Environmental and Economic Implications of Rising Sea Level and Subsiding Deltas: The Nile and Bengal Examples
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Environmental and Economic Implications of Rising Sea Level and Subsiding Deltas: The Nile and Bengal Examples

The effects of natural and accelerated subsidence, combined with a probable decreased influx of fluvial sediment, may accentuate greatly the rise of sea level in low-lying deltas over the next 100 years. By the year 2100 local sea level at the Nile and Bangladesh deltas, respectively, could be as much as 3.3 to 4.5 meters higher than at present. At the higher calculated ranges, Egypt and Bangladesh could lose 26 and 34% of their currently habitable land. The additional loss of shoreline by erosion, loss of mangrove forests, and decreased agriculture and fisheries would exacerbate environmental and economic impacts.

INTRODUCTION

Depending on the impacts of emissions of CO_2 and chlorofluorocarbons, resulting temperature changes in the atmosphere and the corresponding heat transfer to and thermal expansion of the ocean, increased precipitation, particularly the increased melt of polar ice, by the year 2100 eustatic sea level could rise as much as 2.2 meters or as little as 0.2 meters (Fig. 1A). Many models predict an accelerated sea-level rise after 2040–2050 in response to increased melting of the West Antarctic ice shelf (1, 2), perhaps as much as 2–3 cm · yr^{-1}. In the past 100 years, however, eustatic sea level probably has risen less than about 15 cm (3) and tide-gauge records show no obvious recent acceleration in sea level-rise (4, 5), even though the flux of CO_2 to the atmosphere has increased dramatically (6).

Perhaps even more important for local sea-level rise generally is the effect of subsidence or uplift within a coastal area. An area with tectonic uplift equal to the eustatic rise of sea level, for example, will experience no change in relative sea level whereas an equal rate of subsidence will result in a "doubled" sea-level rise. In low-lying deltas local subsidence can be as great as 1 to 10 cm · yr^{-1}, 10 to 100 times the present eustatic rise (Fig. 1B), and greater than even the most pessimistic predictions for future eustatic rise (Fig. 1A). These subsidence rates reflect regional and local tectonic (isostatic) effects as well as the consolidation and dewatering of the thick sedimentary sequences that underlie a delta (7).

Under natural conditions, delta subsidence is offset by deposition of fluvial sediment, particularly during flood overspill of river banks. Sediment reaching the coastal environment can accumulate in a seaward progradation of the shorefront and/or delta front. Channeling, diverting or damming the river, however, can prevent fluvial sediment from reaching the delta, and thus subsidence may not be compensated by sediment accumulation. Ultimately, the decreased flux of riverborne sediment also will result in increased shoreline erosion. Soil conservation, dam construction and the resulting 70% decrease in suspended sediment transport along the Mississippi River, for example, are cited as major reasons for the dramatic coastal degradation of coastal Louisiana in recent years (8, 9).

Decreased or diverted river flow also can lead to increased saltwater intrusion and thus decreased biological productivity in estuarine and coastal waters. Declining health of mangrove forests, many species of which require fresh or brackish water, can have particularly deleterious effects on tropical deltas (10). Mangroves not only are a source of wood and food, but they also provide the habitat and breeding grounds/nurseries for many species of fish and shellfish. In addition, mangroves can act as baffles, retaining sediment and thus retarding coastal erosion.

Removal of groundwater or hydrocarbons can accelerate greatly the rate of local subsidence by increasing the dewatering of the underlying substrata (7). A particularly stark example is Bangkok, Thailand, where a marked increase in groundwater pumping beginning in the late 1950s and the corresponding drop in the water table has resulted in local subsidence as great as 13 cm · yr^{-1} (Fig. 2).

SCENARIOS FOR LOCAL SEA-LEVEL RISE

The consequences of pronounced rises in local sea level are of particular concern for low-lying deltas served by large rivers and inhabited by large human populations (13). Two countries that serve as obvious examples are Bangladesh and Egypt. Half of Bangladesh lies at elevations less than five meters (Fig. 3), and, although occupying a much larger area, much of Egypt's habitable land is concentrated within the Nile Delta (Fig. 4). Major differences between the two areas mean that the perceived impacts may be somewhat dissimilar. For example, the Nile River is effectively dammed so that little water and no sediment presently reach the Delta. In contrast, the Ganges-Brahmaputra River is essentially unchecked, and extreme flood events are almost commonplace. Moreover, in terms of climate, the Mediterranean coast is dry whereas the Bay of Bengal is humid, resulting in the profusion of mangrove forests. Other differences will be noted in the following sections.

Given a projected rise in relative sea level, the sum of eustatic rise and local subsidence, we can define the geographic areas of each country that would be affected by shoreline retreat. Demographic and economic information can then allow us to portray the potential effects of these rises in sea level upon each nation (17).

In this paper we have used two methods for eustatic sea-level rise, a minimum case of 13 cm by 2050 and 28 cm by 2100 (1), and a maximum rise of 79 cm by 2050 and 217 cm by 2100 (2) (Fig. 1A). To these eustatic models, we have added various permutations of natural and accelerated subsidence to compute three cases of local sea-level rise:

1. The best case assumes the minimum rise of eustatic sea level, and that deposition of riverborne sediment offsets natural subsidence; in other words, the delta is approximately in equilibrium.

Figure 1 A. Most proposed rises in eustatic sea level from 1980 to 2100 (hatched pattern) fall between a low scenario (1) and a high scenario (2); for comparison, the 1885–1985 eustatic rise is shown (3).

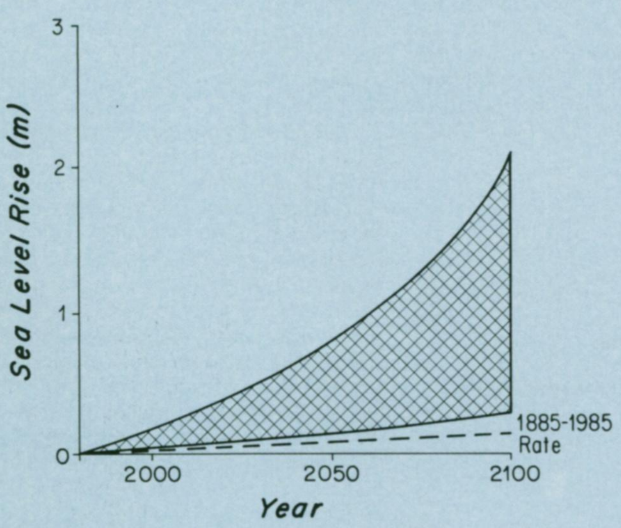
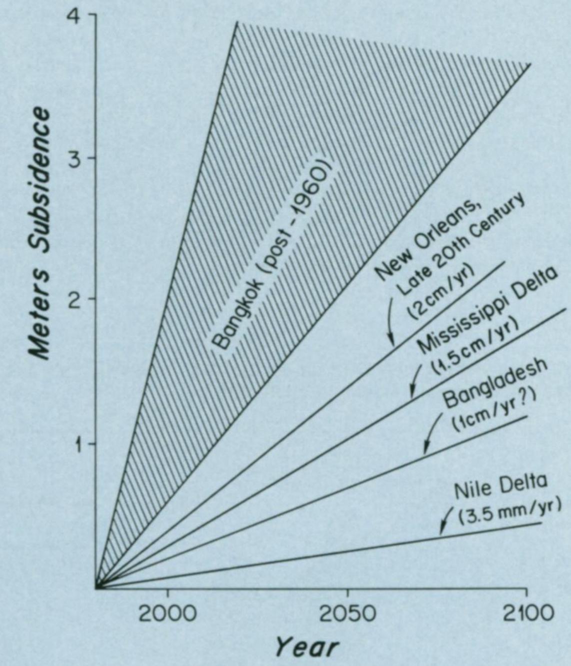


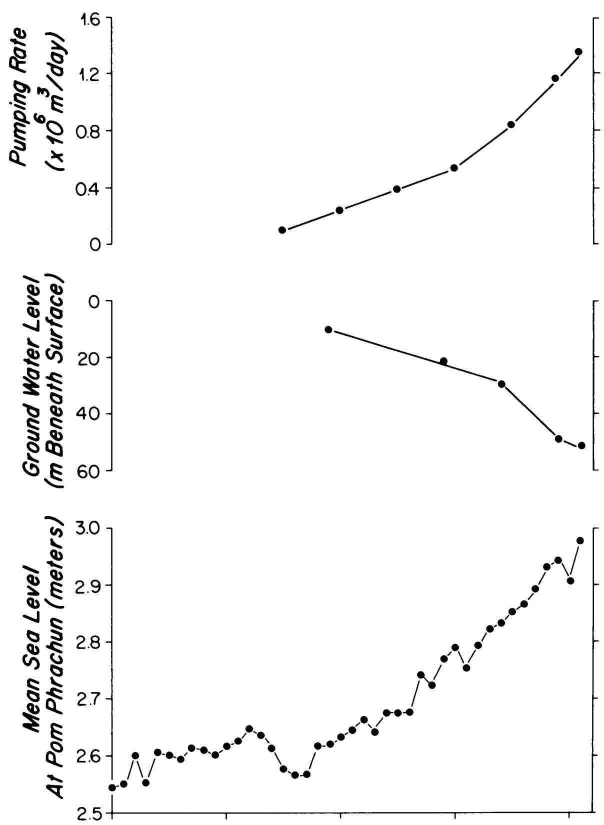
Figure 2 B. Using the same vertical and horizontal scales, local subsidence rates on deltas can be seen to be as much as 100 times greater than the present rise of sea level; all subsidences discussed in text except Mississippi and New Orleans (8, 9).



2. The worst case assumes the maximum rise of eustatic sea level and the complete damming/diversion of the river draining into the delta, thereby adding natural subsidence to relative sea level rise. For simplicity, we assume a uniform rate of subsidence across the entire delta.
3. In the really worst case, removal of groundwater in the lower delta accelerates subsidence. Again, we assume a uniform accelerated subsidence, although in fact greatest subsidence should occur in those areas with the most groundwater removal, probably urban areas. We also use the maximum projected eustatic sea-level rise.

For each country we use the scale of economic activities to characterize the economic implications of the three cases. For example, we estimate the proportion of total population that currently resides in potentially inundated areas and the proportion of gross domestic product (GDP) that currently originates in these areas. Ideally, property values would approximate the economic importance of lost lands (18), but such data were not available and perhaps not appropriate for our cases. This mechanical approach clearly does not take into account future mitigation measures or adaptive responses to relative sea-level rise, such as gradual population migration or changes in economic activities (19). On the other hand, our estimates are conservative in that they do not take into account future economic and population growth; the latter aspect is particularly important in countries with rapidly expanding populations.

Figure 2. Change in sea level between 1940–1982 at the Pom Phrachun tide gauge (near Bangkok, Thailand) compared to removal of ground water and subsequent lowering of the water table (11, 12). Note that the marked rise in sea level (i.e. subsidence) coincided with the increased pumping of ground water.

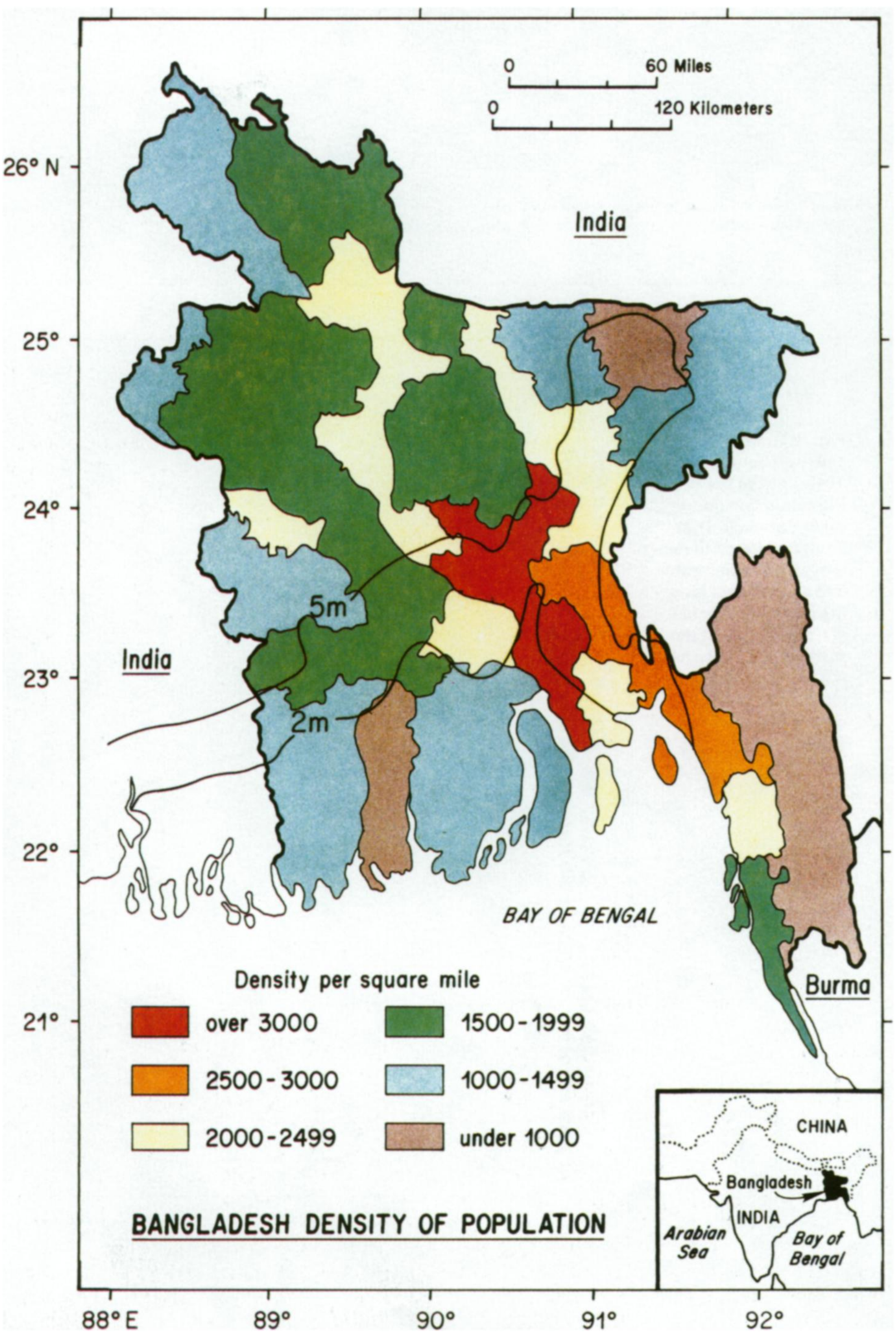


BENGAL DELTA: BANGLADESH

Bangladesh is one of the most densely populated (about 105 million people in an area of 144 thousand km^2) and economically disadvantaged (USD 160 GNP · $capita^{-1} \cdot yr^{-1}$) countries in the world, with an annual population increase of 2.6% (20, 21). The Bengal Delta, which comprises 80% of the country's land area, lies at the confluence of one of the largest river systems in the world—the Ganges, Brahmaputra and Meghna rivers (22) (Fig. 3). Combined, the river system transports an estimated 971 km^3 of water and more than 1000 million tons of sediment annually to the Bay of Bengal, of which as much as 25% might be sand-size bedload (16, 23). This latter figure represents more than 6% of the total fluvial sediment reaching the world ocean. However, only about 8% of the total drainage basin of the Ganges-Brahmaputra-Meghna system lies within Bangladesh (24, 25), the remainder lying within India, Nepal, Bhutan, Tibet, and China.

Containment and diversion of these rivers can serve economic development (e.g. increased hydroelectric power), irrigation, and flood control in Bangladesh. Although annual river flow is high, most of the flow occurs during summer monsoons (June–September), when much of the Delta is flooded. Annual floods in Bangladesh can inundate as much as 35% of the total land area of Bangladesh, a third of which can be covered by two meters or more of flood water (26). Such annual floods can damage 25 to 35% of all rice and jute under cultivation on the floodplains (20, 25). For much of the remainder of the year, however, large parts of the Bengal Delta are rain-deficient. The rationale for damming or diverting the rivers therefore is obvious, but the negative impacts of such projects could be considerable. Activation by India of the Farakka Barrage near the India-Bangladesh border in 1971, for example, diverted much of the flow of the Ganges River into the Hooghly Channel that flows south past Calcutta; the result has been decreased flow of the Ganges into Bangladesh and increased salinities in coastal streams (27).

Figure 3. Map of the Bengal Delta and Bangladesh, showing population densities and the 2 and 5 meter elevation contours.



One difficulty in estimating relative sea-level scenarios for Bangladesh is the lack of data concerning both subsidence rates and river flow. Radiometric dating of buried wood in the delta (28) suggests that subsidence rates average about 1 cm · yr^{-1}, but the data base is so poor that local rates could vary by a factor of five or more. M. Alam (29) cites stratigraphic data from a single water-well to infer a Holocene subsidence rate of 2.5 cm · yr^{-1}. If more closely correct than our assumed 1 cm · yr^{-1}, this could mean a greater subsidence effect than is concluded in this paper. Similarly, high stages of river flow are poorly documented, as is the fate of the sediment transported by the river. Interestingly, the delta does not seem to have prograded significantly in the past 200 years (27). If all the fluvial sediment had been deposited along a nonsubsiding coast, the Bengal shoreline would have prograded by many tens of kilometers. Our assumed 1 cm · yr^{-1} subsidence across the delta would accept about one-half of the annual river load, the rest presumably accumulating in the inner shelf mud wedge adjacent to the subaerial delta (30) or escaping via a nearby submarine canyon, The Swatch of No Ground, to the deep sea (31). On the other hand, if little sediment escapes the subaerial delta, the average rate of subsidence needed to accommodate the entire sediment load must be considerably greater than we have assumed, perhaps nearer the rate inferred by Alam (29).

The extent of accelerated subsidence in coastal Bangladesh from increased groundwater use is difficult to predict, but such a likelihood must be considered. By 1985, more than one hundred thousand shallow tubewells and twenty thousand deep tubewells (generally no deeper than 200 meters) had been drilled in Bangladesh, a sixfold increase from seven years earlier (20, 21). The sedimentary strata beneath the Bengal Delta suggest that accelerated subsidence related to groundwater removal may be less than that documented in other areas that have experienced accelerated subsidence (21), perhaps "only" twice the natural rate.

Taking all these factors into account, the local rise in sea level at Bangladesh by the year 2050 would be between 13 and 209 cm. The best case would result in a small loss of land (less than 1% of the nation's total). In the really worst case, however, 18% of the land would be lost, which currently supports about 15% of the nation's population and activities representing

13 % of the total GDP. By the year 2100, relative sea-level rise would be between 28 and 447 cm, with the projected land loss ranging from near zero to 34 % (Table 1). About 35 % of the nation's population (including nearly all the major population centers) and 31 % of the current GDP are associated with the area affected by the highest relative sea-level rise. If subsidence rates are higher than assumed, then the impact would be even greater.

Additional shoreline retreat could result from coastal erosion related to the demise of coastal mangrove forests, particularly the Sundarban forest in the southwestern corner of the country. This area is presently a national forest reserve, and yet no less than 30 % of the total population in the country depends to some extent on the mangrove environment for their livelihood (32). A marked decrease in freshwater discharge and concomitant reduction in the mangrove forest cover could impose a major disruption in the fisheries and local economies (32). Damming the rivers also could increase dramatically the landward intrusion of brackish water into the groundwater system; presently this intrusion is reported to extend as far as 240 km inland (24).

Tropical storms spawned by the warmer greenhouse-induced climate could have additional impact on the coast of Bangladesh. Cyclonic storms originating in the Bay of Bengal before and after the rainy season devastate the southern part of Bangladesh on a regular basis. An average of 1.5 severe cyclonic storms hit the country each year, and the associated storm surge, as much as six meters higher than normal, can reach as far as 200 km inland (33). Total property loss from storms in the region between 1945 and 1975 has been estimated at USD seven billion (34), and at least 200–300 thousand lives were lost in 1970 when surge waters covered an estimated 35 % of the area of Bangladesh. Climate warming may increase the intensity of storm surges (35), meaning that they will reach farther inland.

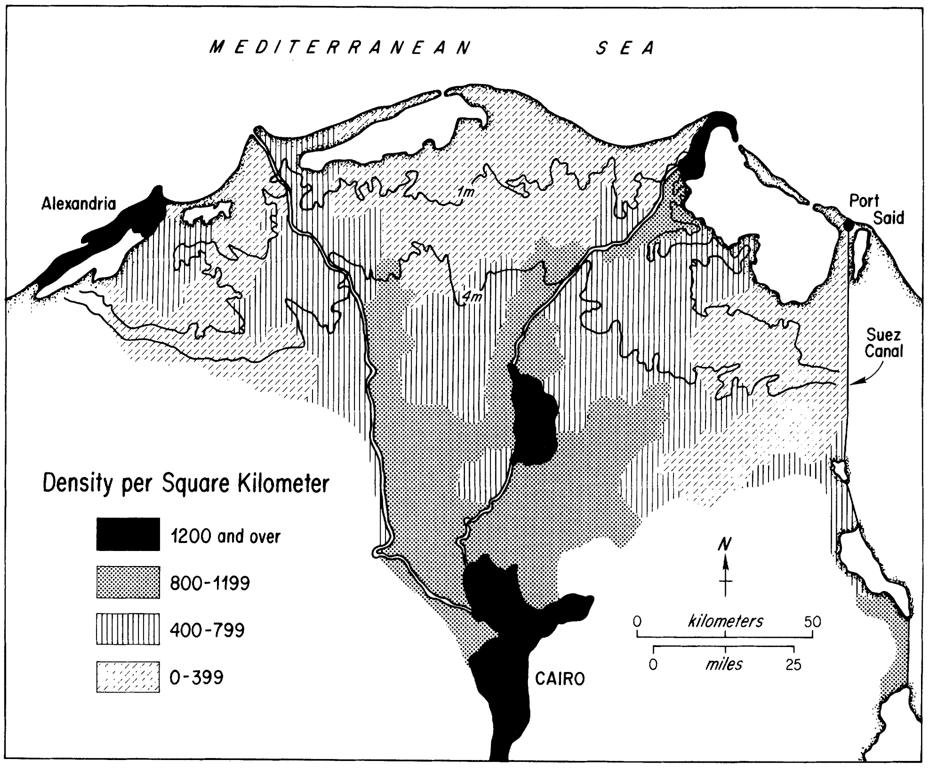


Figure 4. Map of lower Egypt and Nile Delta, showing the 1 and 4 meter elevations. Shaded patterns define various population densities. The four coastal lakes are (from left to right): Maryut, Idku, Burullus and Manzalah, respectively.

NILE DELTA: EGYPT

Only about 3.5 % of Egypt's 1.1 million km^2 are cultivated and settled. This amounts to 1800 human inhabitants for every km^2 of habitable land, almost twice the population density of Bangladesh. Nearly all the productive land lies within the Nile Delta, between Alexandria and Port Said on the coast, and along the inland path of the Nile River (Fig. 4).

The Nile River has been dammed since completion of the High Dam at Aswan in 1964, and no sediment and very little freshwater presently escape to the Mediterranean Sea. Erosion around the river mouth began in 1904, after construction of the Aswan Low Dam (14, 36). Prior to construction of the High Dam, erosion off the Rosetta and Damietta headlands was 18 to 33 m $\cdot$ yr^{-1}; afterwards it increased to 143–160 meters (14, 37). Some of the Delta shoreline is still accreting (38–40), but erosion may become more widespread after a new offshore wave base is established (41).

In contrast to Bangladesh, the Egyptian coast is lined with a near continuous band of Pleistocene aeolian dunes, mostly one to five meters in elevation, landward of which lie a series of large shallow brackish lakes—Maryut, Idku, Burullos, and Manzalah. These lakes supply approximately 50 % of the nation's fish catch (42). Theoretically, the coastal dunes could prevent rising sea level from invading the interior, but the dunes require renourishment from windblown beach sands (14), and an increasingly eroding shoreline combined with rising sea level almost certainly will result in local degradation of the dune system. Perhaps 50-cm rise in sea level could be restrained by the dunes, but higher rises would be increasingly difficult. Breaching the dune system and flooding of the brackish lakes almost certainly would have a negative impact upon local fisheries.

The lack of influx of nutrient-rich Nile waters after 1964 corresponded with a 95 % decrease in the sardine fisheries (43). The annual income loss in 1970, for example, was an estimated USD 14 million at 1970 exchange rates (37). The lack of freshwater influx to the coastal delta also has meant an increased salinization of the soils (44, 45). Increased salinization and desertification, of course, bring an increased demand for drilling shallow and deep wells for groundwater, which in turn can lead to accelerated subsidence.

As the Nile River is already dammed, a best-case scenario regarding relative sea-level rise (which assumes an undammed river) can serve only as a point of comparison. The worst and really worst cases are more realistic, and here we assume natural and accelerated rates of subsidence of 3.5 and 10 mm $\cdot$ yr^{-1}, respectively (46); this latter estimate assumes a silty texture of the underlying sediments (49). Accelerated subsidence is not unlikely given the probable increased utilization of surface waters and the corresponding need to use groundwater for agricultural, industrial and residential activities. Saltwater intrusion from rising sea level, on the other hand, might minimize the use of coastal wells and might require deeper wells to utilize fossil freshwater. Local rise in sea level, then, would range between 13 and 144 cm in the year 2050 (affecting up to 19 % of the habitable land, accounting for 16 % of Egypt's current population and GDP) and 28–332 cm in 2100 (affecting as much as 24–26 % of the habitable land, current population and GDP) (see Table) (50). We assume an additional 1 km (2050) to 2 km (2100) of shoreline loss could occur by erosion; locally, however, it could be much greater, or less.

CONCLUDING STATEMENTS

Subsidence in low-lying deltas, either natural or accelerated, can accentuate greatly the local rise in sea level. By the year 2050, subsidence at the Nile and Bengal deltas could have many times the effect of the minimum predicted rise in eustatic sea level. In fact, by 2100 accelerated subsidence on the Bengal Delta could have equalled or surpassed even the most pessimistic predicted eustatic sea-level rise (see Table). Bangladesh and Egypt probably have little control over the eustatic rise of sea level, which is controlled chiefly by atmospheric emissions from the more developed countries, but they should have considerably more control over the negative impacts of river damming or increased groundwater removal.

The environmental and economic effects of the relative sea-level scenarios discussed in the paper are sufficiently grave to warrant their consideration in future coastal and fluvial planning, not only in Egypt and Bangladesh, but also in other areas with low-lying deltas and large rivers. Most such areas occur in southern Asia, which contributes more than 70% of the fluvial sediment reaching the ocean (16). Recent economic development in southern Asia has initiated increased consideration of large-scale river development projects, but the necessary data concerning rivers, nearshore processes and geology are generally lacking. Clearly, there are tradeoffs involved that justify a careful balancing of long-term costs and benefits. Flood control might mean that sediment will be trapped upstream behind dams or will by-pass the subsiding floodplains and be transported to the coastal zone. Similarly, increased drilling for sanitary drinking water may risk accelerated delta subsidence, thereby offsetting somewhat the more immediate gains to public well-being from the relief of thirst or poor sanitary conditions. Saving crops and lives on the short-term basis therefore may lead to a long-term loss of land (and, at least indirectly, lives). Moreover, this loss of land will magnify itself by forcing coastal populations farther inland, where they will increase the competition for diminished space with existing farms, industries and sites of permanent habitation (51).

Although many problems are perceived, no clear and noncontroversial answers are apparent. Environmental parameters, however, should be documented prior to diversion and damming of rivers or increased groundwater removal. What are the annual water and sediment discharges of the river(s); where is the sediment deposited; and how much riverborne sediment escapes to the coastal area? What are local rates of subsidence and how would increased groundwater/petroleum removal affect these rates? What are the ecological and economic benefits of coastal mangrove forests, and what would be the consequences of their decline?

For example, although we have assumed subsidence rates of 5 and 10 mm for the Nile and Bengal deltas, respectively, these numbers are only assumed averages; locally the rates may be far less or far greater. To obtain actual short-term subsidence rates, for instance, would require areal measurements involving satellite-based geodesy. An annual subsidence rate in Dhaka of 0, 2.5 or 25 mm $\cdot$ yr^{-1} would require far different policy and engineering decisions for minimizing environmental and economic impacts.

The answers to these questions need not imply that proposed river projects should be cancelled, for the economic advantages of the projects might outweigh any negative effects on the coast; such arguments are commonly heard in Egypt regarding the High Dam at Aswan. Rather, the answers may offer viable alternatives regarding engineering decisions. How can river flow be controlled; can sluice gates on the dams allow sufficient passage of the fluvial sediment; can certain areas with high rates of subsidence be preferentially flooded so that sediment accumulation can offset the subsidence? From environmental considerations alone, the question may not be if a diversion project (for example) should be undertaken, but rather how it should be done (52).

Table. Predicted conditions in the Nile and Bengal Deltas in 2050 and 2100. Best case scenario assumes minimal rise in sea level; natural subsidence is offset by river/deltaic sedimentation. Worst case assumes maximal rise in sea level and uncompensated natural subsidence, as the river (Nile/Ganges-Brahmaputra) is completely dammed. The really worst assumes the worst case and also assumes enhanced subsidence due to groundwater/petroleum withdrawal.

EGYPT

	2050			2100		
	Best case (Natural subsidence, natural river flow)	Worst case (Natural subsidence, dammed rivers)	Really worst case (Accl. subsidence, dammed rivers)	Best case (Natural subsidence, natural river flow)	Worst case (Natural subsidence, dammed rivers)	Really worst case (Accl. subsidence dammed rivers)
Total sea level rise	13 cm	101 cm	144 cm	28 cm	257 cm	332 cm
World-wide	13 cm	(79)	(79)	(28)	(217)	(217)
Local subsidence	(0)	(22)	(65)	(0)	(40)	(115)
Shoreline erosion	0 km	1 km	1 km	0 km	2 km	2 km
% Loss habitable land	NA	15	19	NA	21.5	26
% Population displaced	NA	14	16	NA	19	24
% GDP*	NA	14	16.5	NA	19	24

* % Gross Domestic Product in Affected Area

BANGLADESH

	2050			2100		
	Best case (Natural subsidence, natural river flow)	Worst case (Natural subsidence, dammed rivers)	Really worst case (Accl. subsidence, dammed rivers)	Best case (Natural subsidence, natural river flow)	Worst case (Natural subsidence, dammed rivers)	Really worst case (Accl. subsidence dammed rivers)
Total sea level rise	13 cm	144 cm	209 cm	28 cm	332 cm	447 cm
World-wide	13 cm	(79)	(79)	(28)	(217)	(217)
Local subsidence	(0)	(65)	(130)	(0)	(115)	(230)
Shoreline erosion	0 km	1 km	1.5 km	0 km	2 km	3 km
% Loss habitable land	NA	16	18	NA	26	34
% Population displaced	NA	13	15	NA	27	35
% GDP*	NA	10	13	NA	22	31

* % Gross Domestic Product in Affected Area

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13. Sediment load of the lower Nile, for example, decreased from 120 million tons annually to essentially zero with the construction of the Aswan Dam in 1964/65 (14). The Indus River sediment load decreased by 80% with construction of barrages along the river in the late 1940's (15), and the sediment load of the Mississippi River has decreased by more than 50% since the 1920's, a result of upstream soil conservation, construction of dams and the natural diversion of part of the river flow into the Atchafalaya River (8, 9, 16).
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