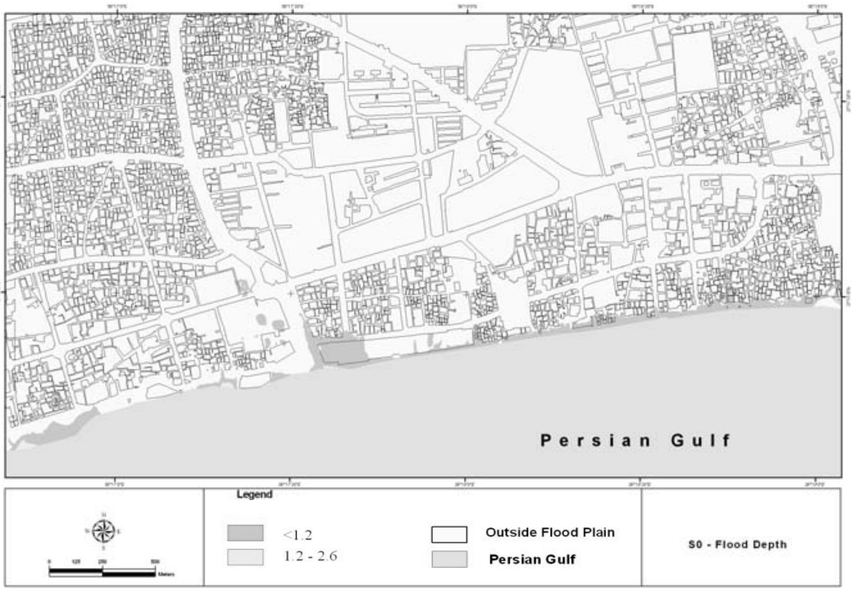


Fig. 2. Floodplain under scenario S0 (m).

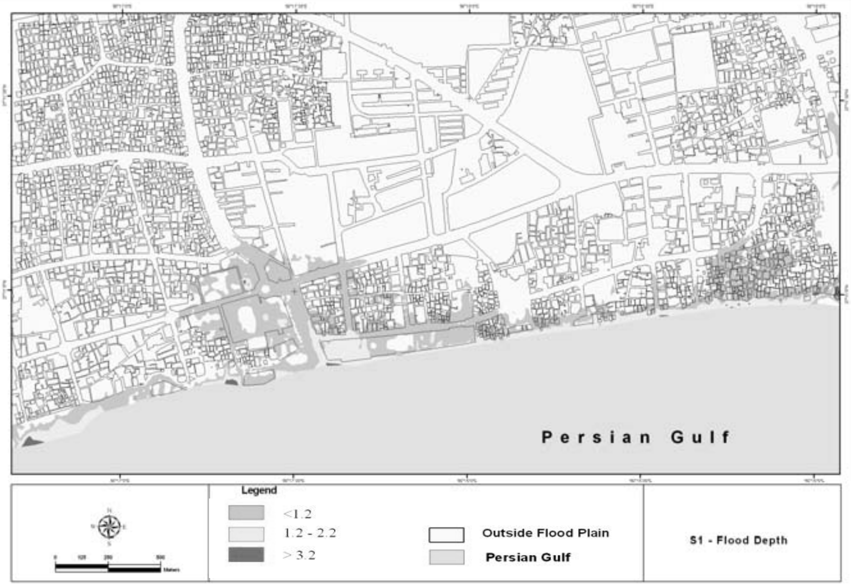


Fig. 3. Floodplain under scenario S1 (m).

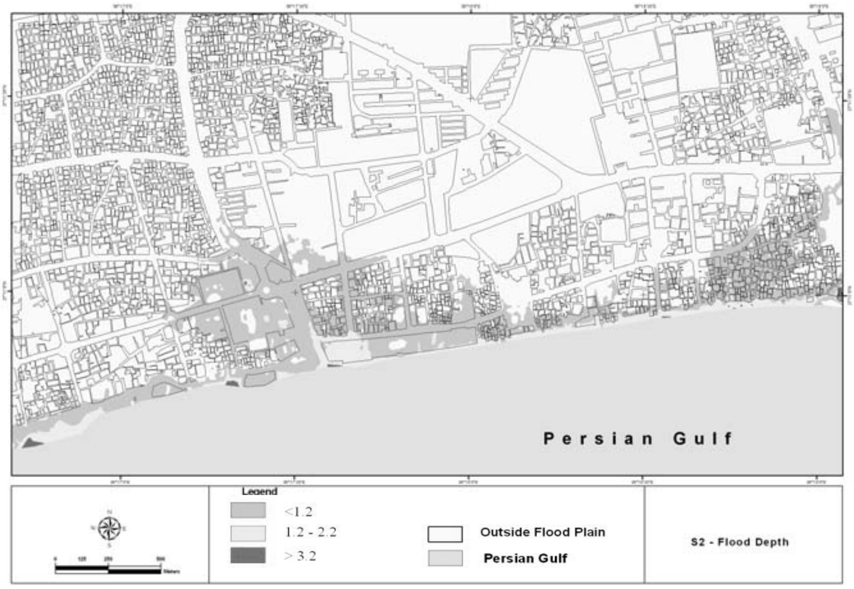


Fig. 4. Floodplain under scenario S2 (m).

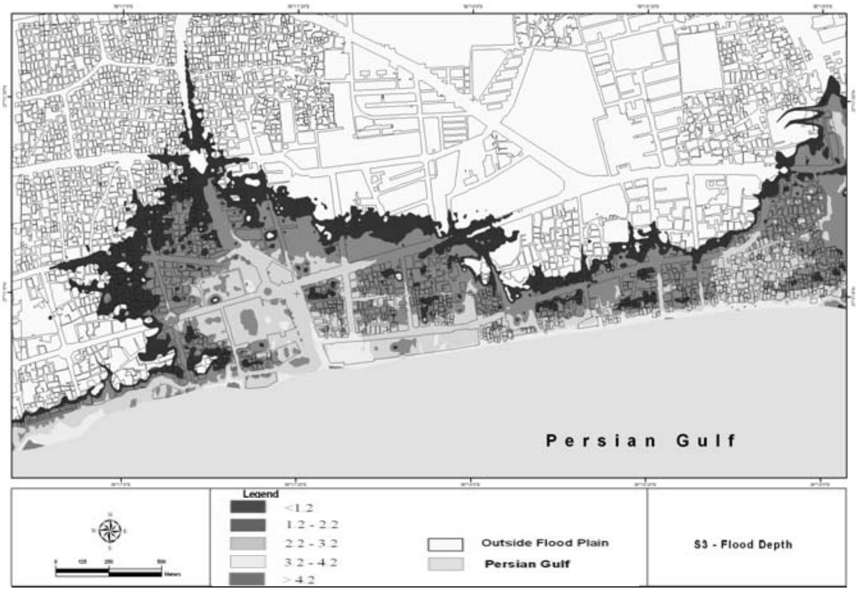


Fig. 5. Floodplain under scenario S3 (m).

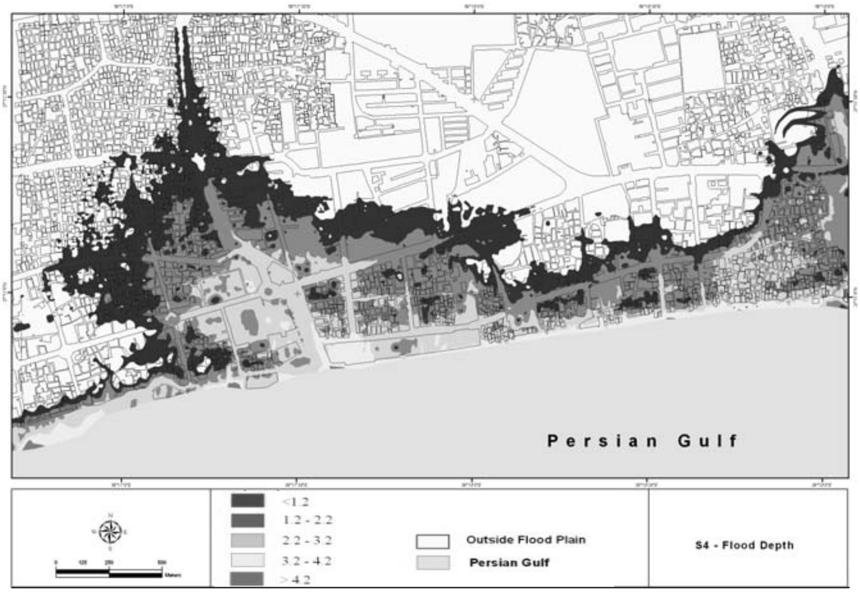


Fig. 6. Floodplain under scenario S4 (m).

- 1:500 maps with 20-cm contours used to classify land use types
- Flood depths estimated from Arc GIS 9 software for a given floodplain
- Databases of residential, commercial, and infrastructural properties
- Population census data

Figs. 2 to 6 show that in the case of the S0 scenario, 79 hectares are flooded and the maximum flood's depth is 562 cm. This value increases to 230 hectares in the S4 scenario. As it is seen, the hazard zone increases from S0 to S4 by almost 3 times. In addition, increasing the hazard zone affects land use. The floodplain area in terms of land use is shown in Fig. 7. Using an excel graph, the amount of inundation for every application in each scenario is shown in Fig. 8.

Fig. 8 confirms that the flood has more influence on residential area and this flood plain area increases considerably in S3 and S4. Total floodplain area in S0 scenario is 79 hectares, and in this scenario Residential area covers 3.51 percent of floodplain. In scenario S4, the total floodplain area is 230 hectares and in this scenario Residential area covers 42 percent of floodplain. In the other view, the ratio of whole flood plain area from S0 to S4 is 3, but this ratio, in the case of residential floodplain, increases to 34. This means the residential area is more affected than other land uses.

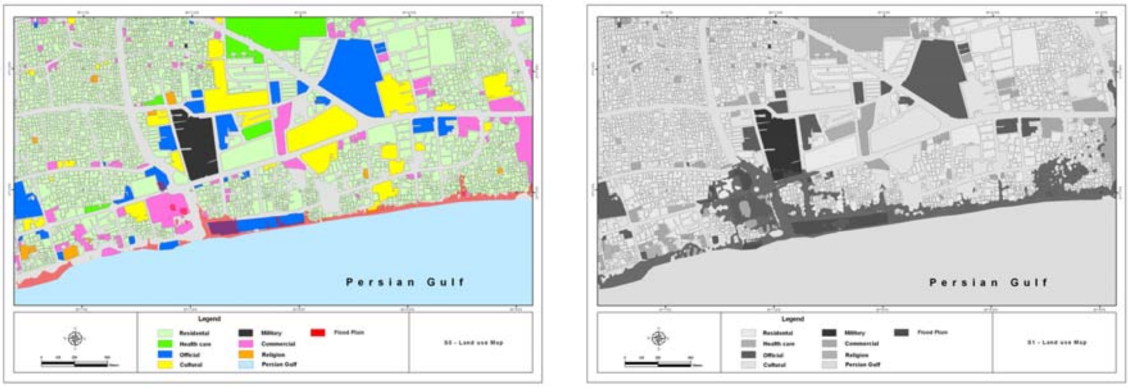
Increases in coastal flood hazards and population growth means that the populations along the coast of Iran will be exposed to greater inundation where improvements in coastal protection are absent or slow to improve.

The result of the flood map shows large increases in the number of people occupying the floodplain in Bandarabbas in S3 and S4 scenarios. The floodplain occupancy from S0 to S1 and S2 scenarios increases moderately. Principally, the number of people at risk is affected frequently due to climate change. With current flood strategies, the coastal systems face greater vulnerability by 2100.

This means that, along the southern coast of Iran, scenario S2 (the likely scenario for Iran), the expected annual number of casualties, and total damage increases. Meanwhile, fresh and saline water with a 46-cm sea level are threatened and the exact amount of SLR must be calculated. Meanwhile, tidal habitat is also affected by increasing water levels. The SLR with other environmental and socioeconomic factors are parts of integrated coastal zone management. The lack of consideration for the above parameters threatens coastal environments in the future.

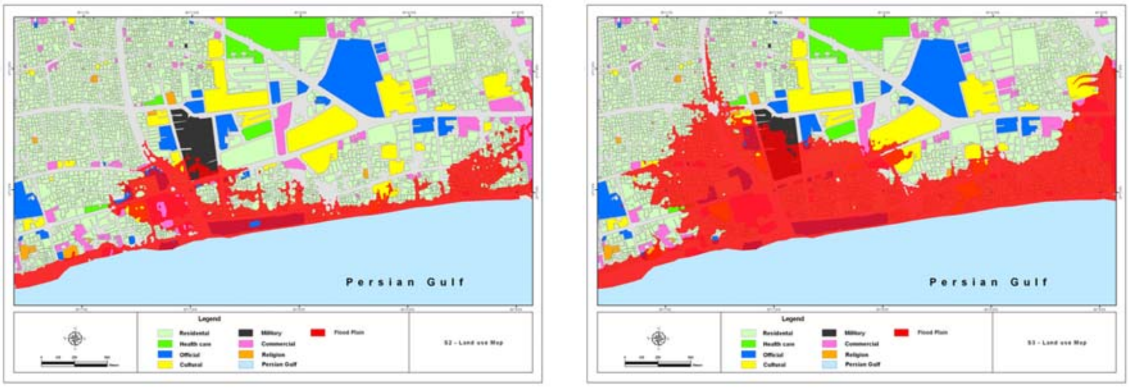
Conclusion

The purpose of this paper is to assess the change in the floodplain under future scenarios using a new approach to determine total SLR, temporary and permanent, due to climatic scenarios in Iran over a period of 100 years. The quantitative method in this paper predicts flood depth for different land uses for future scenarios. This methodology shows broad variation in the number of people and area of various land use exposed to inundation for each scenarios. The floodplain area in the S4 scenario is 3.5 times over S0, but the residential area in S4 is 34 times over the residential area in S0. This means land use is an important parameter in coastal flood management. Also, the application of GIS in multi-dimensional analysis for flood hazard must carefully consider these future scenarios for all land use. The method of this paper helps coastal managers to decrease damage with land use change. The result shows GIS technology reducing complexity, and this study confirms that. Meanwhile the result predicts extreme increases in flood damage in future decades that are proven by previous studies. These studies focus on the importance of land use change and population growth [11, 28, 29]. This shows good agreement with this study. Moreover, the management of land use change and population growth could decrease flood risk as adequate methods.



S0 – Floodplain, different land uses

S1 – Floodplain, different land uses



S2 – Floodplain, different land uses

S3 – Floodplain, different land uses

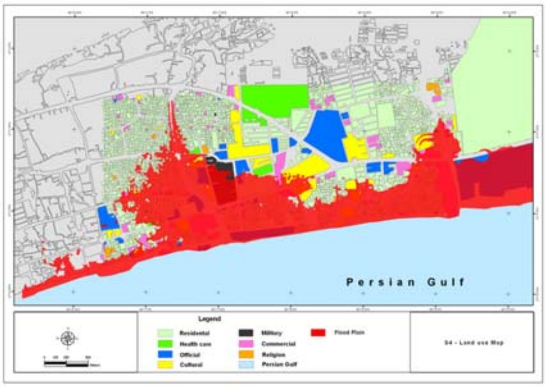


Fig. 7. Floodplain area and different land uses for future scenarios in GIS form.

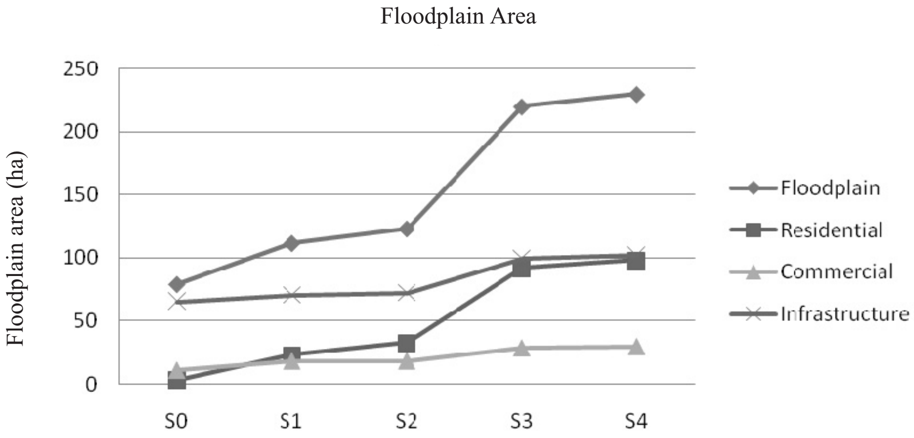


Fig. 8. Floodplain area and different land uses for all scenarios (Iran, Bandarabbas).

Acknowledgements

We thank the department of Civil and Environmental Engineering and K.N. Toosi from the University of Technology, Tehran, Iran for their support of this paper, which is a section of the PhD thesis of PhD A.N. Harati. We also thank the Eng. Mousavi, who provided the GIS tools for this paper.

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