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Potential Impacts of Accelerated Sea-Level Rise on Alexandria Governorate, Egypt

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ABSTRACT

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Alexandria Governorate, containing Egypt's second city, is physically and socio-economically vulnerable to accelerated sea-level rise. Much of the area is low-lying; 35% of the land in the Governorate is already below mean sea level (excluding Lake Mariut). Erosion of pocket beaches along the Mediterranean coast is also a problem, and at least three such beaches have disappeared this century.

Using a GIS-based inundation analysis and an erosion modeling approach on the Mediterranean coast, the physical and socioeconomic vulnerability of Alexandria Governorate to accelerated sea-level rise is investigated. A one-meter rise in sea level could inundate 1,248 km^2, or 68% of the Governorate. This area contains 95% of existing agriculture, 70% of existing industry, 50% of existing residential areas, and has a present population of about 2 million. Sea-level rise would also adversely affect the tourist industry. A rise of only 0.5 meters could remove nearly all existing beaches. Given these severe impacts, protection appears essential.

Beach nourishment appears feasible to maintain the tourist-based beaches and minimize flooding from the Mediterranean. Protection of low-lying areas from inundation will involve actions outside the Governorate, particularly to the east in the Nile delta. Problems of salinization, waterlogging, and flooding also need to be addressed. From a national perspective, these results suggest that a one-meter rise in sea level could displace six million people in Egypt, assuming the existing population and a no protection response.

ADDITIONAL INDEX WORDS: *Delta, subsidence, inundation, erosion, beach nourishment, salinization, waterlogging, drainage.*

INTRODUCTION

Sea-level rise due to climatic changes is expected to have a pronounced impact on low-lying deltas all over the world. In particular, the Nile delta coast in Egypt is expected to be severely affected by sea-level rise. Inundation and erosion, saltwater intrusion, increased soil salinity, changes of coastal ecosystems, and loss of productivity are among important physical impacts which will necessarily induce socioeconomic changes over the whole Egyptian coastal zone.

There are a number of studies on various aspects of the impacts and possible responses to sea-level rise on the Egyptian coast (BROADUS *et al.*, 1986; SESTINI, 1989; MILLIMAN *et al.*, 1989; EL-RAEY, 1990; ANTE, 1990; EL-SAYED, 1991a; 1991b; STANLEY and WARNE, 1993). Their results indicate that a sizeable portion of the northern part of the Nile delta will be lost due to a combination of inundation and erosion, with consequent loss of agricultural land and urban areas, and further agricultural losses will occur due to soil salinization. Fishery resources will also be affected due to declining and ultimate disappearance of coastal ecosystems.

To better assess these physical and socioeconomic impacts, quantitative local surveys on the impact of sea-level rise are required for each part of the coastal system, particularly in and around the Nile delta. This paper presents a detailed quantitative survey of the impact of sea-level rise on the Governorate of Alexandria, which contains one of the oldest cities on the Mediterranean coast and has a large and expanding urban population. The possible impacts and responses to eustatic sea-level rise scenarios of 0.5 m, 1.0 m, and 2.0 m by the year 2100 are considered. It should be noted that a 2.0 meter rise in sea level by the year 2100 is no longer consid-

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ered plausible (WARRICK and OERLEMANS, 1990). Therefore, the results for this scenario should only be considered as a sensitivity analysis. Two main economic areas appear most vulnerable: (i) the Alexandria lowlands – the extensive lowlands south of the Pleistocene beach ridges; and (ii) the Alexandria beaches. Detailed analysis of the impact of sea-level rise on these two areas is presented.

ALEXANDRIA GOVERNORATE

Alexandria Governorate is located on the western edge of the Nile delta between latitudes of 31° 08′N and 31° 26′N and longitudes 29° 27′E and 30° 04′E (Figure 1). Since its construction by Alexander the Great in 332 BC, Alexandria has been an important coastal city. It was the center of the world's first and largest library and has been the home of many world famous scientists, architects, and philosophers. The large number of historic sites are evidence for the flourishing history of the city since Ptolemaic and Roman times. Presently, the city is the second largest economic center in Egypt after Cairo. The Governorate has a total area of about 2,000 km^2 and is divided into six districts: Ameria; West; Center; East; El-Gomrouk; and El-Montaza (Figure 2) with a total area of about 2,000 km^2.

From a physical perspective, Alexandria is less vulnerable to sea-level rise than the Nile delta proper. However, its high population, variable topography, and vital socioeconomic activities make the potential socioeconomic impacts of accelerated sea-level rise of particular concern. In addition, it is Egypt's main summer tourist resort. The 42 km waterfront of Alexandria extends from Abu Quir Bay in the east to Agami in the west. The city is the most important import/export link between Egypt and Europe. The following summary on Alexandria is based on EL WAKEEL *et al.* (1980); ALEXANDRIA COMPREHENSIVE PLAN (ACP) (1984); DOWIDAR (1988); and EL-SAYED (1991a; 1991b).

Geomorphology, Storms, and Tides

In contrast to the low-lying coast of the Nile delta, the shoreline of Alexandria is generally undulating and interrupted by rocky headlands producing small embayments and pocket beaches. The city originally developed on the remnants of three parallel and intermittent calcareous sandstone and limestone ridges or hills, with elevations that vary between 5 and 30 meters above mean sea level (ASL) (Figure 1).

South of the limestone ridges is an extensive lowland, with a width of more than 20 km and Lake Mariut. Most of this lowland lies outside the Governorate (Figure 2). This whole area is vulnerable to inundation, waterlogging, increased flooding, and salinization given acceler-

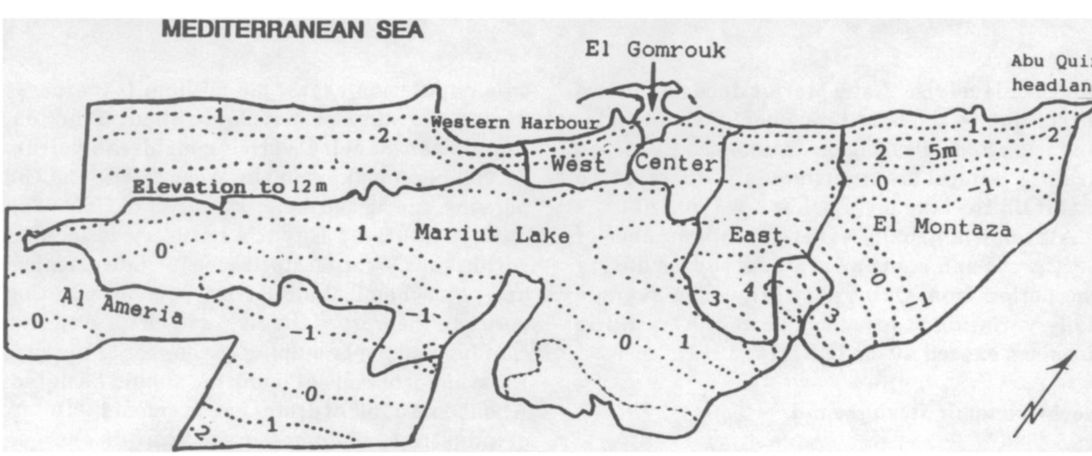

Figure 1. Alexandria Governorate, showing the local six districts and contour elevations (1986 data).

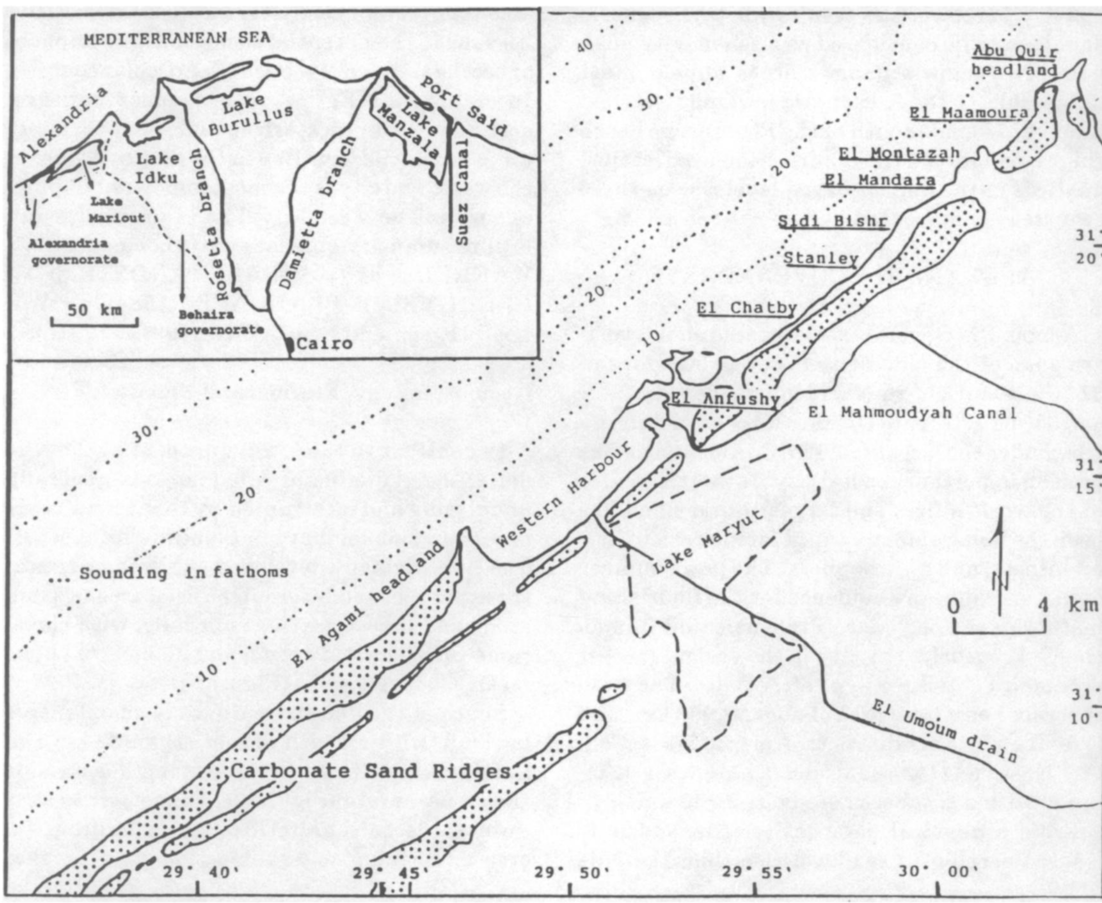

Figure 2. Alexandria waterfront based on Abdel-Hakim, 1957. Beaches are underlined. Calcareous sandstone and limestone ridges are stippled.

ated sea-level rise. Lake Mariut does not have a direct link to the Mediterranean. To control inundation and salinization around the Lake, hydraulic pumps are continuously operated to maintain the lake level below −2.8 m ASL.

Alexandria usually experiences a number of northwest and southwest storm surges during the period from October to May. The average daily variation of mean sea level in Alexandria does not exceed 40 cm (FRIHY, 1991).

Socioeconomic Background

The city population is about 3.1 million (1990 data), although unofficial estimates place the true population nearer 3.5 million. It increases during the summer months to about 5 million. Population density varies considerably from 60,000 persons/km^2 in the West district to 133 persons/km^2 in the Ameria district (ACP, 1984).

About 40% of Egypt's industry is located within the Governorate. These include chemical and petrochemical industries, cement, and tanneries to the west of the city, and fertilizers, food canning and paper pulping to the east of the city. Existing problems of pollution should be noted. About 6×10^6 m^3 of drainage water and 1×10^6 m^3 of industrial and domestic waste are discharged daily into coastal waters (EL-SHARKAWY, 1991), including Mex Bay to the west, Abu Quir Bay to the east, and Lake Mariut to the south. The western harbor of Alexandria handles about 80% of Egypt's trade. An international airport is located south of the city, and there is a dense surface network of transportation and communication systems. Agriculture is also important in the Governorate. At present more than 42,000 ha are cultivated in the southern sector of Alexandria. There are proposals to expand agriculture to the west and southwest of Alexandria.

Groundwater Resources and Waterlogging Problems

Groundwater in the region occurs under both artesian and non-artesian conditions. All the groundwater that is used for agricultural and domestic purposes comes from considerable depths. West of Alexandria, groundwater is the most important source of water for agricultural uses.

The water table lies at or near sea level around Alexandria. The depth of the water table varies from less than a meter to 50 meters depending on the locality, topography and season. The highest water level occurs in February to April depending on the rainy season (AYYAD and Le FLOC'H, 1983). Under these conditions, waterlogging is already observed to be a problem in several areas west and south of Alexandria. It has been associated with excessive urbanization of the surrounding areas such as the Agami area (Ameria district). Preliminary estimates suggest that the area in the Governorate experiencing waterlogging is increasing with time.

RELATIVE SEA-LEVEL RISE SCENARIOS

A general trend of relative sea-level rise along the northern Egyptian coast can be established from archeological evidence (EL-SAYED, 1988), from dated core sections (STANLEY, 1990; CHEN *et al.*, 1992; STANLEY and WARNE, 1993; WARNE and STANLEY, 1993) and from tide gauge analysis (FANOS, 1990; FRIHY, 1991). A relative sea- level rise of between 0.4 mm/yr and 2.0 mm/yr was estimated at Alexandria based on these studies.

Analysis of monthly records of mean sea level at Alexandria from January 1944 to December 1989 indicates a relative sea-level rise of about 2.0 mm/yr. This is in direct agreement with the earlier results of FRIHY (1991). Assuming a mean eustatic sea-level rise of 1.8 mm/yr during the last one hundred years (DOUGLAS, 1991), this indicates a very low subsidence rate of only about 0.2 mm/yr. This conclusion is supported by the geological analysis of STANLEY and WARNE (1993). Therefore, in this study we ignore subsidence for all practical purposes and apply the eustatic scenarios of 0.5, 1.0, and 2.0 meters directly as relative sea-level rise scenarios.

ALEXANDRIA LOWLANDS

A 1957 map of Alexandria shows that the city was built on three parallel ridges with intervening troughs of low elevation connecting the mainland to the sea (Figure 1). Urban development has resulted in partial levelling of these ridges. A large scale map of the elevation of the Governorate in 1986 is shown in Figure 2. The population distribution and industrial and agricultural land use has changed rapidly over the last few years: a process which is expected to continue. Some suitable data is available to carry out preliminary impact estimates (ACP, 1984; CENSUS, 1986). In addition, we have updated our data with unpublished sources as much as possible.

In order to accurately estimate the impact on the lowlands, Geographic Information System (GIS) analysis has been used.

Methodology

Geographic data for the Governorate of Alexandria were digitized manually for each district and fed to a microcomputer (IDRICI version 3.2 software). These data include the following layers:

(1) Population Distribution (CENSUS, 1986) (see Tables 1 and 2).
(2) Topography. Contour interval of one meter and a scale of 1:100,000.
(3) Land Use Maps (ACP, 1984). Scale: 1:100,000.
  (a) Industrial Areas.
  (b) Residential Areas.
  (c) Agricultural Maps.
(4) Socioeconomic Distribution Maps (ACP, 1984). Scale: 1:100,000.
  (a) Commercial and Business.
  (b) Municipal Services.
  (c) Communal Facilities.

Table 1. *Distribution of working population by economic activities in the six Alexandria districts (census, 1986). Children, elderly people, non-working women, and unemployed are not counted.*

Economic Activity	El-Montaza	East	Center	West	El-Gomrouk	Al-Ameria	Total
Agriculture & hunting	18,017	14,017	16,983	12,599	3,245	16,765	81,626
Exploitation of mining & quarries	1,072	1,577	874	748	128	851	5,250
Conversion industries	39,554	54,873	44,398	45,223	8,877	7,271	200,196
Electric, gas, & water	1,981	2,383	2,551	1,868	256	515	9,554
Building worker	18,978	23,887	1,957	12,521	1,982	5,693	65,018
Commerce, restaurant, & hotel	14,796	21,678	26,177	21,425	5,695	4,267	94,038
Conveying, transport, & storage	14,253	1,675	16,213	21,485	5,043	4,858	63,527
General services	4,585	7,276	7,372	2,197	1,027	380	22,837
Total working population	113,228	127,366	116,525	118,066	26,253	40,600	542,046

An MSS satellite image was classified into land use classes and used as a check against the most recent land use information. It showed general agreement. The possibility of future updates of the GIS using satellite images should be noted.

The digitized data were transferred from vector to raster files with a resolution of 80 meters. Images were then scaled, registered and checked against ground truth observations. A number of control points were used for careful verification. Precise estimates of the possible physical and socioeconomic impacts of the different sea-level rise scenarios were developed by overlaying different layers within the GIS.

In addition, a questionnaire was administered to the inhabitants of the lowland areas vulnerable to sea-level rise. It was designed to assess their awareness and feelings on responses concerning the problem of sea-level rise. The questionnaire was applied using person-to-person interviews with a random sample of 200 people from three districts. The sample size is too small to be considered statistically valid, but interesting perspectives of people's perception of sea-level rise were made.

Physical Impacts

A significant area of the Governorate lies below mean sea level, 700 km^2 or about 35% of the existing land (Figure 3). This includes land in three districts: Ameria, Montaza, and Center. This area is presently home to over 1.1 million people (Table 3). An area of 1,248 km^2 (over 61% of the existing land) is situated below the one-meter contour (Figure 4) and is presently home to over 2 million people (Table 3). Only a relatively narrow strip of the city, parallel with the coast and less than 1 km in width, is above 2 meters.

Socioeconomic Impacts

By area, the agricultural, industrial, and residential sectors are decreasingly vulnerable to sea-level rise, respectively, as agriculture occupies the lowest areas (Table 3). For instance, below the one-meter contour there is 95% of the total agricultural area, 70% of the industrial areas and 50% of the residential area. However, the economic consequences of such losses has not been evaluated and the potential industrial and

Table 2. *Population and population density in Alexandria districts (census, 1986).*

Parameters	El-Montaza	East	Center	West	El-Gomrouk	Al-Ameria	Total
Population	606,990	771,190	649,399	559,040	122,342	167,337	2,876,298
Number of building units	58,916	50,639	195,175	321,965	6,201	50,437	683,333
Average person/building	10	15	3	2	19	3	Average 8–9
Area (km^2)	108.6	131.570	19.2	20.7	4.5	2,394	2,678.57
Population density (/km^2)	5,589	5,855	47,057	34,178	27,187	69	119,935

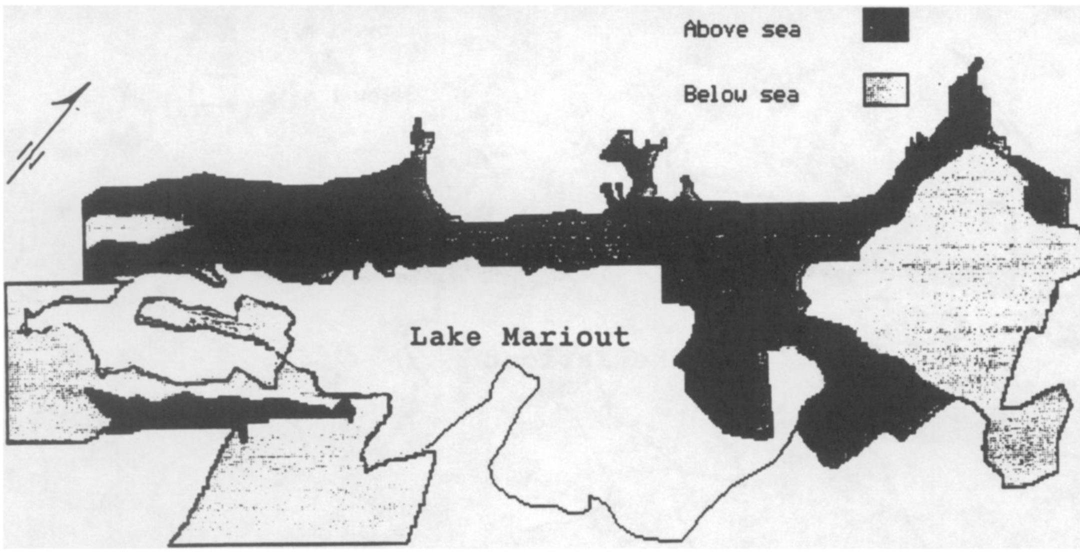

Figure 3. Area above and below sea level in the Alexandria Governorate as displayed by the GIS.

residential sector losses may exceed those of the agricultural sector.

Overlaying district boundaries and topographic maps indicates that the most vulnerable areas are located within the Ameria, Center, and Montaza districts. In general, Ameria district is an industrial area, Center district is a high class residential area and Montaza district is a middle class residential area.

The area which could be inundated by a one-

Table 3. *Total area (in km²), population, and land use estimates versus elevation for the Alexandria Governorate. The area of Lake Mariut (69.8 km²) is not included.*

Elevation	Above −3 m	Above −2 m	Above −1 m	Above Sea Level	Above 0.5 m	Above 1.0 m	Above 1.5 m	Above 2.0 m
Total area	2,009.59	1,982.93	1,618.09	1,309.16	992.33	771.84	632.6	490.9
	100%	98%	81%	65%	49%	38%	31%	24%
Population	3,176,299	3,155,007	2,483,865	1,994,715	1,574,589	1,143,567	921,125	689,785
	100%	99%	78%	63%	50%	36%	28%	21%
Agricultural area	1,031.7	825.36	154.8	103.2	72.2	51.6	–	–
	100%	80%	15%	10%	7%	5%		
Industrial area	29	28.7	20.3	14.5	10.1	8.7	5.8	2.9
	100%	99%	70%	50%	35%	30%	20%	10%
Residential area	51	45.9	40.8	35.7	28.2	25.5	20.4	12.8
	100%	90%	80%	70%	55%	50%	40%	25%
Municipal services (area)	10	9	8	6.5	6	5	4	3
	100%	90%	80%	65%	60%	50%	40%	30%
Commercial area	6	5.88	5.7	5.1	4.8	4.5	4.2	3.9
	100%	98%	95%	85%	80%	75%	70%	65%
Communal facilities (area)	4	3.96	3.92	3.6	3.4	3.2	3.12	2.8
	100%	99%	98%	90%	85%	80%	78%	70%

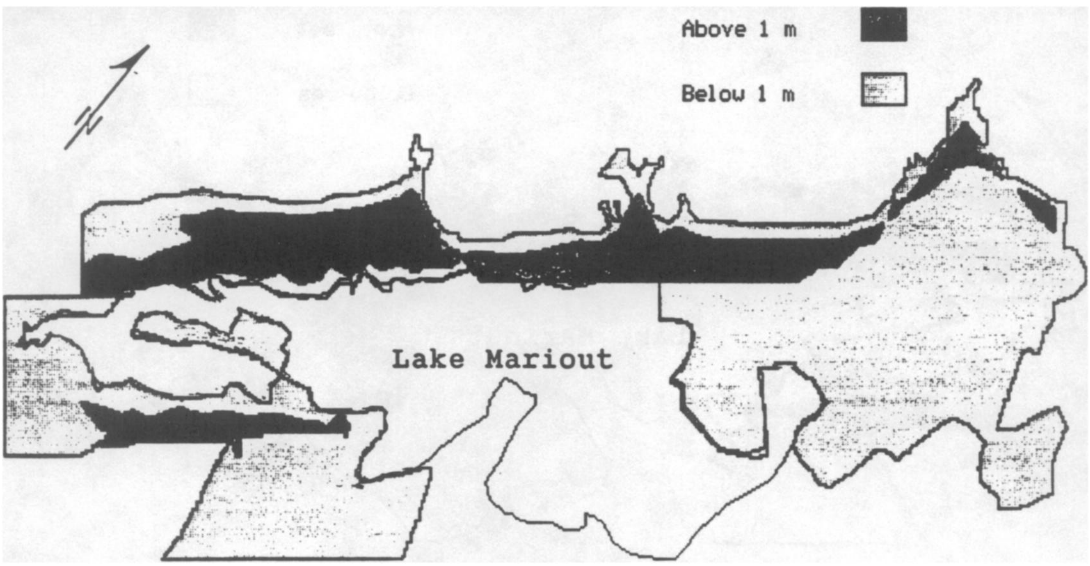

Figure 4. Area above and below 1.0 m above sea level in Alexandria Governorate as displayed by the GIS.

meter rise in sea level is presently inhabited by about 2 million people (Figure 5). Assuming a population increase of the form:

$$P = P_o e^{mt} \quad (1)$$

where $m = 0.02$/yr (obtained from fitting to existing data from ACP (1984)), a population exceeding 8 million people is predicted for Alexandria by the year 2030. This suggests that a population of over 4 million people could be living in the area vulnerable to a one-meter rise in sea level by that time.

Table 4 presents the best estimates of the present economic values of vulnerable areas for each scenario assuming no protection. These are based on estimates of land value plus residential installations only (1990 values). It is seen that the losses exceed U.S. $33 billion for all scenarios. In all cases, no revenues were assumed.

Public Perception and Awareness

The level of awareness concerning sea-level rise is low even in high class residential areas (Table 5). In addition, it is found that a high percentage of interviewed people do not care very much about this future problem, even after discussion and favor a 'do nothing' response. Less than 20% of the inhabitants said they would be willing to move away from the area if sea level rose, suggesting that ultimately there will be strong political pressure for protection.

ALEXANDRIA BEACHES

More than 2.5 million local visitors enjoy the summer season at Alexandria every year. Compared to the neighboring delta coast, the estimated average erosion rate at Alexandria is low, being about 0.2 m/yr (FRIHY *et al.*, 1992). However, the long-term consequences of such recession on the tourist beaches in Alexandria should not be underestimated. At least three pocket beaches have disappeared in the last decade due to erosion: Silsilla, San Stefano, and Saba Bacha. Eight, of the twelve existing beaches, are presently eroding (Figures 1 and 6; Table 6). On some beaches, freshwater showers built on the shore 20 years ago are now 5 to 10 meters out in the sea, suggesting recession rates of 0.25 to 0.5 m/yr.

The coastal road in Alexandria (Corniche) is protected from the sea by a concrete bulkhead.

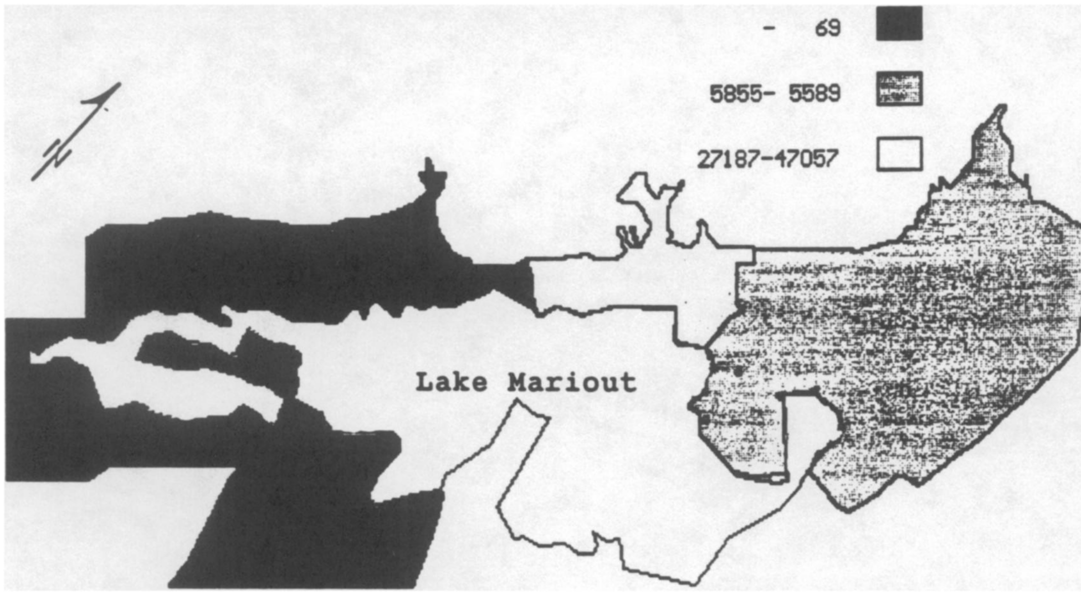

Figure 5. Population density by Alexandria Governorate by district (Census, 1986) as displayed by GIS.

Table 4. *Estimates of economic loss (land and installations) in vulnerable areas, assuming no protection. Agricultural revenues not included.*

District	Sea-Level Rise Scenario (m)	Area (km^2)	Price of Land (U.S. $\$/m^2$)	Occupation of Installations (%)	Value of Installation (U.S. $\$/m^2$)	Total Loss ($\times 10^9$ U.S. dollars)
Center	0.5	1.8	200-300	50	500	0.93
	1.0	2.93	200-300	50	500	1.53
	2.0	3.339	200-300	50	500	1.78
El-Montza	0.5	99.6	100-120	20	300	16.9
	1.0	102.3	100-120	20	300	17.4
	2.0	106.14	100-120	20	300	18.01
Al-Ameria	0.5	1,040.0	5-10	5	100	15.49
	1.0	1,108.1	5-10	5	100	16.35
	2.0	1,410.7	5-10	5	100	17.6
TOTAL	0.5	1,141.4				33.32
	1.0	1,213.33				35.28
	2.0	1,520.179				37.39

Table 5. *Public perception and questionnaire results.*

District	Awareness Before Questionnaire (%)	Do Not Care (%)	Retreat	Accommodate Later (%)	Protect Later (%)
Center	5	95	Not possible	35	65
El-Montaza	15	85	Not possible	20	80
Al-Ameria	25	75	Not possible	10	90

Figure 6. Examples of Alexandria beaches showing (A) beach berm of Maamoura during spring; (B) and (C) beach erosion along the eastern end of El-Asafra and El-Mandara beaches; (D) Miami beach; (E) Stanley beach; (F) El-Chatby beach, (G) artificial beach nourishment at El-Asafra beach, and (H) Sidi Bishr beach.

Table 6. *Physical data on Alexandria Beaches. Nourishment cost is based on experience with single nourishments (using trucks).*

Beach Location	Beach Width (m)	Length (m)	Area (m^2)	Average Height of Beach Berm (m)	Slope Degree	Change	Nourishment Cost (U.S. $ millions)
Abu Quir	20	1,000	20,000	2.11	7.0	Erosion	0.375
El Maamoura	40	3,200	128,000	2.12	6.0	Erosion	–
El Montaza	15	2,000	30,000	1.95	6.5	Erosion	–
El Mandara	25	800	20,000	1.80	8.0	Erosion	0.4
El Asafra	30	1,060	31,800	1.93	15.0	Erosion	0.8
Sidi Bishr	20	2,400	48,000	1.65	4.0	Near stable	–
Gleem	50	200	10,000	2.25	16.0	Deposition	–
Stanley	20	250	5,000	3.10	7.0	Erosion	0.125
Roshdy	20	190	3,800	2.22	14.0	Erosion	0.031
Sporting	12	255	3,060	1.40	9.0	Near stable	–
El Chatby	40	2,000	80,000	1.54	6.0	Erosion	1.0
El Anfoshy	30	800	25,500	1.96	5.0	Deposition	–
TOTAL		14,155					2.731

The main part of the coast is rocky and has little or no beach sand fronting it. Private and public bathhouses are situated along most of the Corniche. The shoreline is generally undulating with small embayments and pocket beaches. Storm surges (which occur mainly from November to March) can cause overtopping of the Corniche and damage to the bath houses.

To date, various methods have been used for artificial nourishment of beaches: namely stockpiling, continuous supply, and offshore dumping. In a master plan for the Nile delta, TETRA TECH (1984) recommended sand nourishment combined, in some cases, with hard structures to combat erosion and to create wider recreational beaches. In projects in Alexandria, a direct stockpiling and fill placement method are used. Six beaches in Alexandria are already nourished: Abu Quir, El Mandara, El Asafra, Stanley, Roshdy, and El Chatby. For some long beaches, short groins have been constructed to reduce sand movement and loss. Grain size analysis indicates that inland desert sources would be suitable as beach fill. The quality of offshore sources near Alexandria has not been evaluated. The estimated total cost of the six beach nourishment projects has been less than U.S. $3 million (Table 6) (EGYPTIAN PROTECTION AUTHORITY, *personal communication*, 1990).

The objective of this section is to study the impact of sea- level rise on Alexandria beaches and to evaluate possible economic losses. In order to carry out this study, we only consider the change of erosional rates of these beaches due to sea-level rise. Given the lack of longshore transport, this seems a reasonable first approximation.

Erosion Modeling

BRUUN (1962) formulated a two-dimensional relationship between rising sea level (S) and the rate of shoreline retreat (R):

$$R = S * L/(h^* + B) \tag{2}$$

where L is the active profile length; h^* is the active profile depth; and B is the berm elevation (measured using standard surveying techniques). The active profile depth (h^*) can be difficult to determine as discussed by NICHOLLS *et al.* (1994). For these studies we used the two depths defined by HALLERMEIER (1981).

$$d_1 = 2H + 11\sigma \tag{3}$$

$$d_i = (H_s - 0.3\sigma)T_s(g/5000\,D)^{0.5} \tag{4}$$

where d_1 is the greatest depth where intense on/offshore transport and significant alongshore transport will occur within a typical year; d_i is the greatest depth where significant on/offshore transport occurs within a typical year; H_s is the mean significant wave height in deep water; σ is the standard deviation of significant wave height; T_s is the mean wave period; D is the typical median sand diameter near 1.5 d_1; and g is the acceleration due to gravity.

Wave data at Abu Quir Bay, 35 km east of Alexandria, were compiled from FANOS and KHAFAGY (1989). The averaged wave data have summary statistics: $H_s = 0.75$ m; $\sigma = 0.55$ m; $T_s = 7.3$ sec; a typical median sand diameter (D) of 0.11 mm was assumed, following the procedure described by HALLERMEIER (1981). Therefore, from equations 2 and 3, the following values are estimated: $d_1 = 7.55$ m and $d_i = 17.93$ m. These two depths were plotted on a 1:100,000 bathymetric map and the average distance (L) from each contour depth (d_i) and (d_1) to the shoreline were measured (Table 7).

Shoreline recession can be estimated using the Bruun Rule for each depth of closure. The resulting recession was averaged for each scenario (Table 7). The resulting shoreline retreat values (R) for each sea-level rise scenario are shown graphically in Figure 7. The estimated values of shoreline retreat represent beach erosion due to sea-level rise only and do not include other coastal processes which may be important in determining shoreline position.

Even with a 0.5-meter rise, the estimated recession exceeds the existing beach width for 10 of the 12 beaches considered. This is interpreted as indicating total loss of the beach and exposure of the rocky coast behind the beach to wave action and possible erosion. The potential for erosion of the rocky coast is difficult to evaluate, but more frequent damage to the Corniche and associated infrastructure would be expected during storms if the beaches were lost.

Socioeconomic Impact on Beaches

One of the most serious impacts of sea-level rise on Alexandria Governorate would be the threat to recreational beach communities. Esti-

Table 7. *Application of the Bruun Rule to Alexandria Beaches (1990).*

Beach Locations	$(d_1 + B)$ (m)	L (km)	Shoreline Retreat (R) (m) SLR* = 0.5	SLR = 1.0	SLR = 2.0	$(d_i + B)$ (m)	L (km)	Shoreline Retreat (R) (m) SLR = 0.5	SLR = 1.0	SLR = 2.0	Average Shoreline Retreat SLR Scenarios 0.5 m	1.0 m	2.0 m
Abu Quir	9.66	0.8	41.40	82.82	165.62	20.04	2.9	72.36	144.72	289.44	56.88	133.77	227.53
El Maamoura	9.67	1.1	56.87	113.75	227.49	20.14	3.1	76.96	153.92	307.84	66.92	133.84	267.67
El Montaza	9.50	0.7	36.84	73.06	147.36	19.88	1.9	47.79	95.57	191.06	42.32	84.33	169.21
El Mandara	9.35	0.8	42.76	85.56	171.12	19.73	3.0	76.03	152.06	304.12	59.41	118.81	237.62
El Asafra	9.48	0.8	42.19	84.39	186.77	19.86	2.8	70.49	140.98	281.96	56.34	121.69	225.37
Sidi Bishr	9.20	0.6	32.61	85.22	130.44	19.58	2.7	68.95	137.90	275.80	50.78	101.56	203.12
Green	9.80	0.5	25.51	51.00	102.04	20.18	2.8	69.38	138.76	277.52	47.47	94.88	189.78
Stanley	10.65	0.4	18.78	37.56	75.12	21.03	2.6	61.82	123.64	247.28	40.30	80.60	161.20
Roshdy	9.77	1.2	61.41	122.82	245.64	20.15	1.8	44.67	89.34	178.68	53.04	106.08	212.16
Sporting	8.95	0.4	22.34	44.69	89.37	19.33	2.0	51.73	103.46	206.92	37.04	74.08	148.15
El Chatby	9.09	0.5	27.50	55.01	110.01	19.47	1.6	41.09	82.18	164.36	34.30	68.59	137.19
El Anfoshy	9.51	0.9	47.32	94.64	189.28	19.90	1.4	35.18	70.36	140.72	41.25	82.50	165.00

*SLR = sea-level rise.

mates of losses of land, installations, and visiting tourists are based on a sea-level rise scenario of 0.5 m (Table 8). The socioeconomic impacts of beach erosion are dramatic and economic losses (land and installations) will exceed U.S. $2.5 billion. Losses for the one-meter scenario will be even larger as the two surviving beaches (Gleam and El Chatly) under a 0.5-meter scenario will be lost, while damage during storms will increase everywhere.

Tourism is primarily oriented towards swimming and sunbathing activities that directly use the beach and shore. Therefore, the coast, its slope, climate, and quality of land and sea are of prime importance to this industry. Most tourist facilities such as hotels, camps, and youth hotels are located within 200 to 300 m of the coast. The average number of international tourists in summer is about 55,000 per day, plus many national tourists, served on beaches by about 700 official employers per day. An average business loss is estimated at U.S. $127 million/year. Other relevant socioeconomic data are listed in Table 9. There are also important archeological sites along the Alexandria coast, including the Fort of Gayet Bay, the Hydro-Biological Institute, Royal Jewellery, the archeological area of Mostafa Kamel, the area of El Anfoshy, and El Montazah Palace.

Alexandria's beaches will continue to gradually disappear over the next few decades even for present rates of sea-level rise. The losses will accelerate with a more rapid rise and tourism will suffer. Coastal installations will be damaged or destroyed, including cabins, casinos, and houses, in addition to major government and private buildings located adjacent to beaches. Coast dwellers, who live in areas that are affected by erosion and flooding, are fully aware of the implications of a short-term failure in the sea defense system. However, they are unable to perceive the long-term problem of global sea-level rise because of the lack of information and awareness.

OTHER IMPACTS

Other likely impacts of sea-level rise in Alexandria Governorate include (EEAP, 1992): (a) increasing salinization of water resources and waterlogging; (b) flooding and inundation of Alexandria Governorate from Behaira Governorate, which lies to the east in the Nile delta proper; (c) increasing flooding by storm surges, with di-

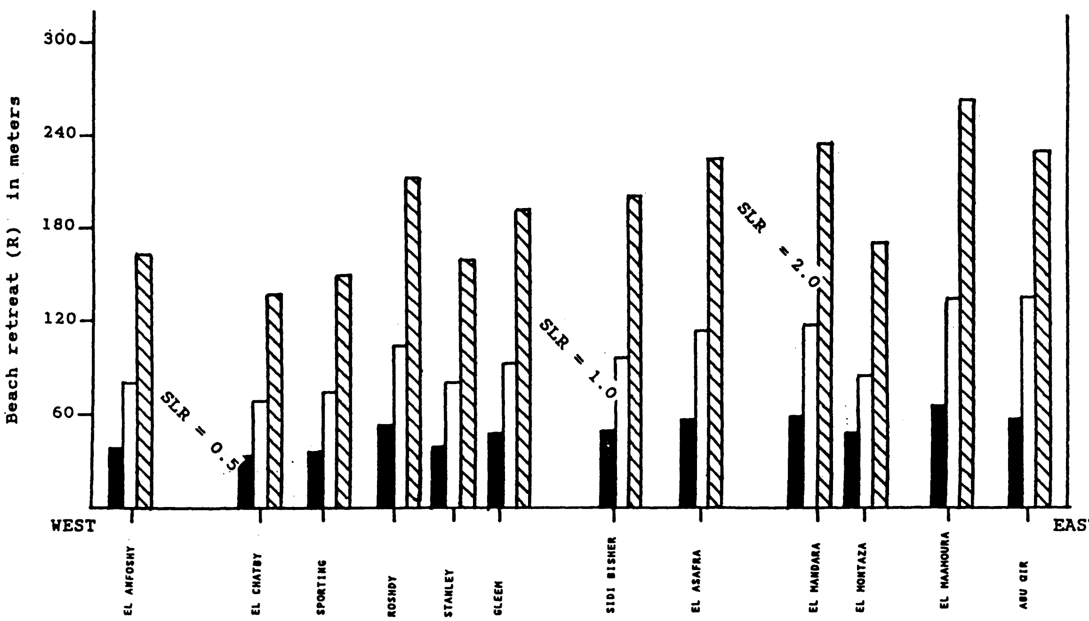

Figure 7. Potential beach erosion calculated using the Bruun Rule along Alexandria's beaches, assuming a sea-level rise (SLR) of 0.5, 1.0, and 2.0 meters by the year 2100. Actual erosion will be less in most cases as the pocket beaches will be completely removed by a 0.5-m rise in most cases.

Table 8. *Expected impact of a 0.5 m rise in sea level on Alexandria Beaches (evaluated 1990–1991).**

Beach Locations	Shoreline Retreat (m)	Original Area (m^2)	Area Loss (m^2)	Original Volume of Sand (m^3)	Volume Loss (m^3)	Number of Employees Affected	Economic Loss in U.S. Dollars (millions)	Visitors Loss per Year	Business Losses in U.S. Dollars (millions)	Protection Costs (Nourishment) U.S. Dollars (millions)
Abu Quir	56.88	20,000	T.L	42,200	T.L	57	11.36	1,420	8.10	1.80
El Maamoura	66.92	128,000	T.L	271,360	T.L	184	641.28	16,700	24.60	6.81
El Montaza	42.32	30,000	T.L	58,500	T.L	282	1,410.00	42,300	3.00	2.48
El Mandara	59.41	20,000	T.L	36,000	T.L	95	47.60	2,380	5.70	1.28
El Asafra	56.34	31,800	T.L	61,374	T.L	49	29.89	3,760	4.50	1.73
Sidi Bisher	50.78	48,000	T.L	79,200	T.L	51	243.84	25,400	21.00	3.02
Gleem	47.45	10,000	9,488	22,500	21,348	15	19.00	570	2.30	0.30
Stanley	40.30	5,800	T.L	15,500	T.L	81	20.20	3,030	11.70	0.47
Roshdy	53.04	3,800	T.L	8,436	T.L	53	15.11	1,723	2.10	0.34
Sporting	37.04	3,060	T.L	4,284	T.L	–	14.21	–	5.10	0.20
El Chatby	34.30	80,000	68,800	123,200	105,644	30	55.04	8,600	7.70	1.32
El Anfoshy	41.25	25,500	T.L	47,040	T.L	55	15.87	5,520	30.60	0.97
TOTAL	–	404,660	–	769,594	–	952	2,523.40	111,403	126.40	20.72

*Original area, existing area of the beach; area loss, area loss due to shoreline retreat; original volume, existing volume of beach sand; volume loss, volume loss of sand due to shoreline retreat; T.L, total loss (of a beach). Business losses are based on percentage area losses, and socioeconomic data. Loss due to a given sea-level rise scenario is estimated by percentage loss of beach area. Protection costs are based on total volume losses and extrapolation of existing nourishment costs (Egyptian Protection Authority, *personal communication*, 1990) as well as actual estimation based on existing market prices of sand. Economic losses represents land and installations.

Table 9. *Socioeconomic data on Alexandria Beaches (1990–1991).*

Beach Location	Classification	Average Number of Tourists/Day During Summer	Installations	Price/m^2 U.S. Dollars	Price of Land and Installations U.S. Dollars (millions)	Number of Official Employees During Summer	Approximate Number of Shops Affected	Estimated Business Earning During 1991 U.S. Dollars (millions)
Abu Quir	Public	500	Houses + shops	200	4.0	20	600	8.10
El Maamoura	Tourist	10,000	Cabins	3,000	384.00	110	1,800	24.60
El Montaza	Tourist	15,000	Cabins + hotels	4,000	500.0	100	210	3.00
El Mandara	Public	1,000	Cabins	1,000	20.0	40	420	5.70
El Asafra	Public	2,000	Cabins	500	15.9	26	330	4.50
Sidi Bishr	Public	10,000	Cabins	2,000	96.0	20	1,530	21.00
Gleem	Public	600	Cabins	2,000	20.0	16	180	2.40
Stanley	Tourist	1,500	Cabins + hotels	2,000	10.0	40	870	11.70
Roshdy	Public	650	Cabins + casino	1,500	5.7	20	150	2.10
Sporting	Public	000	Cabins	1,500	4.6	00	390	5.10
El Chatby	Public	10,000	Cabins + casino	800	64.0	35	660	9.00
El Anfoshy	Public	4,000	Cabins	450	11.5	40	2,250	30.60
TOTAL		55,250			1,136.0	667		127.80

rect impacts and implications for erosion, coastal roads, and coastal installations; (d) port facilities will require upgrading. These impacts and costs have not been investigated as part of this study.

PROTECTION COSTS

Beaches

The protection of the beaches and associated infrastructure must depend upon continuous and periodic nourishment. The total cost of protection is estimated to be only U.S. $21 million and $42 million for the 0.5-meter and one-meter scenario, respectively. Longshore losses are not expected due to the headlands controlling the pocket beaches, lowering costs as compared to more open-coast beaches. Experience with beach nourishment is already being gained in Alexandria, and given the high costs of beach erosion in terms of loss of land and infrastructure (U.S. $2.5 billion for even a 0.5-m rise in sea level), nourishment appears to be the appropriate response. Additional hard protection such as seawalls will be required in some areas along the Corniche where there is presently no beach. This requirement has not been evaluated.

Lowlands

As has been mentioned earlier, the city is built on three intermittent calcareous ridges, parts of which are leveled and constitute a potential pathway for rising water to reach the lowland south of the city. Maintaining the beaches in front of these pathways using nourishment will help to prevent surface water from reaching the lowland south of the city through these paths, particularly during storm surges. Some small dikes may also be necessary.

Inundation, increased flooding, and waterlogging due to other causes such as inundation further to the east have not been considered. Protection of the lowlands will include action outside the Alexandria Governorate, to limit or stop these impacts. The potential costs of these protection measures have not been considered as part of this paper.

Table 10 summarizes the estimated population in the vulnerable areas for the years 1990 and 2030, the lowland area lost, and the value of losses for each sea-level rise scenario, assuming no protection.

IMPLICATIONS FOR EGYPT

It has been widely reported that 8 million people would be displaced in Egypt by a one-meter rise in sea level, assuming no protection and existing population levels (BROADUS *et al.*, 1986; MILLIMAN *et al.*, 1989). This estimate is based upon 4 million people being displaced in the Nile delta, and the entire population of Alexandria also being displaced. This study shows that this

Table 10. *Summary physical and socioeconomic impacts on Alexandria Governorate, assuming No Protection.*

SLR* Scenario (m)	People Displaced (millions) 1990 Population	Projected 2030 Population	Area Loss (km_2)	Economic Losses (billions of 1990 U.S. Dollars)
0.5	1.81	4.02	1,017.2	40.2
1.0	2.02	4.50	1,237.8	44.9
2.0	2.30	5.11	1,518.7	52.9

*SLR, sea-level rise.

would not be the case and about 2 million people would be displaced in Alexandria. Thus, from a national perspective 6 million people would be displaced by a one-meter rise in sea level, based on existing population. However, this vulnerable population can be expected to have increased significantly before accelerated sea-level rise causes serious impacts. The World Bank estimate is that the 2020 population of Egypt will be nearly 92 million, 74% above the 1990 population (BOS and BULATAO, 1990).

CONCLUSIONS

The results of this study indicate that:

(1) A global sea-level rise of only 0.5 m will erode most of Alexandria's beaches and also place a large portion of Alexandria's lowland at risk of inundation.

(2) The agricultural sector will be the most severely affected sector, by area, followed by the industrial and the urban sectors, respectively. However, the order in terms of economic impact may be different.

(3) Total economic losses have been estimated to exceed U.S. $40 billion for all sea-level rise scenarios, assuming no protection. The Ameria district will suffer severe impacts due to its low elevation.

(4) Periodic beach nourishment, building of some dikes in locations vulnerable to saltwater intrusion, and protection of the delta to the east is believed to be the best response to protect Alexandrian beaches and lowlands. While Alexandria is physically vulnerable to sea-level rise, the city has the wealth and capability to combat its effects.

These results draw attention toward the extreme importance of upgrading awareness of decision makers, planners, and the population at large of the possible future impacts of sea-level rise. In particular, it is recommended that:

(1) Detailed vulnerability assessments, including physical and socioeconomic impacts, be undertaken for the entire Nile delta using recent satellite land use classifications and high quality topographic information. The area of the study should be extended in phases, first to include Behaira Governorate, covering the delta west of the Rossetta branch, and then the rest of the northern delta coast.

(2) The impact of sea-level rise on freshwater resources should be assessed. Management of saltwater intrusion and waterlogging problems should be considered.

(3) Our research and planning should be useful whether global warming occurs or not. Strict planning and periodic monitoring of land use changes by satellites should become a routine part of the development of this area.

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