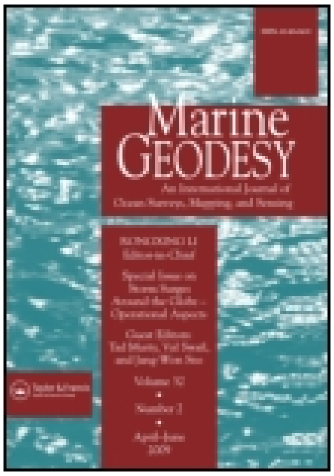

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Climate change and sea level rise in Bangladesh, part II: Effects

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Climate Change and Sea Level Rise in Bangladesh, Part II: Effects

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Global climate is changing as a consequence of global warming due to industrial, agricultural, and other human activities. The major effects of global warming are changes in the hydrological cycle and rise in sea level. Bangladesh is most vulnerable to the effects of climate change and sea level rise due to the low elevation of the land areas, the low gradient of the rivers, and exposure to the sea. It has been predicted by the application of a numerical model that there will be changes in the hydrodynamics of flow of the rivers in Bangladesh due to increase in river discharge and rise in sea level. As a result there will be significant effects on flooding, drainage, agriculture, tides, waves, and vital wetlands in Bangladesh. Probable critical effects on water resources planning and management are the focus of this article. Comprehensive management and sustainable use of resources will provide possible solutions to adapt to short- and long-term changes.

Keywords agriculture, coastal zone, drainage, saltwater intrusion, tides, waves, wetland

About 60% of the world population lives within 60 km of coastline. The coastal zones of the South Asian seas region is most vulnerable to sea level rise and other potential effects of climate change because of its increasing population and unprotected coastline. The Bengal delta, one of the largest such coastal plains in the world, accounts for 80% of the land mass of Bangladesh. Bangladesh is most vulnerable to sea level rise and increase in river discharge because of its geographical location, flat topography, river system, unprotected coastline, impoverished economy, and densely populated land area. The flood situation in Bangladesh is becoming more vulnerable due to population explosion. The population has increased from 40 million to over 120 million in a little over 30 years. Because of this pressure, people are forced to live in flood-prone areas and attempt agriculture on unsuitable lands. Hence normal floods cause greater loss of life and prop-

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erty. The long-term implications of global warming with the addition of population explosion could make Bangladesh more vulnerable to flooding in years to come, so more extreme floods will cause an exponential increase in loss of life and extensive damage to infrastructure.

Increase in magnitude and frequency of flooding due to extreme events of rainfall and rise in sea level will cause critical effects on flooding, drainage, agriculture, fisheries, forests, industry, and settlement thereby affecting water resources planning, operation, and management in Bangladesh. There will be an interaction between social conditions and the effects of climate change. Since Bangladesh is a developing country and dependent on agriculture, socioeconomic conditions could be particularly important. Hence impact analysis is very important to cope with future scenarios of climate change and sea level rise to facilitate preventive planning and sustainable development.

History of Flooding and Recent Major Floods in Bangladesh

Flooding in Bangladesh is a recurring phenomenon. Available records of floods in the lower reaches of the Ganges-Meghna-Brahmaputra (G-M-B) river system show the occurrence of major floods. Recurrent floods between 1787 and 1830 also changed the old course of the Brahmaputra. After a major flood in northern Bengal in 1922, a Flood Committee was formed and a report was published in 1927 on the north Bengal floods between 1870 and 1922. From statistical analysis of available records, this report revealed that severe floods can occur every 7 years, and catastrophic floods every 33–50 years.

Available records of flood-affected areas (Ahmed, 1988) since 1954 shows that major floods occurred in 1954, 1955, and 1974, and exceptional major floods occurred in 1987 and 1988. The devastating earthquake of 1950 was one of the major causes of the 1954 flood. Considerable rise of river beds occurred following the earthquake of 1950 in Assam.

About 18–20% of the total land area of Bangladesh is vulnerable to normal flooding, and this increases to about 30–35% in major floods. The flood of 1987 exceeded all previous records when about 40% of the country was flooded. There was heavy rainfall throughout the country, particularly in the northern part of Bangladesh. The Ganges attained 76,000 m^3, the highest flow recorded since 1934 at Hardinge Bridge over the Ganges in Bangladesh (near the Indian border). The excessive flow aggravated the flood situation, causing drainage congestion of the flooded land.

The flood of 1988 was the worst flood of Bangladesh in living memory. About 70% of the land was inundated, and 50 million people were affected. Concentrated heavy rainfall on the Meghalayan plateau and other parts of India, Bhutan, and Nepal brought exceptionally high flow in the Meghna and Brahmaputra Rivers and their tributaries, starting from June up to the end of July. After the third week of August, the Brahmaputra started rising very fast. On 30 August the Brahmaputra flow at Bahadurabad reached 99,500 m^3 (Bingham, 1989), breaking all previous records. The Ganges and Meghna also attained very high flow at this time. On 28 August there was a full moon, and there was high tide in the ocean. In early September, water spread rapidly across the flood plain, and Dhaka, the capital of Bangladesh, was seriously flooded for the first time. Flood levels at 10 of the 34 flood monitoring stations in Bangladesh exceeded their highest recorded levels, while at 22 other stations it exceeded the level of the 1987 flood (Abbas, 1989). The spring tide due to the new moon, in conjunction with the solar eclipse on 11 September, resulted in a considerable delay in the recession of flood water from the southern part of Bangladesh. Figure 1 shows the main river discharges between 1986 and 1988 and flood levels in 1988.

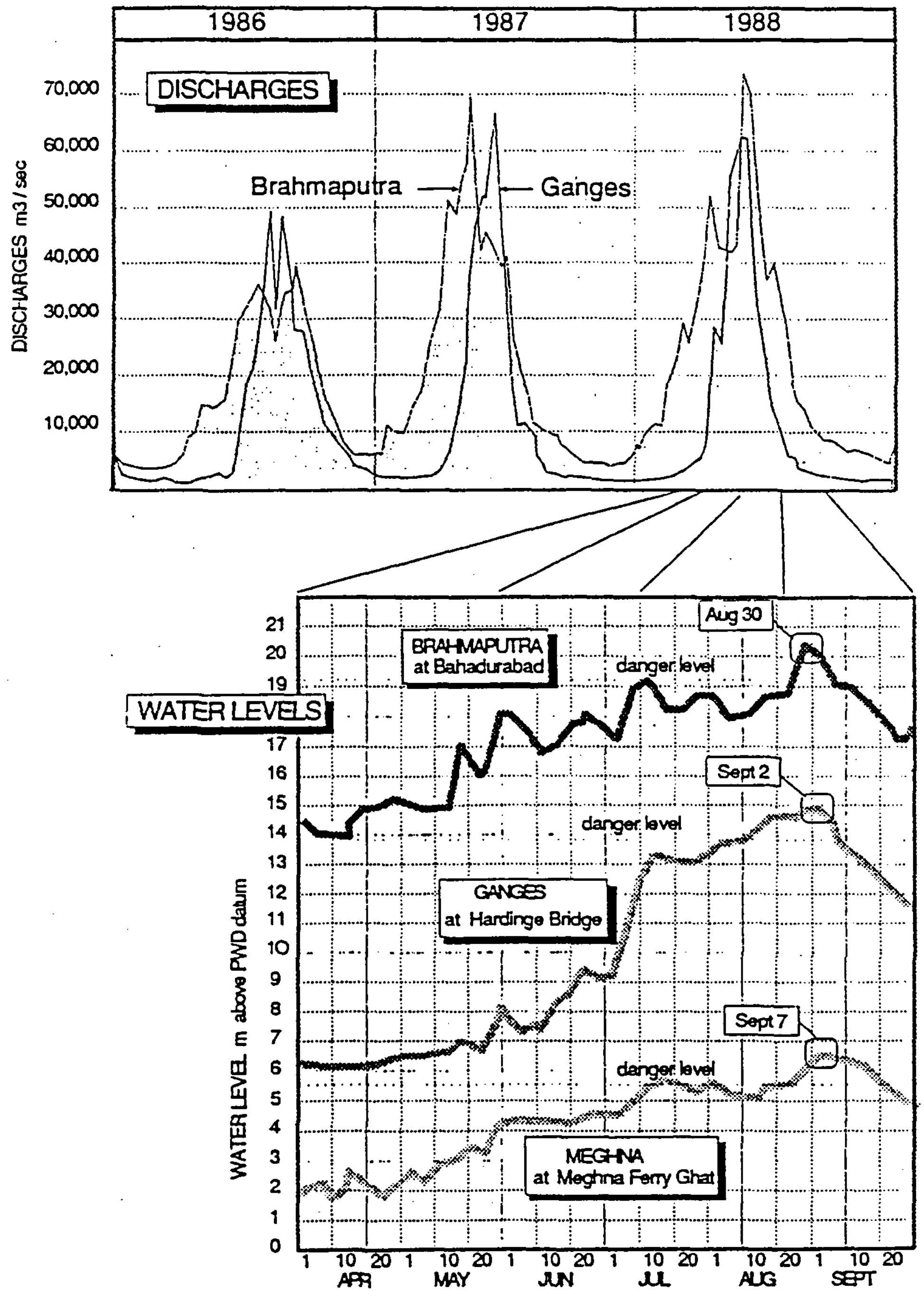

Figure 1. Main river discharges in Bangladesh, 1986–1988, and flood levels in 1988. (*Source*: World Bank, 1991.)

In general, rainfall within Bangladesh contributes 10–15% to its streamflow. Hence it is very important to estimate the rainfall in the entire basin of the G-M-B rivers, while more than 92% of the catchment area lies outside Bangladesh. One significant feature of the 1988 flood was that rainfall in the upper catchment was not caused by a moving depression in the Bay of Bengal, which is usually the case. It is necessary to study the long-term rainfall pattern in the upper catchment of the G-M-B rivers so that it can be ascertained whether the heavy rainfall of 1988 was a recurring phenomenon, or climate variability due to the greenhouse effect.

Changes in Sea Level

Global mean sea level has been changing by several processes on different time and space scales. Glacio-isostatic rebound, oceanographic, atmospheric, and tectonic effects are important for such changes. *Eustatic sea level variation* is associated with the volume change of sea water. *Relative sea level rise* (RSLR) can be different due to local uplift and subsidence.

Gornitz and Lebedeff (1987) estimated the past changes in sea level (Table 1) and described the following causes which affect sea level. Among the most important on time scales of a thousand years or more are glacio-eustatic variations in the ocean volume due to melting and growth of ice sheets, and glacio-isostatic changes due to adjustments of the earth's lithosphere to changes in ice and water loads. Over millions of years, changes in seafloor spreading rates, the volume of the ocean ridge system, and subsidence of passive margin oceanic lithosphere can also affect sea level significantly.

On a shorter time scale (decades or centuries), local tectonic movements can generate sea level trends comparable in magnitude to eustatic and isostatic changes. Sea level could also be affected partly by subsidence caused by pumping of oil or groundwater withdrawal or by shifts in prevailing wind patterns and ocean currents. Sea level rise due to sedimentation, although significant near river deltas, is negligible on a global scale. The global sea level rise corresponding to the deposition of the suspended load from the world's siltiest rivers amounts to only around 0.02 mm/year (Gornitz & Lebedeff, 1987).

Table 1
Estimates of past changes in sea level

Process	Rate
1. Glacio-eustatic changes in volume of ocean water	10 mm/yr, over 7,000 yrs following deglaciation
2. Glacio-isostatic changes in volume of ocean basins	1–10 mm/yr
3. Seafloor spreading; cooling and subsidence of oceanic lithosphere; change in volume of ocean floor	0.01 mm/yr
4. Sediment accumulation, global; local river deltas	0.02 mm/yr 1–3 mm/yr
5. Tectonic uplift/subsidence	1–3 mm/yr

Source: Gornitz and Lebedeff, 1987.

Direct rainfall and river runoff may be significant factors in short-term changes (seasonal) in sea level along some coasts. Rainfall and runoff contribute significantly in producing the 100-cm sea level variation observed in the Bay of Bengal (Komar & Enfield, 1987). Sea level changes on a short time scale (several years) are associated with El Niño/ Southern oscillations. One of the most intriguing changes in sea level within the Pacific ocean is that associated with El Niño. El Niño represents an anomalous oceanic event characterized by the sudden appearance of abnormally warm surface waters off the coasts of Peru and Ecuador.

Differences in atmospheric pressure, winds and ocean currents, and density of sea water also cause spatial and temporal variation in eustatic sea level in relation to the geoid (the surface of constant gravitational potential corresponding to the surface which ocean would assume if ocean temperature and salinity were everywhere 0°C and 35‰, respectively, and surface air pressure was everywhere constant). Changes in geoid itself, due to redistribution of mass within the earth, are irrelevant on decadal-century time scales.

Over time scales of decades or centuries, the most important climate-related factors to sea level changes are likely to be thermal expansion of oceans and melting of ice (but not floating ice shelves or sea ice) due to increase in surface temperature. Most of the observed sea level changes (eustatic) in the last 100 years has been ascribed to thermal expansion of the upper layers of ocean and melting of Alpine glaciers and may thus be an early response to global warming. The prediction of relative sea level rise is much more important than that of the absolute rise, since most effects are caused by the action of total water level and not just the change in mean sea level.

The analysis by Gornitz and Lebedeff (1987) using tide gauge data from 130 stations estimated an average rate of sea level change of 1.2 ± 0.3 mm/year over the period 1880–1980. Barnett (1988) obtained a mean value of sea level rise of 1.15 mm/year over the period 1880–1986. Most analyses revealed a trend in global sea level rise of between 10 and 20 cm per century. Figure 2 shows global mean sea level rise over the last century. The estimates show that the rate of sea level rise have increased during the last 50 years, relative to the preceding 50 years. Globally, the rate of sea level rise has increased by 0.6 mm/year between 1932 and 1982.

Continued rise in sea level is likely in the near future because of thermal expansion of sea water and melting of Antarctic ice sheet as a consequence of global warming. Estimates of future sea level changes are based on the global temperature rise scenarios. The IPCC (1992) science working group estimated a global sea level rise of 66 cm by the year 2100 according to the best-estimate, "Business-as-Usual" scenario. The High scenario for the next century ranges between 31 cm and 110 cm of sea level rise, according to IPCC (Figure 3). Other estimates give a range of sea level rise scenarios between 56 cm and 345 cm for the next century (IPCC, 1992).

Sensitivity of Flooding to Different Scenarios of Climate Change

Numerical hydrodynamic models have been developed to simulate the effects of different scenarios of sea level rise and increase in river discharge on flooding in Bangladesh (Begum, 1992). The models have been applied to the Ganges-Meghna delta to simulate the effects of 0.2 m, 0.6 m, and 1.4 m rise in sea level, and 10%, 15%, and 20% increase in river discharge. The results of simulation show (as shown in Part I of this article) that there will be increase in magnitude and extent of flooding due to changes in the hydrodynamics of flow. This will cause significant effects on the water resources management of Bangladesh.

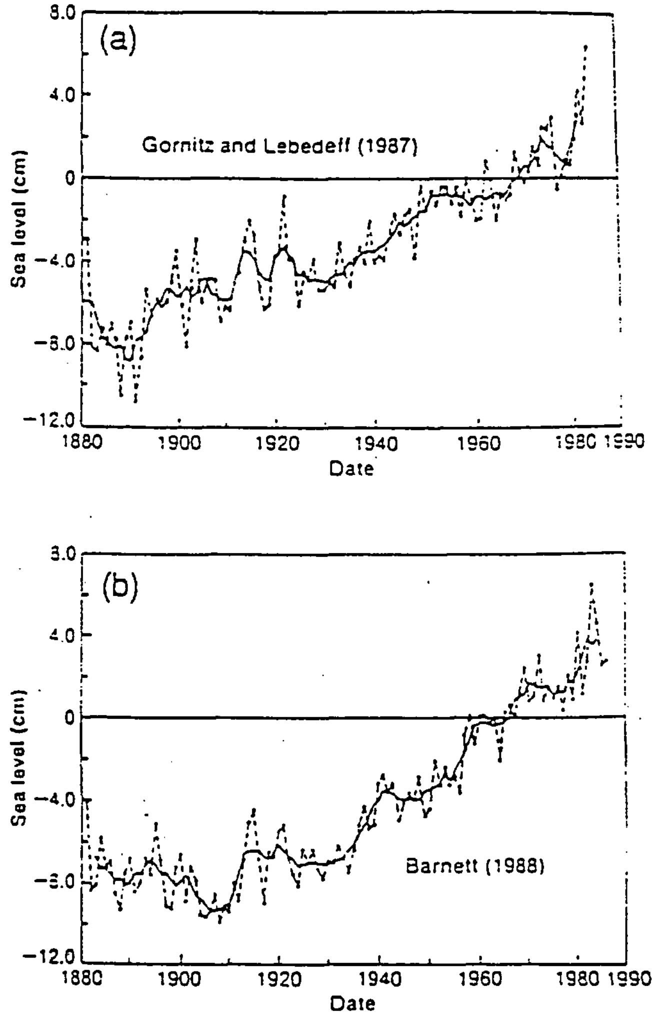

Figure 2. Global mean sea level rise over the last century. (*Source*: Gornitz & Lebedeff, 1987.)

Effects of Sea Level Rise in Bangladesh

The effects of sea level rise and other potential changes in climate will be different along the Bangladesh coast because of local morphologic and hydrologic conditions, land elevation, population density, and the degree of development of the flood protection and water management systems. The effect of sea level rise would be more critical, since the Bengal delta is subsiding. The low gradient of the rivers, high flow and sediment load of the rivers (during rainy season), unprotected coastline, high astronomical tides, frequent storm surges, flat topography, and large wetland forms a unique coastal morphology. Continuous interaction among the physical, chemical, and biological components results in a complex system along the Bangladesh coast. The parameters likely to be influenced by sea level rise, increase in river discharge, and other potential changes in climate may be grouped under three mutually interacting major components, physio-chemical, ecological, and human interests, as shown in Figure 4. The effects of climate change and sea level rise on different parameters in Bangladesh are discussed here in detail.

Flooding and Erosion/Sedimentation

Bangladesh experiences moderate to severe flooding every year. Frequent storm surges also cause severe coastal flooding. The flood situation is further aggravated by the high tide in the Bay of Bengal. It has been found from sensitivity analysis (as shown in Part I of this article) that the water level rises to about 6 m near the Meghna estuary with a 1.4-m rise in sea level. Even with a 0.2-m rise in sea level, water level rises between 4.5 and 5 m near the estuary. Since most of the coastal area is below 1.5 m above mean sea level (MSL) and the area near the confluence of the Ganges and Meghna is below 3 m above MSL, both depth and area of inundation will increase extensively. However, the water level in the Ganges and Upper Meghna also increases significantly due to backwater effect as a result of changes in the hydrodynamics of flow (as shown in Part I of this article). Hence the severity and extent of flooding will increase even in the upstream portion of the river. On the other hand, a rise in sea level will move the shoreline landward and thus add to the nonlinear shallow-water effect to increase the surge height. Sensitivity analysis also shows that the combined effects of increase in river discharge and rise in sea level further adds to the severity of flooding. This will result in large losses of life and farm land. Low-lying agricultural areas will be seriously affected, leading to the shifting of agriculture, reduced crop yields, and loss of cultivable areas. Increased flooding will also cause problems with existing irrigation and drainage system.

The erosion-sedimentation pattern will change with a sea level rise and associated backwater effect. There will be reduction in the discharge capacity of the rivers because of backwater effect. As a result, sedimentation may shift upstream. This would diminish the river gradient, resulting in a decrease in transport capacity and thus moving the river bed sedimentation farther upstream. Sedimentation will further reduce the discharge capacity and result in higher water levels. Hence the actual increase in flood frequency will be higher than might be anticipated. The morphology of rivers and coasts may also change due to changes in flow and transport/deposition pattern of sediment as a result of increasing upstream flooding and a rise in sea level.

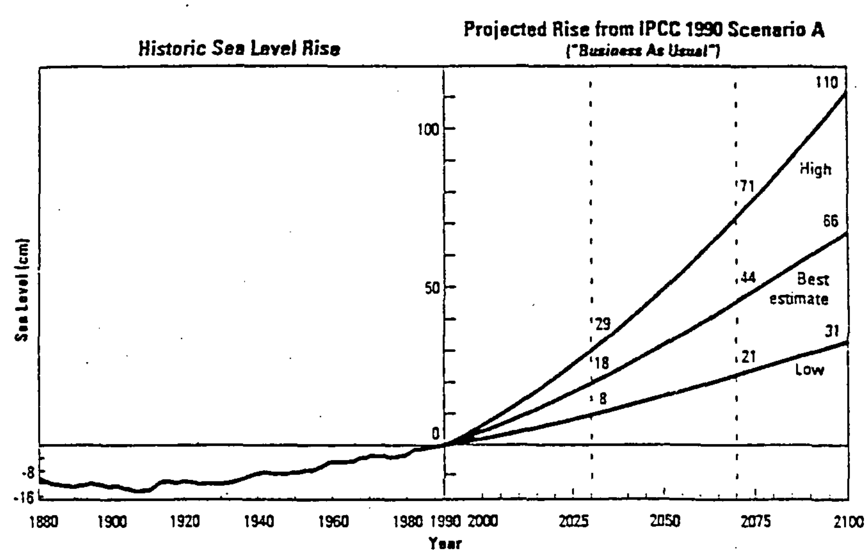

Figure 3. IPCC estimates of future sea level rise. (*Source*: IPCC/CZM, 1992.)

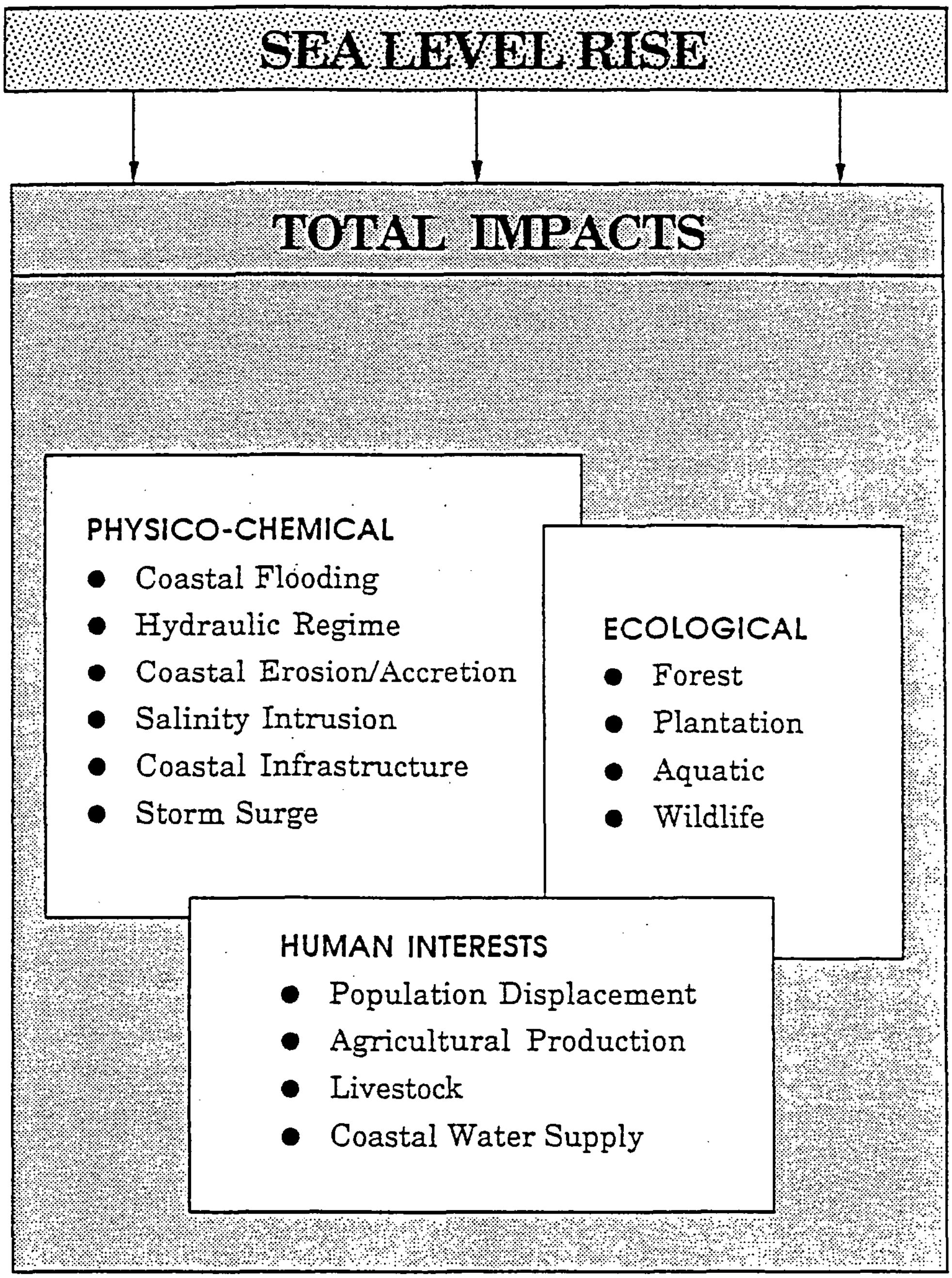

Figure 4. Effects of climate change and sea level rise on different parameters in Bangladesh.

Change in flow and erosion/sedimentation patterns is a complex interacting hydrodynamic phenomenon which affects the hydraulic regime. This will create a need for economically feasible reconstruction and extension of water management systems and structures.

Tides, Waves, and Coastal Erosion

The present flood situation is also aggravated by the high tides in the Bay of Bengal. Tides in the Bay of Bengal originate in the Indian Ocean and are amplified by the nonlinear shallow-water effect. The tidal range along the Bangladesh coast varies between 3 and 6 m. The high tidal wave action thus contributes to shoreline erosion in Bangladesh. The rise in sea level will move the shoreline farther landward and thus add to the nonlinear shallow-water effect. As a result, the tidal range will increase. The characteristics of tides are controlled by a number of local factors, the most important of which are relative mean sea level, the shape of the coastline, and the depth and shape of the continental shelf (Barua, 1991). A rise in sea level will reduce the bottom friction of the tidal flow and hence the tidal range will increase. Hence increasing tidal range and tidal wave action due to sea level rise is likely to augment coastal erosion in Bangladesh and to change the coastal morphodynamics.

Recently, in some parts of the Chittagong coastal belt, erosion has increased at an alarming rate. A vast area including the Export Processing Zone, the Naval Establishment, and a large industrial estate could be in danger if the present rate of erosion continues. This may be an early indication of the anticipated acceleration of coastal erosion due to changes in tidal regime as a result of sea level rise. Loading on coastal structures such as breakwaters, lochs, bridges, etc., will increase. Port facilities will have to be adjusted to a higher sea level.

The available tide gauge data are not long enough to show any trend of changes in sea level. In addition, it is difficult to compare data from different tide gauges along the Bangladesh coast, since the gauges are not linked to a common datum. The accurate estimation of sea level changes/trends from tide gauge and geologic data is a priority area for future research.

Effects on Agriculture

Rise in sea level, increase in river discharge, and other potential changes in climate will significantly affect agriculture. Cropping intensity and cropping patterns within Bangladesh vary between regions and within regions according to regional and local differences in the depth and duration of rainfall, soil moisture properties, salinity level, and availability of irrigation. Rice is the main crop in Bangladesh throughout the year. There are different seasonal varieties of rice, e.g., Aus, Aman, and Boro.

Because of changes in depth, duration, timing of flooding, and salinity intrusion, agriculture will be affected especially in the low-lying coastal areas. In some areas even deep-water rice will be affected because of flooding too early in the rainy season for crop growth. The main effect of increasing flood levels in the upstream portions of the Meghna and Ganges Rivers would be on the Aus and deep-water Aman paddy crops (Brammer, 1993). The land area suitable for Aus paddy and jute would be reduced, and farmers would grow lower-yielding varieties of Aman, which are tolerant of deeper flooding.

Even in the dry season (postmonsoon), because of the slow rate of drainage, the land will be too wet for sowing dryland crops. There will be a shift in the growing areas of Boro paddy due to changes in the flooding/drainage pattern. The cultivation of modern varieties of Boro paddy with irrigation on low-lying land may be affected by the greater water depth on the land at the time of planting or by the increased risk of flooding before the crop can be harvested (Brammer, 1993). Hence there will be changes in agricultural pattern and practice due to loss of cultivable areas and reduction in yield. This will create a need to modify existing cropping practices to cope with changing climate and rise in sea level.

Salt Water Intrusion

Sea level rise will affect seepage and salt water intrusion, especially in the coastal areas of Bangladesh. There will be an increase in seepage in areas where the phreatic groundwater level is kept low in an artificial way (e.g., polder areas). This is due to the fact that the head difference between sea level and the phreatic groundwater level will increase when the sea level rises. Increased seepage in such areas will increase salt load in the polder areas. Seepage water may become more saline, since salt water intrusion into rivers and estuaries will be more extensive with a rising sea level. There will be effects on agriculture, aquaculture, and water supply due to salt water intrusion. To avoid this damage, irrigation and drainage facilities have to be improved. Natural drainage will be affected because of higher water levels outside the area, and there will be need for artificial drainage. Rise in sea level and enhanced salt water intrusion will affect the freshwater resource. The north–south gradient of groundwater in Bangladesh will also be affected by a sea level rise.

Proper design of systems to deliver fresh water to deltaic areas is very important. Salinity management using fresh water to form a buffer against salt water intrusion allows coastal systems to remain open to some extent, thus allowing the movement of fish species which use brackish water and wetlands as important habitat.

Sanitation, Waste Disposal, and Health Hazards

Because of increased flooding in low-lying coastal areas, there will be immediate disruption of sanitation systems. The spread of infectious diseases could be markedly increased if the flooding of coastal areas increases. The inundation of sewage lines might result not only in immediate spread of disease, but the damage to such sanitation system components could mean the long-term disruption of waste removal capabilities and the spread of disease, until adequate repairs could be accomplished. This would cause serious environmental problems.

Another concern with sea level rise is the potential for flooding of waste disposal sites—e.g., garbage dumps—along coastal areas. This could also result in an increased spread of infectious diseases, depending on the specific material present in such dumps and the extent of their disposal due to flooding. The flooding of dumps containing hazardous industrial wastes could also lead to environmental problems. The spread of various toxic chemicals from such waste disposal sites would affect human health as well as the environment—e.g., vegetation damage and contamination of crop lands by toxic chemicals. All these potential environmental consequences argue for the careful consideration of steps it may be necessary to initiate now in order to cope with a projected sea level rise (e.g., protection or relocation of waste disposal facilities along coastal areas) in Bangladesh.

Wetlands

The natural coastal forest of the Sundarban in Bangladesh, covering an area of about 6,000 km^2, is one of the largest natural single areas of mangroves in the world. Wetlands are of great importance from an ecological point of view: They serve as nursery grounds for birds and a habitat for other animals. Wetlands also provide protection from storms and flooding. Wetlands have the ability to adapt to sea level rise if there is sufficient vertical accretion from organic and inorganic sediments. Sediment serves not only as building material but also delivers the necessary nutrients for wetland vegetation. Two critical problems for wetlands that would result from sea level rise are submergence and salinity increase (Day & Templet, 1989). Submergence occurs when vertical accretion of the wetlands surface cannot keep pace with the rate of water level rise. Hence sediment input to wetlands is very important. If wetlands do not accrete vertically at a rate equal to the rate of sea level rise, wetlands will be stressed and ultimately disappear. This will lead to a variety of interrelated environmental problems and ecologic degradation. Hence sediment management along the Bangladesh coast is most important and should include plans for both transport and retention of suspended sediments. In addition to sediments in river water, resuspended sediments from bays and the nearshore zone are also an important source. Biomass production by vegetation can contribute as much to vertical accretion as mineral sediment input (Day & Templet, 1989). Therefore, maintenance or establishment of vegetation is critically important.

A deeper penetration of tide water due to increase in tidal range would cause the formation of tidal levees and extend the mangrove zone. However, in a country like Bangladesh, where inland areas are occupied by agriculture or settlements and protected by dikes, the mangrove zone would become narrower by erosion and might even disappear.

Water Resources Management

Effects of sea level rise and other consequences of climate change will give rise to water resources management problems in Bangladesh, especially in the exposed coastal zones. The effect of sea level rise would be most critical on the Bangladesh coast, since relative sea level rise would be much higher as the delta is subsiding and also due to the population explosion. Moreover, most of the coastal area is below 1.5 m above MSL, and there is an unprotected coastline of about 710 km. About 25% of the total population lives in the coastal zone. Hence a higher flood/storm surge will cause more damage to infrastructure and exponential increase in loss of life. In order to deal with the problem, comprehensive management is needed. This will create a need for economically feasible reconstruction and extension of water management systems and structures.

Socioeconomics

Since Bangladesh is a developing country and dependent on agricultural production, socioeconomic consequences could be particularly important. The most critical effects would be on the agricultural economy. Increase in depth and area of inundation in the coastal area and also in the upstream portions of the Meghna and Ganges Rivers would seriously affect the agricultural areas, leading to shifting of agriculture, reduced crop yields, and loss of cultivable areas. Irrigation and drainage facilities need to be modified with changing climate. It would be necessary to increase the drainage capacity in low-lying areas, and increased provision for drainage might also be required for coastal poldered areas. Provision for artificial drainage needs to be increased because of higher water levels outside the area. Hence as a whole, the cost of drainage will increase.

Changes in salinity may also affect agriculture and groundwater. Dry-season cropping would be affected more. Considerable ecologic changes could occur in the Sunderban forest because of changes in sea level and salinity. Changes in species or reduced timber production could have considerable economic impact.

Because of increased floods and tidal levels, it may be necessary to protect urban areas from flooding by providing embankments and artificial drainage. The heights of

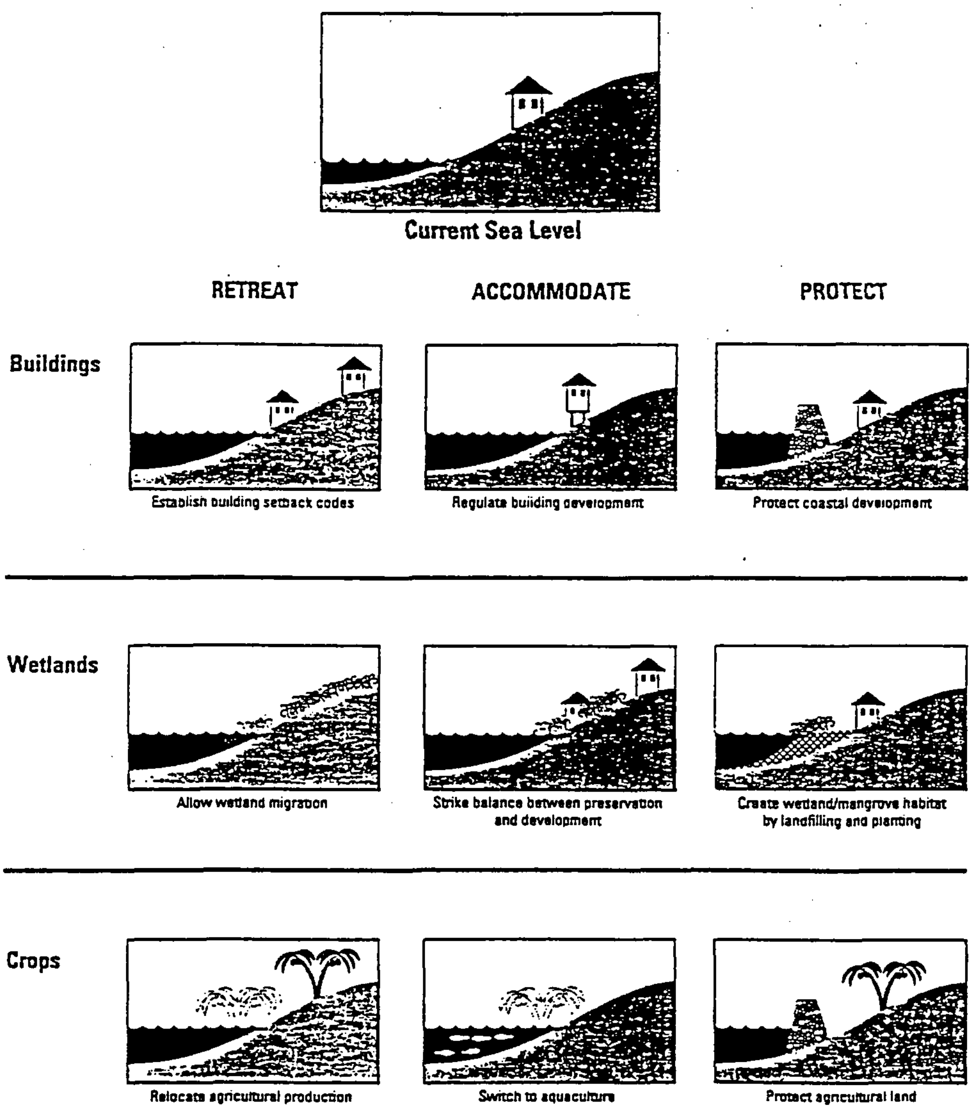

Figure 5. Future coastal zone management plans. (*Source*: IPCC/CZM, 1992.)

road and railway embankments or existing flood protection embankments may need to be raised (Brammer, 1993).

Increased flooding and a changing agricultural environment will lead to changes in human settlement. There will be an interaction between social conditions and the effects of climate change and sea level rise. Human response may vary between complete abandonment of the coastal area and adequate protection. This will create a serious problem in a densely populated country like Bangladesh. Policy could be influenced by economic considerations. The expected damage—i.e., loss of life, farmland, and infrastrucure—will influence the decisions to be made.

Socioeconomic developments are in many respects faster in the coastal zone than elsewhere because of increasing population pressure. People tend to migrate to the coastal zone because of overpopulation and lack of arable land elsewhere. About 20% of the rice acreage of Bangladesh is within the coastal zone. People settle in reclaimed vulnerable areas and exploit coastal resources. The development of infrastructure and the use of coastal resources results in rapidly increasing stress on the natural and socioeconomic systems of the coastal zone.

The people of Bangladesh already live at the margin of survival. It is not possible to retreat from the coastal area in a densely populated country such as Bangladesh. It will be a challenge for a country with an impoverished economy to cope with the changes if preventive measures are not taken for future planning and development. To cope with and to adapt to sea level rise and potential changes in climate, response strategies and methodologies should be adopted. Comprehensive management and sustainable use of resources will provide possible solutions to adapt to the short- and long-term changes.

Conclusions

Bangladesh is most vulnerable to the effects of sea level rise and other potential changes in climate because of local morphologic and hydrologic conditions. Changes in the hydrodynamics of flow due to possible sea level rise and increase in river discharge will cause significant effects on the physical system, ecology, and human interests. Low-lying coastal areas will be seriously affected, leading to shifting of agriculture, changes in settlement patterns, loss of cultivable areas, and problems with existing irrigation and drainage systems. The most serious effect would be on the agricultural economy. The morphology of rivers and coasts may also change as a result of changes in flow and the transport/deposition patterns of sediment, and changes in tidal regime. Sediment management is most important to protect the vital wetlands of Bangladesh and to prevent ecologic degradation. In addition to sediments in river water, management of resuspended sediments from bays and nearshore zones is also important.

Comprehensive management plans should provide information and possibilities for physical planning, the location of infrastructure, the development of human settlements, sustainable use, and protection of the coastal zones resources (Figure 5). Such plans can be considered as a framework for the solution of both short- and long-term problems to cope with the consequences of sea level rise and other effects of climate change.

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