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ORIGINAL PAPER

Vulnerability assessment and adaptation to the impacts of sea level rise on the Kingdom of Bahrain

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Abstract This paper assesses quantitatively the impact of sea level rise (SLR) at the global and regional scale as a result of climate change (CC) on the coastal areas of the Kingdom of Bahrain's islands (36 Islands). The standard Intergovernmental Panel on Climate Change (IPCC) guidelines was modified as appropriate for the situation of the study area. Geographic Information Systems (GIS) coupled with Remote Sensing (RS) were used as the main techniques of collecting, analyzing, modeling simulating and disseminating information to build SLR scenarios in a geographically referenced context. Also, these tools were used to assess vulnerability and risk of the coastal area of the islands with the expectation that coastal planner and government authorities will profit from integrating these knowledge into a broad based environmental decision making. Three SLR scenarios: low, moderate and high were developed to examine the impacts from SLR on all islands. The low SLR scenario (Optimistic) assumes a 0.5-m rise above current sea level, the moderate scenario (Intermediate) assumes a one meter rise, and the high scenario (Pessimistic) assumes a 1.5 m rise in sea level. Two more SLR scenarios were assumed to perform risk analysis, a 2 and 5 meter rise above current sea level. The simulation of SLR are quite straightforward, emphasizing on the uses of both of the data that are incorporated from the satellite images and the created Digital Elevation Model (DEM) to estimate SLR scenarios that are adapted in the study. These data were used to predict consequences of the possibility of the rise in sea level at different scenarios which may alter the landuse and patterns of human communities. Results indicate that low-lying coastal areas of Bahrain islands are at risk from the effects of any SLR resulting from CC. These islands are vulnerable under different SLR Scenarios. More than 17% of the country total area may be inundated under 1.5 m

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SLR in 2100. The total area that might be lost under different sea level scenarios will vary from more than 77 km^2 if SLR reaches 0.5 m, to about 100 km^2 under 1.0 m SLR and may reach 124 km^2 under 1.5 m SLR scenario. The total inundated areas due to risk scenarios will reach 133 km^2, if the SLR rises to 2.0 m, and it is estimated to be more than (22%) of the main island total area. Under the second scenario, if the SLR reaches 5.0 m, the main islands will lose approximately half of its area (47%) equal to 280 km^2. Hawar islands group will lose about (30%) of its total area under 2.0 m SLR, which is about 15.5 km^2.A SLR adaptation policy framework (APF) and adaptation policy initiatives (APIs) are suggested for planners to build upon for reducing the likely effects of SLR in the Kingdom of Bahrain. The framework is composed of four steps namely, acquisition of information, planning and design, implementation and monitoring and evaluation. A general policy framework for a national response to SLR is suggested. Additionally, a range of policy adaptation options/initiatives to sustain coastal developments under the likely effects of SLR are recommended.

Keywords Climate change · Digital elevation model · Geographical information system (GIS) · Remote sensing · Small islands

Introduction

The Kingdom of Bahrain is one of the small islands states that might be at a great risk due to SLR/CC (IPCC 2001). The country consists of 36 small islands. The first group consists of five islands, which are major and inhabited: Bahrain, Muharraq, Sitrah, Jiddah and Umm Nassan. The second group, Hawar islands are uninhabited and virgin, Fig. 1. The islands have flat sandy coastline. More than 10% of the total area of the islands surface is estimated at 0.5 m above mean sea level, (80 km^2). Table 1 and Fig. 2 display the surface elevation above mean sea level for the study area. The five major islands represent 93% of the total land area, most of which are located in these islands. Two-thirds of the population (total 650,604 in 2001) live within 2.0 km of the coastline (CSO/SA 1970–2001).

SLR above the Mean Sea Level (MSL) may pose substantial threat to the Bahrain islands resources because of their low-lying physiographical setting and the infilling activities that have been carried out throughout the years. Critical infrastructures such as major roads, causeways along with many socioeconomic compounds are concentrated on the newly reclaimed areas. These areas support various economic activities including hotels, resorts, airport and industrial complex (BIC/UNFCCC 2005).

As a small island state, Kingdom of Bahrain has a limited capacity to adapt to relative SLR/CC, including accommodating landward migration of coastal habitats. This is a result of the small land mass, high population densities and population growth rates. It may be physically and economically difficult to retreat from landward migrating coastal habitats, or to establish zoning setbacks from coastal habitats for new development (Al-Jeneid and Abido 2004).

The slope is the primary variable controlling the magnitude and range of SLR impact over time for many coastal areas. 88% of the study area are flat to nearly level (0–1 %), Table 2. Thus, the flat coastlines of the islands are expected to be

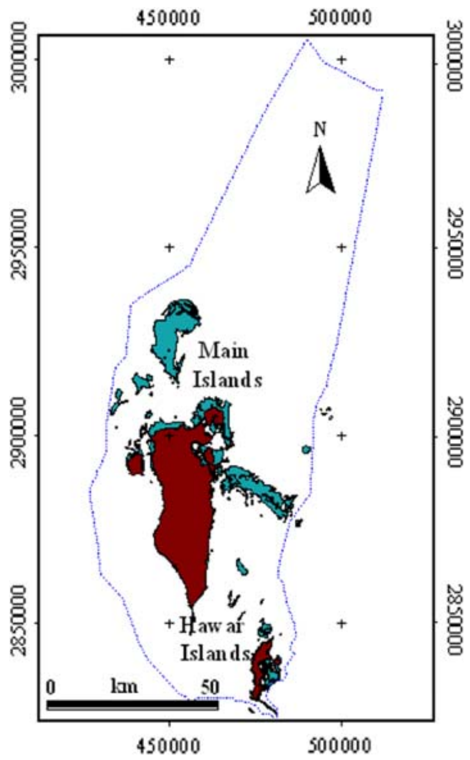


Fig. 1 The Kingdom of Bahrain archipelago

Table 1 Surface elevation above mean sea level

SLR	Area/km	Total (%)
0–0.5	79.75	11.14
0.50–1	22.01	3.08
1–1.50	24.51	3.42
1.50–2	25.22	3.52
2–5.0	173.36	24.22
>>5	390.87	54.61
Total	715.72	

highly impacted by SLR and gradual submergence of the coastal area is quite likely over time.

The objectives of this paper are to identify and quantify the vulnerable low lying coastal area of the islands to the adverse effects of CC/SLR, categorizing these vulnerable sectors, regions and resources in response to three projected SLR scenarios: a conservative, moderate and worst rate per century. Moreover, to assess the degree of future risks induced by SLR in response to two projected SLR scenarios. Finally, to develop a feasible and effective adaptation measures that might be adopted in the Kingdom of Bahrain to minimize the impacts of such possible changes.

Fig. 2 The surface area estimated at 0.5 m above mean sea level of Bahrain Archipelago

Table 2 Slope and corresponding area (FAO 1990)

Type	Slope (%)	Total area	%
Flat to nearly level	0–1	559.5	88
Very gently slope to sloping	1–10	150	21
Strongly sloping to moderately steep	10–30	6.20	0.86
Steep to very steep	>>30	0.50	0.07
Total area		716	

Methodology

This assessment addresses the impact of sea level rise (SLR) and procedures followed to build up the SLR Scenarios and to assess the vulnerability of the coastal areas of the 36 islands of the Kingdom of Bahrain using Geographical Information Systems (GIS) integrated with Remote Sensing (RS) and geoprocessing approaches. Moreover, it identifies vulnerable sectors, regions and resources and assesses the degree of future risk posed by SLR in order to enhance the national capacity to address the possibility of accelerated sea level rise (ASLR). The methodological framework followed depends on the ''Common Methodology'' (IPCC 1992), a seven steps guide that provides an approach to vulnerability analysis (VA) for (ASLR), taking into consideration all new ideas and approaches developed upon this methodology. The methodology builds on IPCC: Technical Guidelines for Assessing

Climate Change Impacts and Adaptations, (Carter et al. 1994) and tracks the changes in UNEP's Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies (Feenstra et al. 1998).

There is a range of different approaches or methods that can be used in the assessment of CC impacts. These include quantitative and predictive models, empirical studies, expert judgment and experimentation. In addition to formal modeling approaches, consideration should also be given to methods of stakeholder involvement, and the use of expert judgment. There are also other tools that may be used, such as geographic information systems (GIS) and RS. (Feenstra et al. 1998).

An attempt was made to evaluate the implication of unsupervised/supervised (Hybrid) classification to produce landuse/landcover thematic map as an approach to extract features needed to accomplish this study. Hybrid classification is particularly valuable in analysis where there is a complex variability in the spectral response patterns for individual cover type present (Lillesand et al. 2002; Schowengerdt 1983). The Digital image classification steps followed in this work include unsupervised classification, field survey, supervised classification and accuracy assessment. Landcover/landuse scheme establishment depends on the prior knowledge of the study area and after the field work, visiting trips to check out the existing ground type of classes were identified. Classification schemes represent a necessary component to effective landcover/landuse management planning (Jensen 1996). The choice of these land cover/landuse classes was guided by: (i) the objective of the study, (ii) expected certain degree of accuracy in image classification and (iii) the easiness of identifying classes on QuickBird images.

GIS and RS technologies have been integrated and used in order to model, simulate and assess SLR around the coastal area of the islands. A GIS Database has been build by integrating all the data needed using ArcInfo, ArcView and Arc GIS. The most essential data sets required for this study consist of a current landuse/landcover map and a digital elevation model (DEM). IRS/SPOT/QuickBird satellite images (2002) have been utilized and classified to produce a map of the study area. Seven terrestrial classes were identified from the IRS image, merged with two marine classes produced from SPOT image, Fig. 3 and Table 3.

A high-resolution DEM (5×5 m) for all the islands was developed, using topographic maps with a contour interval of 5 m, and a spot heights coverage contain more the 6,000 points, and a bathymetry point coverage contain more than 20,000 points of sea floor. The basic contour data for the DEM was based on digitized contours. Contours from the analogue topographic maps had been digitized manually. Subsequently, the contours are registered, vectorized, edited and tagged with elevation values. The ArcInfo GIS was employed to carry out this step. These layers were built as shape files using ArcView, then imported by PCI software as shape files. In the case of modeling SLR, the primary input data are elevation values contained in the DEM, Figs. 4 and 5. This is the source of database uncertainty. The root mean square (RMS) error (in altitude) of this DEM was equal to 0.29 m, and this describes the uncertainty associated with the interpolated heights.

This DEM used to produce 3D views for the study area, which offer a simple and direct method for displaying structured and technical natural phenomena. Moreover, the 3D documents increase the information available from the data input and represent a synthesis of scientific documents that increase implicit value of the data, Fig. 6 and Table 4.

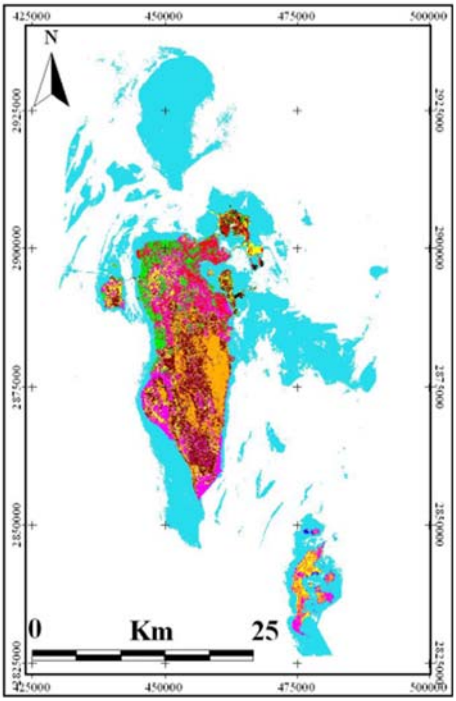


Fig. 3 Landuse/landcover thematic map

Table 3 Landcover/landuse total area (km^2), and % from total area, and their description

Landcover/ Landuse = Classes	Total area	Total area (%)	Description
1. BuiltUp area	83.97	10.33	All types of residential areas, and density industrial areas (Airport, Oil & Gas)
2. Agriculture area	81.10	11.35	Palm trees garden area and cultivated areas with vegetables and trees
3. Bare soil 1	104.72	14.65	Sandstone
4. Bare soil 2	165.63	23.17	(Dammam formation): Dolomite, limestone, calcareous limestone and marl
5. Bare soil 3	109.03	15.25	(Rus formation): Limestone, dolomitic limestone and chalk with subsidiary marls and shales
6. Sabkha 1	167.81	23.47	Inland sabkha and Coastal sabkha: Salinized area
7. Mud	2.45	0.34	Fine thick mud accumulated surrounding Hawar Islands

Sea level rise scenarios

Various possible impacts of CC on the earth depend on the increasing concentration of greenhouse gases (IPCC 1990, 1994, 1999, 2001). One of the possible impacts associated with CC is an acceleration of the SLR. The IPCC has developed different future scenarios on the possible rate of the SLR until the year 2100. Carter et al.

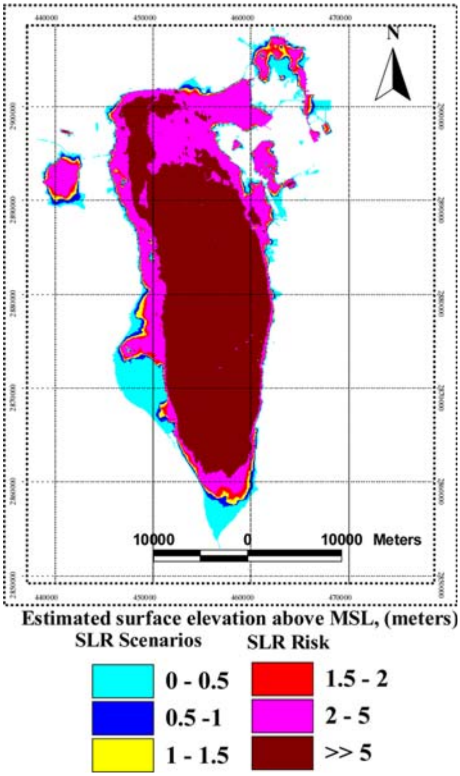


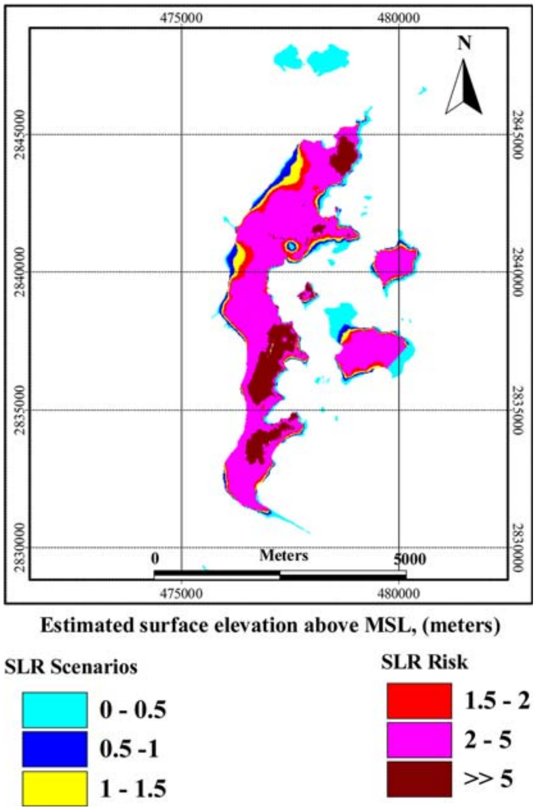
Fig. 4 DEM of the first group of Bahrain Archipelago

(1994) defined the scenarios as ‘‘a coherent, internally consistent and plausible description of a possible future state of the world.’’

SLR scenarios are constructed to assess CC impacts and adaptations in the coastal zone. Sea level has been rising globally during the last century by a rate between 1 and 2 mm/yr (Church et al. 2001). The IPCC report projects global sea levels for the next century to change by 9–88 cm. A total rise of up to 1 m is possible by the year 2100 (relative to 1990). To deal with this change, coastal managers require site-specific information on relative (i.e., local) changes in sea level to determine what might be threatened. Therefore, as a first step, global sea-level rise scenarios need to be transformed into relative sea-level change scenarios which take account of local and regional factors, such as vertical land movements, in addition to global changes.

The aim of a vulnerability and adaptation assessment in this study is to clarify the potential impacts of CC on critically important sectors. In the case of Bahrain’s coastal zones, this involves an estimate of the spatial extent of future inundation from projected SLR, together with an assessment of its impact on human settlements, agriculture, and natural ecosystems. It also implies the identification of strategic adaptation options. This process requires that a scenario be created of what Bahraini coastal areas might look like in a future without CC, and that this scenario can be compared with a parallel vision of what coastal zones would look like under predicted conditions of CC. In order for this to be done, two climate scenarios must

Fig. 5 DEM of Bahrain Archipelago, Hawar



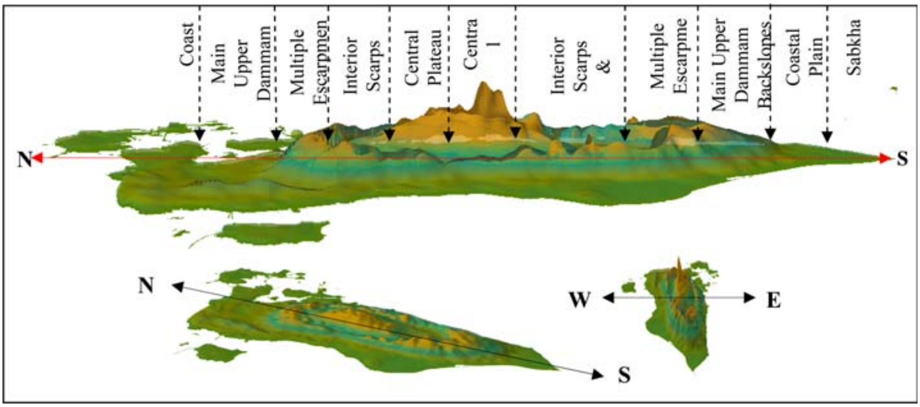


Fig. 6 Study area plain in 3D view from different directions

be created: a baseline scenario, aimed at representing a future in the absence of CC and a CC scenario, aimed at representing a future under increased greenhouse gas concentrations and the resulting changes in sea level.

Table 4 Landcover/landuse total area (km^2)of the first group main islands, and % from total area, and their description

Elevation	BuiltUp area	Agriculture	Bare soil 1	Bare soil 2	Bare soil 3	Sabkhas	Total
0–0.5	16.21	1.67	21.51	0.83	7.47	24.21	71.9
0.5–1	4.73	0.7	7.76	0.32	2.1	4.24	19.84
1–1.5	5.24	0.61	8.91	0.25	2.29	4.19	21.49
1.5–2	5.53	0.62	8.43	0.38	2.8	4.34	22.11
2–5	7.79	0.1	20.24	36.05	54.83	34.18	153.2
>>5	82.1	10.63	103.32	33	78.11	69.25	376.43
Total	39.5	3.7	66.85	37.83	69.49	71.16	664.97

The SLR scenarios had been simulated and isolated from the DEM. The CC scenarios, based on IPCC (2001) assumptions were formulated as a methodological standard tool for the impact and risk assessment to be performed in this study. The global MSL is projected to rise by 0.09–0.88 m between 1990 and 2100 for the full range of SRES scenarios (IPCC 2001). The regional rate of increase in sea level in The Arabian/Persian Gulf is about 2.3 cm in (2.1 mm + –0.1 mm per year) (Sultan et al. 1995).

Three classical CC scenarios: low, moderate, and high—were developed to examine the impacts from SLR on all the islands. The low SLR scenario (Optimistic) assumed a 0.5-m rise above current sea level, the moderate scenario (Intermediate) assumed a one meter rise, and the high scenario (Pessimistic) assumed a 1.5 m rise in sea level. These scenarios were arbitrary chosen for three reasons: The first is concerned with the inadequacy of available data record on natural mean SLR in the Kingdom of Bahrain. The collected record is less than 20 years; the second is the unavailability of regional estimation on subsidence and uplifting of land surface and seabed; the third is the DEM RMS error, which is estimated to be 0.30. The range between the low and high estimates is supposed to cover these uncertainties.

The GIS application provides a set of SLR maps, displaying the effects of SLR on an area. These maps are based on a DEM of the case study areas and a range of global and regional sea levels. Areas that might be submerged by SLR have been determined straightforward. The landcover/landuse data had been overlayed on the reclassified DEM. The resulted data were used to predict the consequences of the possible rise in sea level at different scenarios over the next 100 years due to global warming, which may alter the landuse and patterns of human communities.

Vulnerability assessment

The low-lying nature of the coastal zone of Bahrain's islands, coupled with significant land reclamation investments and extensive industrial, commercial, and residential activity, emphasizes the country's critical vulnerability to CC-induced SLR. At present there is no major national plan to assess vulnerability to impacts of SLR. Actually, the hazard is frequently considered minimum. This is mainly due to the lack of relevant studies and to a very limited public awareness on SLR impact potential.

Ecological and socio-economic systems are currently facing tremendous pressures due to the rapid urbanization, industrialization, and economic development. The global CC and the resulting ASLR are among the hardest impacts that fall upon those coastal zones. The SLR phenomenon is going to accelerate the degradation of the coastal and marine resources of the Kingdom of Bahrain. These resources are being over exploited in the last 30 years due to economic forces as well as weaknesses in policies, regulations, and information. The multiplicity of institutions and ambiguities in their jurisdictions; and the lack of integrated approaches have multiple the management and planning problems of the coastal and marine resources in the country, (BIC/UNFCCC 2005).

The coastal zone of the first main group islands is intense economically and demographically (ROPME 1999). Inundation from SLR could lead to serious displacement of people, commercial and industrial activities (Nasrallah and Balling 1993). The Hawar group islands represent protected areas that are surrounded by coral reefs and shallow water. These are uninhabited areas and declared as national protected areas. Inundation from SLR could lead to loss of biological diversity and adverse impacts on the diverse populations of birds, dugong, green turtle, corals and fish, and sea grass. A conservative assumption about the scenarios is adapted to facilitate the analysis; it was assumed that these islands' coastal zone geography and economic activity levels in 2100 would be similar to what they are in 2002.

Vulnerability assessment (VA) study revealed that significant sectors and ecosystems in the Kingdom of Bahrain islands have been identified as being vulnerable to the effects of SLR. Moreover, vulnerability may increase in the long run due to the massive reclamation activities associated with development projects that have been going on in the country for years. Reclamation is reducing the stock of coastal wetlands (i.e., saltmarshes, mangroves, and intertidal areas) by about 1.5 km^2 per year. These reclaimed sea lands have been added annually to the total area of the country since 1970. Furthermore, the added area is likely to be doubled to meet further development needs, which in turn may drive additional challenges. Based on vulnerability assessment, four issues are of great concern to the authorities and decision makers: Coastal land loss, Ecosystem disturbance, Erosion and degradation of shorelines, and Deterioration of ground water resources.

Impact Assessment

Inundated Coastal Areas

Results indicated that coastal areas of all the islands are vulnerable under different SLR Scenarios, Table 5. More than 17% of the country total area may be inundated under 1.5 m SLR in 2100. The total area that might be lost under different sea level scenarios will vary from more than 77 km^2 if the SLR to 0.5 m, clumped to reach approximately 100 km^2 under 1 m, and exaggerated to more than 124 km^2 under 1.5 m. The estimated inundated areas in all the islands by different SLR Scenarios,

Table 5 Inundated areas (%) under different SLR scenarios

SLR Scenarios	Hawar	Bahrain	Muharraq	Sitra	Nsaleh	Umm Nassan	Jeddah	Total	Total (%)
0–0.5	7.29	52.69	10.09	3.83	0.19	3.39	0.16	77.64	10.87
0–1	9.43	65.49	13.57	4.60	0.32	6.01	0.21	99.63	13.95
0–1.5	12.43	79.31	17.46	5.64	0.42	8.59	0.26	124.12	17.37

indicate that the main biggest island Bahrain will lose nearly 53 km^2 under 0.5 ASLR, reach to more than 79 km^2 under 1.5 ASLR. Muharraq island will be the second in loosing its coastal area, where under 0.5 m it may be lose more than 10 km^2, and it will reach to more than 17 km^2.

The Hawar islands chain are even lower lying than the main islands. Where sea levels rise by 0.5 m, 14% (>7 km^2) of the combined land area of these islands would be inundated, and if the sea rises by 1 m, the inundated area will be more than 9 km^2 (18%). The main threats of SLR will probably come from loosing the island habitats' ecological functions as being home for a number of resident sea birds and nesting sites for other migratory species. A 1.5 m sea-level rise could inundate almost 24% (>12 km^2) of the total area of Hawar islands.

Inundation will unequally affect Bahrain's vulnerable infrastructure. For the main islands of Bahrain, Muharraq, Sitrah, Jiddah, and Um Na'assan, where the majority of socioeconomic activities are concentrated, inundation would adversely affect cities, roads, agricultural areas, as well as beaches and salt marshes, Table 6. Most of this loss would be in sabkha and salinized areas (42 km^2), followed by Bare soil1 (>23 km^2), Built up areas in both classes (17 km^2), agricultural lands (>13 km^2), and Bare soil2 (12 km^2). Although their percentage is relatively low, roads and urban areas (Built up area) would bear the heaviest economic monetary losses. This in turn will affect coastal development, wetland (sabkhas), agricultural areas, resources, and recreation along the coasts of the country. The most serious impact of SLR would be the inundation of low-lying lands, affecting mangroves, coastal salt marshes, inland sabkhas, groundwater aquifers, coral reefs, fish stocks, and biodiversity. Furthermore, increased coastal erosion was expected.

The extent of inundation on the Hawar Islands, given their status as wetlands of international importance, is particularly noteworthy. The islands in this chain are even lower lying than the main islands. Where sea levels to rise by 0.5 m, 14% (>7 km^2) of the combined land area of these islands would be inundated, and if the sea rise by 1 m, the inundated area will be more than 9 km^2 (18%). The main threats of SLR probably will comes from loosing the island habitats' ecological functions as being home for a number of resident sea birds and nesting sites for other migratory species. A 1.5 m sea-level rise could inundate almost 24% (>12 km^2) of total area of Hawar islands, Table 7.

More recently, some studies have begun to express future SLR in probabilistic terms, enabling rising levels to be evaluated in terms of the risk of exceeding a critical threshold of impact. (IPCC, TSIAV 2001) [189]. Two different SLR scenarios are adopted to evaluate potential impact. Table 8 displays these two risk scenarios,

Table 6 The estimated inundated areas (km^2) by class on the main group islands

Landcover/landuse	SLR scenarios		
	0–0.5	0–1	0–1.5
Agriculture	7.03	9.76	13.16
BuiltUp area	8.63	12.74	16.95
Bsoil1	15.29	19.23	23.74
Bsoil2	7.26	9.35	11.97
Bsoil3	2.39	3.33	4.16
Sabkha	29.09	35.58	41.88
Total	69.69	89.99	111.76
% Total Area	11.75	15.18	18.85

Table 7 Inundated areas (km^2) in all the islands by different SLR scenarios

SLR scenarios (m)	Area Inundated under different SLR in km^2 in all the islands							
	Hawar	Bahrain	Muharraq	Sitra	Nsaleh	Umm Nassan	Jeddah	Total
0–0.5	7.29	52.69	10.09	3.83	0.19	3.39	0.16	77.64
0–1	9.43	65.49	13.57	4.60	0.32	6.01	0.21	99.63
0–1.5	12.43	79.31	17.46	5.64	0.42	8.59	0.26	124.12

Table 8 Probabilistic SLR scenarios as risk assessment for each island

SLR Risk Scenarios	The main group islands								
	Hawar	Bahrain	Muharraq	Sitra	N. Saleh	Umm Nassan	Jeddah	Total	% Total
0–2	15.54	93.41	22.07	6.92	0.49	10.58	0.31	**149**	20.9
2–5	52.21	212.87	31.46	15.20	0.94	20.10	0.434	**333.21**	46.64

at 2 and 5 m SLR over the MSL of the study area until 2100. The potentially inundated area of each island and the total area that may be lost under both scenarios are presented.

The total inundated areas due to risk scenarios will reach 133 km^2, if the SLR rises to 2 m, and it is estimated to be more than (22%) of the main island total area. Under the second Scenario when the SLR to 5 m, the main islands will lose approximately half of its area (47%) which is equal to 280 km^2. Hawar islands group will lose about (30%) of its total area under 2 m SLR, which is about 15.5 km^2, Table 8, while Table (9) displayed the loss of each class under SLR risk scenarios.

Adaptation action plan

Agriculture and cultivated lands

The agriculture sector relies on heavy irrigation and currently provides job opportunities to more than 3,400 people and contributes to national food security goals (CSO/SA 1970–2001). The loss of agricultural land due to 1.50 m SLR will amount to 13 km^2 which represents 16% of these lands in the country. Similarly, a 1 m SLR

Table 9 Probabilistic SLR scenarios as risk assessment for each land use class

SLR Risk	0–2	0–5
Agriculture	16.10	49.00
BuiltUp 1	13.75	42.76
BuiltUp 2	8.21	13.07
Bsoil 1	28.41	50.55
Bsoil 2	15.17	35.44
Bsoil 3	5.14	11.36
Sabkha	46.94	78.74
Total	133	280.92
Total area (%)	22.6	47.37

will inundate 10 km^2 or 12%. A 50-cm SLR will lead to a loss of 7 km^2 (9%). Other impacts from the inundation of agricultural lands include damage to drainage systems, an increase in water logging problems, and higher groundwater tables. The increase of temperatures at an effective doubling of the CO_2 concentration will lead to the increase of the water consumption of this sector, and the poor irrigation practices will exacerbate soil salinity and evaporation rates, putting even greater pressure on the water resources. These impacts are likely to contribute to adverse impacts on crop production levels, mainly palm trees which are highly susceptible to groundwater salinity levels.

Coastal zones and marine ecosystems

Corals and fish stock: Coral reefs are already stressed by changes in the Arabian/ Persian Gulf temperatures, and siltation from coastal erosion and dredging and reclamation activity. Coral reefs have proven to be key indicators of CC. Global warming would cause additional stress to these sensitive ecosystems. Coral bleaching events as severe as that occurred in 1996 and 1998 may become common under CC/ SLR in the coming years. The effect of higher CO_2 levels on the Arabian/Persian Gulf chemistry may lead to reduced coral calcification growth rates and could reduce the density of coral carbonate skeletons and lead to accelerated coastal erosion. Natural adaptation will probably be too slow to avert a decline in the quality of the coral reefs. Deterioration of corals habitats would negatively affect associated fauna, thus affecting fish stocks, and eventually threaten the livelihoods of 6,000 fishermen and the national economy of (30,000–42,000) (CSO/SA 1970–2001). *Mangrove:* Mangrove areas are already under high stress due to land reclamation activities, and its area reduced from 24 km^2 in 1956 to less than 10 km^2 in 2000 (Abido and Saeed 2002; Khalaf and Madani 1999; Zaiani 1999; EA(?) 1995). In the event of SLR, major portions of mangrove ecosystems would be inundated and, lead to a gradual retreat of plantations to areas inland. However, in view of land reclamation and associated commercial land development pressures, it is unlikely that there will be suitable areas to accommodate the gradual retreat of mangrove plantations. The total area of mangrove plantations affected, though not directly quantified in the SLR vulnerability assessment, is expected to be quite high. *Salt marshes:* Coastal salt marshes on the main islands will be among the hardest hit areas due to rising sea levels in terms of the extent of impact. The total area that would be affected by a 1 m rise in sea level is about 35.6 km^2. This represents about 39.5% of all the submersed areas.

Coastal erosion

The coasts of all the islands are sandy and easily erode-able (Doornkamp et al. 1980). It is expected that low-lying areas of the beach may likely be exposed to some forms of coastal erosion. Most of Bahrain's coastal plains have heights less than 5 m above sea level. The wave-induced movement of sand along the western and eastern beaches is primarily southward and consequently heavy transport of sediments occurs toward the southernmost parts of islands, and especially along the Ras Al Barr sandbar at the lower end of Bahrain Island. This process is likely to be exacerbated under conditions of SLR, with increases in effective wave heights and intensification of littoral transport along the western and eastern coasts. Furthermore, higher sea levels coupled with erosion may lead to sea penetration inland in particularly low lying areas less than 5 m above sea level.

Water resources

Even without CC, the Kingdom of Bahrain faces increasingly serious problems with water. Rapid population growth and expanding economic activity are already putting enormous pressure on groundwater resources.

The Kingdom of Bahrain's water supply and hydrology systems are likely to become increasingly vulnerable to CC. About 75% of freshwater demand is met by groundwater withdrawals, resulting in a severe decline of the groundwater table through saltwater intrusion (Al-Zubari 2003). At present, over half the volume of the original groundwater reservoir has been lost to salinization, sharply reducing its availability for municipal and agricultural purposes. Salinity is a major environmental problem in the country, and although climate is a key factor in determining the rate of salinization and the complexity of the impacts.

Water supplies on main islands will be increasingly vulnerable to salt-water intrusion into ground water from SLR. One possible impact of would be a regression in the position of the freshwater/saline waterfront leading to further saltwater intrusion and deterioration of the aquifer. Moreover, SLR would lead to a new line of contact further inland between salt marsh areas and groundwater which would likely lead to more seepage of salt water into the main groundwater reservoir.

There are also indirect impacts from CC in general as higher temperatures might lead to higher levels of water consumption in agricultural activities and households, further depleting scarce freshwater supplies.

Adaptation recommended

Adaptation measures are an important strategy in reducing the adverse impacts of CC on the Kingdom of Bahrain's natural and human systems. The development and implementation of adaptation strategies will require the active involvement of all parties in the country, government sectors, private sector and the community. Significant challenges exist in developing these adaptation strategies due to uncertainties in CC science and in projections of possible future CC at a regional or national level.

There are no current thoughts on the technical and institutional aspects of adaptation to SLR in the Kingdom of Bahrain. At present no policy perspectives to include long-term evolution and associated SLR influence. A hard and long-term commitment has to be made in order to encourage coastal managers and general public to impacts of SLR and associated direct and indirect social and economical impacts, as changes related with SLR are slow and almost unnoticeable. Coastal managers should realize the need to begin advance planning for SLR.

The vulnerability of coastal areas to SLR can be reduced by initiating effective policies that aim at minimizing risks of exposure, reinforcing adaptive capacity of the society as well as ecosystems, and adopting mitigation measures at national levels (Klein and Tol 1997).

There are several types and forms of adaptation (e.g., El Raey et al. 1999). This study focuses on a matrix of strategies and measures that are tailored to fit the study area local conditions, and take into account existing constraints and opportunities. Two broad elements of an adaptation strategy are essential for The Kingdom of Bahrain to adapt to future SLR, Basic Policy Initiatives (BPIs), and Ecosystem Protection Initiatives (EPIs).

Basic Policy Initiatives (BPIs)

Basic policy initiatives are needed to protect investments in vulnerable areas, minimize coastland loss of vulnerable low-lying areas, conserve natural ecosystems, control coastal erosion, and protect groundwater resources. The basic policy initiatives should recognize the ever-continued pressures on coastal areas and the need of the society for developing these sites including the vulnerable ones. These needs and major impacts of SLR are to be addressed in a plan composed of actions and processes. Specific arrangement should emphasize on:

(1) *Integrate SLR considerations into national development plans and policies*: Aiming at introducing shift in the consideration of formulating policies and national development plans. Since SLR is a gradual process, it is still possible to consider adaptation measures now that can render future infrastructure investments less vulnerable to SLR. Priority action needed are:
    (a) Accommodating SLR in the design of new policies regarding building codes and coastal structures.
    (b) Formulating sector specific development guidelines (tourism, industry, etc...) to highlight the potential problems arising from SLR to investors.
    (c) Formulating a policy framework for integrated coastal and marine resources management.
    (d) Formulating guidelines and legislation for the implementation of integrated coastal zone management.
(2) *Spot main coastal protection area*: Vulnerable coastal areas contain industrial compounds, recreational facilities and human settlements. These areas are of high priority and public investment. Priority action needed are:
    (a) Identification and delineation of critically vulnerable areas.
    (b) Creation a GIS based coastal database management system for facilitating decision-making process regarding coastal areas, marine environment and its resources.
    (c) Investigating the feasibility of hard structure (dikes, levees, etc..) and soft measure (periodic beach nourishment) options to protect priority vulnerable areas (populated and developed areas).
    (d) Establishing and maintaining an effective agricultural drainage system.
    (e) Rehabilitation of endangered ecosystems and revitalization of its components with special emphasis on coral reef areas, mangrove, and other important bird areas in main Bahrain and Hawar islands.
    (f) Raising public awareness on the potential effect of CC in general and SLR in particular.
    (g) Enforcement of legislations regarding coastal areas and marine resources.
    (h) Formulation integrated water resource management plans to rationalize water use and protect aquifers from being excessively salinized.

(i) Accommodate SLR in building codes and coastal structures in on going projects.
(j) Review and update legislations related to water usage.

(3) *Public awareness and Stakeholder capacity*: The Bahraini society is not aware of the consequences of the global CC. Better environmental public awareness is needed. This process needs to be facilitated by individual public debates, increase media interest in the problem and intensify activities by non-governmental organisations in this area. Public interest and support are crucial for the application of the long-term governmental strategy and CC policy. Few of the NGOs in the country are interested in the CC and its dissemination. There is a need for capacity building to enable the environmental authority, to play a major role in planning, coordinating and implementing adaptation programs of action. Their capacity needs to be strengthened in terms of human, financial, technical and technological resources. Priority action needed are:

(a) Strengthening the national capacity (marine authorities) for monitoring SLR dynamics and trends through upgrading and networking existing monitoring stations.
(b) Developing legal, institutional and human resources capacity for EA and national research institutions.
(c) Conducting training programs in CC/SLR information management, vulnerability, risks assessments and planning for adaptations.
(d) Development capacity of farmers to adapt to new techniques in farming and management of salt affected soils.
(e) Strengthening regional cooperation and networking among ROPME sea area countries to facilitate exchange of data and information on CC/ SLR issues.

Ecosystem protection initiatives (EPIs)

Many of the sensitive wetlands in Bahrain are currently subject to pollution, over-exploitation, and adverse effects of coastal envelopment projects that require extensive dredging and land reclamation. Further disturbance as a consequence of SLR will slowly degrade major functions of these systems, thus adversely affecting biodiversity. The major adaptation action needed to limit ecosystem deterioration must directed toward Mangrove and other wetland (Sabkhas) areas, coral reefs and other marine resources, and groundwater resources

(1) *Mangrove and other wetland (Sabkhas) areas*: Mangrove plantations are experiencing formidable threats reclamation and infilling activities that threaten their existence. Mangrove stands are also vulnerable to SLR having no capacity for inland retreat. Priority action needed are:

(a) Establishment of a protective zone that encircles the Mangrove site with a buffer zone.
(b) Reforestation of mudflats and other appropriate locations along the beach.

(c) Reviving traditional agricultural system around mangrove using tertiary treated sewage effluent.
(d) Launching a national campaign to raise public awareness among various sectors of the society.

(2) *Coral reefs and other marine resources*: Coral reefs have already experienced bleaching events. Other types of damage due to mismanagement are evident such as pollution from point sources and from tanker traffic. Priority action needed are:

(a) Rehabilitation of corals in proper sites
(b) Enforcement of legislations regarding marine resources
(c) Establishment of coral reef monitoring protocols locally
(d) Creation of a network for regional collaboration

(3) *Groundwater Resources*: The importance of groundwater resources in Bahrain cannot be overemphasized. Groundwater resources are experiencing severe pressures from over-extraction practices. SLR will likely intensify seawater intrusion into the aquifer leading to a continuous salinization and rapid deterioration of its quality. Priority action needed are:
(a) Formulation an integrated water resource management plans to rationalize water use and protect aquifers from being excessively salinized.
(b) Legalize and institutionalize reuse of sewage treated water.

Conclusion

The vulnerability and adaptation of kingdom of Bahrain to potential impacts of SLR has been worked out using RS and GIS techniques. Numerical estimates of the magnitude of losses have been estimated based on plausible scenarios. It was found that the Kingdom is highly vulnerable to SLR. Recommendations for adaptation policy and priorities are presented and discussed

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