PAPER

SEA LEVEL RISE — POSSIBLE IMPACTS ON THE INDUS DELTA PAKISTAN

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ACKNOWLEDGEMENTS

The Korangi Issues Papers are a series of occasional publications aimed at highlighting particular topics related to the Indus delta mangrove ecosystem and its sustainable use. In many cases, insufficient information is available to deal with the issues completely, and the papers may raise more questions than they answer. However their overall purpose is to increase awareness of these issues and to open an informed debate on them.

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SEA LEVEL RISE - POSSIBLE IMPACTS ON THE INDUS DELTA, PAKISTAN

by

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ABSTRACT

The mangrove ecosystem in the Indus Delta contributes significantly to the coastal economy of Sindh Province, Pakistan. Various factors, particularly the reduction of flows of freshwater, silt and nutrients down the Indus and the rise in mean sea level are combining with direct human pressures, such as fuelwood and fodder collection, to threaten this ecosystem. Global warming and the resulting sea level rises need careful consideration for conservation measures to be taken. The local rate of sea level rise of 1.1 mm/yr over the last 100 years is lower than the present eustatic sea level rise of about 2.0 mm/yr and considerably lower than predicted "business as usual" rates of 6.0 mm/yr. Several processes will be affected by sea level rise - the balance between delta erosion and sedimentation, the increase in the tidal range and salt water intrusion. With deeper coastal waters erosion will predominate and the delta will tend to flatten and lose its digitate character. Reduced flows down the Indus due to further upstream abstraction will mean that less silt is available to build up the soils in which the mangroves are growing; the raising of substrate levels will not be able to keep pace with rapidly rising sea levels. However, initial rises in the sea level will inundate some of the slightly higher-lying mangrove areas more regularly, thereby promoting their growth. It is predicted that for sea level rise up to 2.0 mm/yr, the balance will favour mangrove survival and growth. Above this rate the balance will be shifted towards progressive loss of mangrove areas. Implications for mangrove management include replanting with longer propagule species such as *Rhizophora marina* and encouraging *Avicennia mucronata* colonisation on the higher-lying areas, similar to existing zonation observable in mangrove areas on the Baluchistan coast.

1. INTRODUCTION

The mangrove ecosystem within the Indus Delta in Pakistan, which extends from Karachi to the Indian border, contributes significantly to the coastal economy. Besides protecting the Sindh coast from the full force of south-west monsoon winds and waves, the mangroves provide natural nursery grounds for coastal fisheries and an important habitat for resident and migratory birds. They are a source of fuelwood for coastal populations, fodder for their animals, and browsing for their camels. Given the economic significance of this ecosystem, its progressive degradation through both natural and man-induced stresses has received concerned attention over the last decade.

The sustainable management of the mangrove ecosystem is the focus of IUCN's Korangi Ecosystem Project, which aims to develop a management plan for the Korangi-Phitti creeks as a model for the delta as a whole. A full description of the project is given in the third Korangi Issues paper (IUCN 1992). The project is looking at various factors which include:

- Substantial reduction in river discharge and sediment load in the delta region due to human activities such as the construction of dams, barrages, flood control system and so on;
- Substantial increase in pore water salinities in the mangrove habitats and vastly decreased diversity of mangrove species;
- Eustatic (worldwide) sea level rise.

The first stress has been looked at by Meynell (1991) who recently studied the possible consequences of reduced freshwater flows down the Indus. Pore water salinities in the mangrove habitats and its influence on the ecophysiology of mangroves are being investigated by a team of scientists from the US and the Pakistan National Institute of Oceanography, under a cooperative project supported by the US National Science Foundation (Ahmed, 1991). This Issues Paper focuses on the increased rates of sea level rise which may result from global warming, and the progressive, and possibly irreversible impact this will have on the Indus Delta ecosystems.

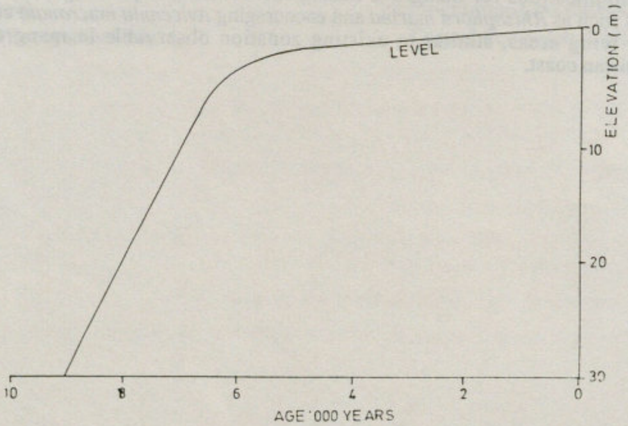


Fig. 1. Holocene Sea Level Changes

2. THE REALITY OF SEA LEVEL RISE

The last glacial period reached a peak between 24,000 to 18,000 years ago. As the ice sheets started retreating 10,000 years ago, worldwide sea levels rose by 40 metres to reach modern sea levels around 5000 - 6000 years ago, giving a mean sea level rise of approximately 8 mm/yr (Fig.1). This figure has been worked out from Holocene strandlines, prehistoric high-tide marks, which indicate the relative sea levels (Lajoie, 1986). The observed sea level results from the real vertical movement of the sea surface relative to the movement of the land itself caused by tectonic changes, uplift or subsidence.

At present the estimated eustatic sea level rise is about 2 mm/yr (Hicks and Crosby, 1974; Lajoie, 1986). The term "eustatic" refers to real, worldwide changes in sea level. Short term sea level change, however, is difficult to measure as different techniques e.g. geodetic and tidal-gauge, yield dissimilar results (Brown, 1978). Deviations have been noted, and in some areas a period of erosion may be followed by years of accretion. For example, conditions of both sea regression and transgression prevail at Juneau, Alaska and in the Mississippi delta (Fig. 2).

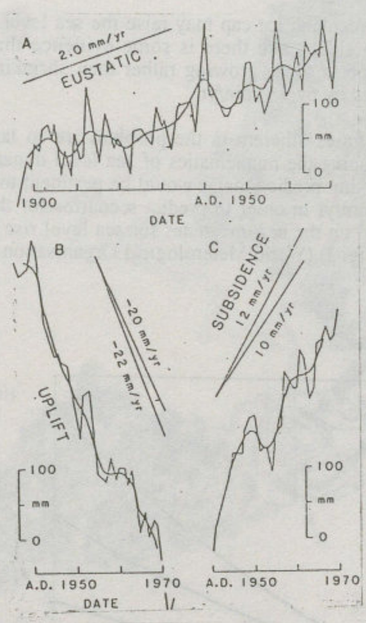


Fig. 2. Tide-gauge records

A. San Francisco, California - the secular drift of this record (-2 mm/yr) is similar to that found in other parts of the world and, therefore, probably represents eustatic rise in sea level.

B. Juneau, Alaska—the extreme apparent drop in sea-level represents crustal uplift due to either tectonic uplift or residual glacio-eustatic rebound.

C. Mississippi Delta—the apparent rise in sea-level represents subsidence due to sediment compaction and isostatic adjustments of the crust to the sediment load of the Mississippi delta. The eustatic rise (2 mm/yr) was subtracted from the relative rates to obtain the uplift and subsidence rates. Modified from Hicks and Crosby (1974).

During the last decade the increased rate of sea level rise has emerged as an alarming consequence of global warming. In this paper we do not question whether global warming is occurring, but consider what the different scenarios might be if this phenomenon is taking place.

Global warming causes the sea to rise in two ways. The first is through thermal expansion of ocean waters, the second through the melting of glaciers and ice caps, adding to the total volume of water in the oceans.

Considering these factors various figures ranging from 2 to 11 mm/yr for eustatic sea level rise have been put forward; over the next 100 years, this means an increase between 20 and 110 cm. A seemingly sensible scenario for the year 2050 envisages a total rise of 44 cm in sea level, at 7.3 mm/yr, based on certain parameters.

- An increase of 3^{o} to $5^{o}C$ in global temperature will result in a rise of 10 to 30 cm in sea level, as a result of thermal expansion of the oceans. There seems to be a consensus that "there is little scope for argument" on this (Ince, 1990).
- The melting of small glaciers and ice caps will contribute 6 cm to sea level rise.
- The melting of the Greenland ice cap may raise the sea level by about 8 cm. This figure is on the high side, since there is some evidence that the Antarctica and Greenland glaciers appear to be growing rather than shrinking. If this is true, sea level would be lowered by over 1 mm/yr.

The inaccuracies and uncertainties inherent in the problem are so large that there is little justification in rigorously pursuing the mathematics of sea level dynamics (Ince, 1990). In view of the complexity of making predictions, it would be pertinent to use eustatic sea level increases of 2 mm/yr and 6 mm/yr in order to predict scenarios for the Indus Delta 50 and 100 years hence. This is based on the best estimates for sea level rise assuming 'business as usual' worldwide emissions (Fig. 3) (World Meterological Organisation, 1990).

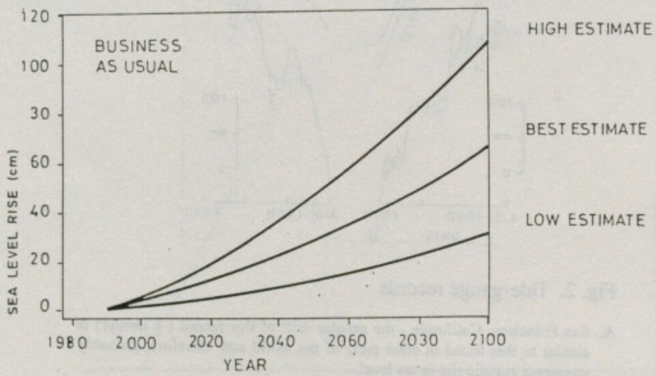


Fig. 3. Sea Level Rise predicted to result from business as usual emissions

Source : World Meteorological Organisation

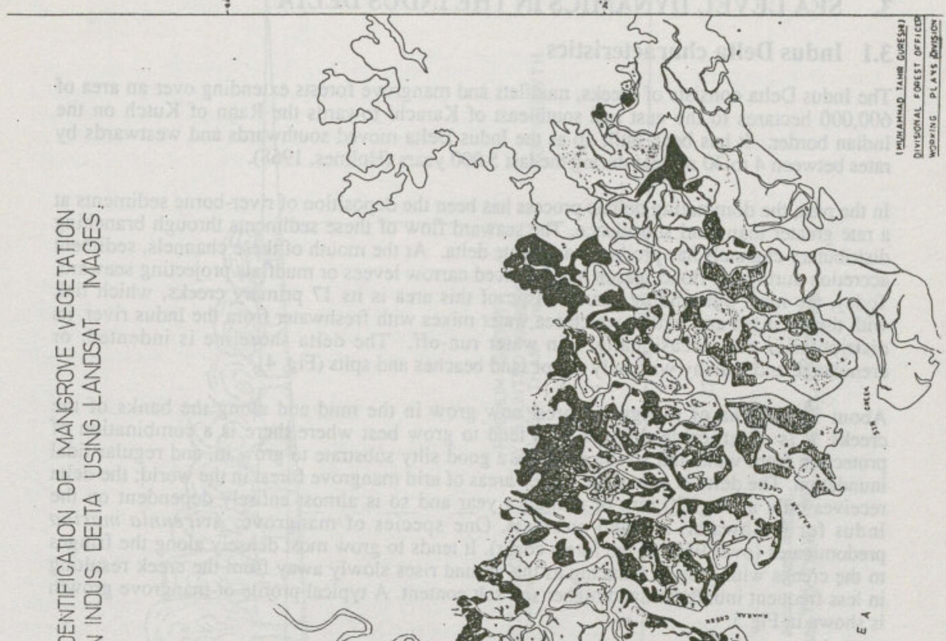


Fig. 4. Map of Mangrove Vegetation in the Indus Delta interpreted from 1977 LANDSAT imagery.

3. SEA LEVEL DYNAMICS IN THE INDUS DELTA

3.1 Indus Delta characteristics

The Indus Delta consists of creeks, mudflats and mangrove forests extending over an area of 600,000 hectares to the east and south-east of Karachi towards the Rann of Kutch on the Indian border. It has been built up as the Indus Delta moved southwards and westwards by rates between 4 to 30 m/year during the last 5,000 years (Holmes, 1968).

In the past, the dominating deltaic process has been the deposition of river-borne sediments at a rate greater than land subsidence. The seaward flow of these sediments through branching distributary channels has produced a digitate delta. At the mouth of these channels, sediment accretion during the flood season has produced narrow levees or mudflats projecting seaward. Today, the most outstanding characteristic of this area is its 17 primary creeks, which link with the open sea and within which sea water mixes with freshwater from the Indus river, its distributaries and occasionally, rain water run-off. The delta shoreline is indented, or crenulated, and marshy with only minor sand beaches and spits (Fig. 4).

About 160,000 ha of mangrove forest now grow in the mud and along the banks of the creeks. It is observeable that the trees tend to grow best where there is a combination of protection from wind and strong currents, a good silty substrate to grow in, and regular tidal inundation. The delta is one of the largest areas of arid mangrove forest in the world; the delta receives only about 220 mm of rainfall a year and so is almost entirely dependent on the Indus for freshwater, silt and nutrients. One species of mangrove, *Avicennia marina* predominates (over 95% of the forest cover). It tends to grow most densely along the fringes to the creeks with growth reducing as the ground rises slowly away from the creek resulting in less frequent inundation and higher soil salt content. A typical profile of mangrove growth is shown in Fig.5.

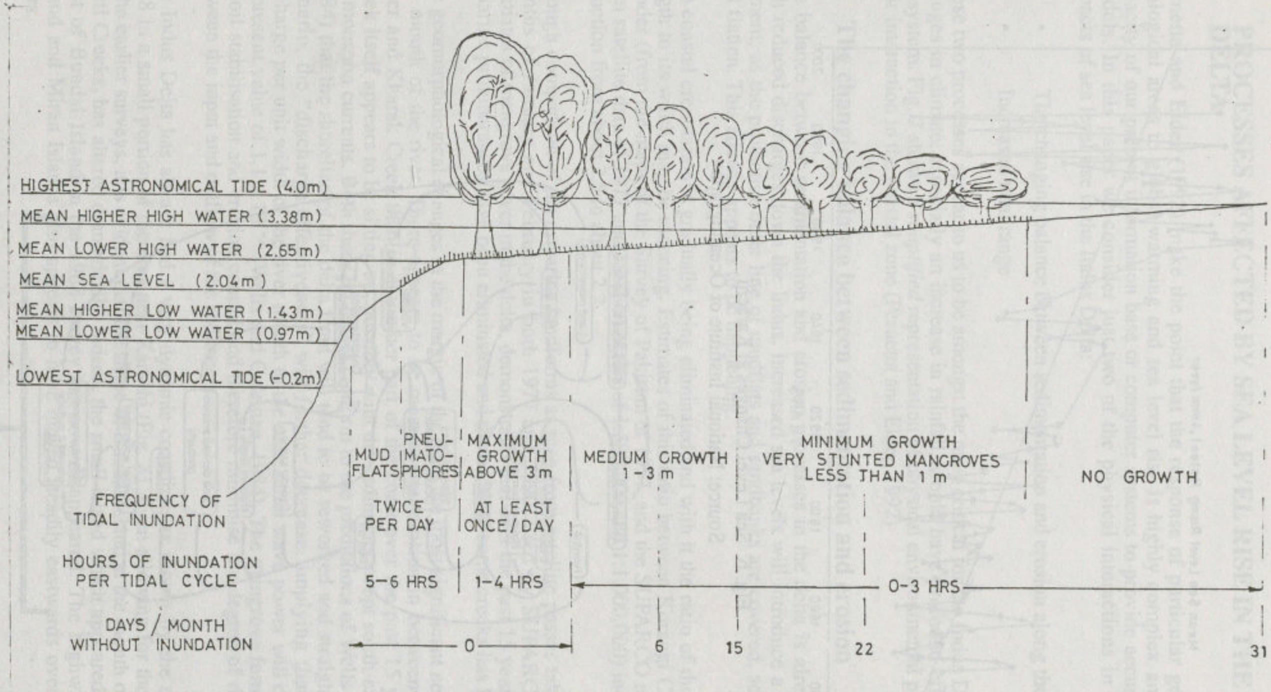
It is also observable that in areas subject to erosion, e.g. on the inside bends of creeks, and on raised areas which are not regularly inundated, growth is more stunted. The mangrove trees on the inside bends appear to be stressed by higher currents which tend to remove nutrients and substrate, while those mangroves on higher-lying areas are limited by excessive soil salinity caused by evaporation of sea water. Pore water salinities of up to 70-80 ppt have been observed by Ahmed and his co-workers (Ahmed 1991).

3.2 Reduction in flows of the Indus

More and more evidence is being cited (Schubel 1984, Wells & Coleman 1984, Meynell 1991) which suggests that the delta regime is retrogressing due to the drastic reduction in river-borne sediments and drying up of the Indus distributaries over the past 50 years. The total outflow of the Indus used to be about 150 million acre feet (MAF) per year (181 billion cu.m.) (Meynell 1991); with the construction of dams and irrigation channels, the flow presently reaching the delta is estimated to be about 20 MAF (25 billion cu.m.) This figure is expected to be further reduced to a minimum of 10 MAF (12.5 billion cu.m) as additional upstream water use is allowed. Similarly silt discharge has reduced from 400 million tonnes per year to 100 million tonnes per year (Wells and Coleman 1984). This may be further reduced to 30 million tonnes per year.

3.3 Sea level changes in the Karachi area

From the Karachi tide-gauge records of the past 100 years a rate of 1.1 mm/yr rise in the local sea level has been estimated (Fig.6). The gradient of this rise remains more or less the same when the data is analysed in 30 year segments, even for the most recent period (1960 - 1990), although during recent years there seems to be much greater variation in the mean sea level. The observed change in sea level is virtually equal to the real one, since the Indus Delta is on a passive continental margin and isostatically stable. This rate of change is lower than the present mean sea level rise worldwide.



Note:- Heights of tides are shown as above chart datum.
Tidal information from Pakistan Tide Tables 1991. Using Dec. 1991 figures.

Fig. 5. Schematic Profile of Fringing Mangroves in Indus Delta creeks.

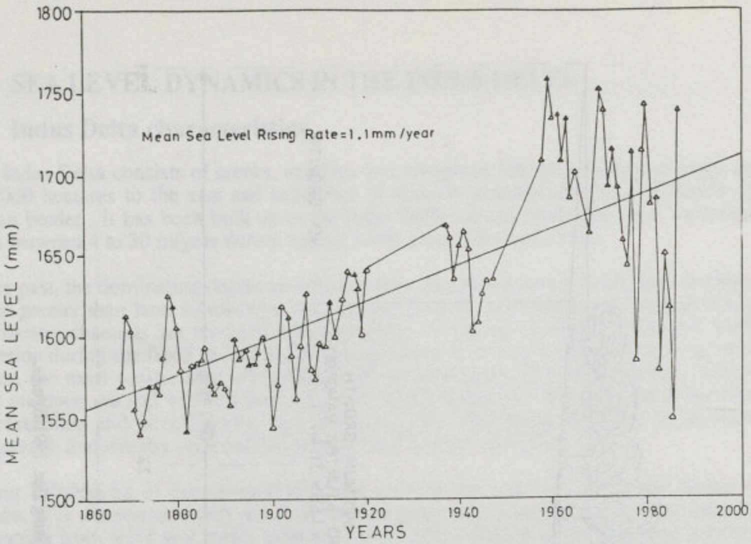


Fig. 6. Sea Level Changes at Karachi
Source: National Institute of Oceanography

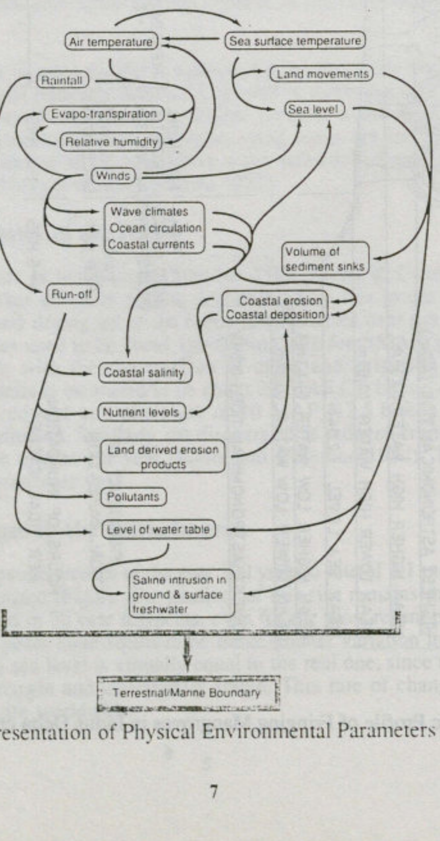


Fig. 7. Simplified Representation of Physical Environmental Parameters and the Interactions in Coastal Zone.

4. PROCESSES AFFECTED BY SEA LEVEL RISE IN THE INDUS DELTA

Pernetta and Elder (1992) make the point that the response of particular geographic and ecological areas to global warming and sea level rise is highly complex and beyond the capacity of our present information base or computer systems to provide accurate predictive models. In this paper we consider just two of the physical interactions in assessing the impacts of sea level rise in the Indus Delta:

- The changing balance between sedimentation and erosion along the coastline
- Increased tidal range

These two processes appear to us to be amongst the most critical for the Indus Delta, although changes in climate, especially an increase in rainfall, would have profound effects upon the ecosystem. Fig. 7 shows a *simplified* representation of physical environmental parameters and their interaction in the coastal zone (Pernetta and Elder, 1992)

4.1 The changing balance between sedimentation and erosion

The balance between sedimentation and erosion processes in the delta is already changing with reduced discharges down the Indus. Increased sea levels will introduce a new dynamic element; as the protective outer line of mudflats and sandbanks are covered, so the coastline will flatten. This already appears to be happening.

The coastal crenulation is gradually being eliminated and with it the ratio of the delta margin length to its width may be reducing. Estimates of this ratio between Korangi Creek and Keti Bunder (from the maps of the Survey of Pakistan of 1957, and the SUPARCO maps prepared from satellite data of 1977 and 1990 on scales of 1:500,000 and 1:1,000,000) indicate a slight reduction from about 2.5 to about 2.2.

A rough comparison of the estuarine landforms as seen from satellite passes taken during the months of January and February in both 1977 and 1990, used by SUPARCO to prepare estimates of mangrove cover in the delta, demonstrates that over the past 15 years some of the estuarine protuberances have been eliminated and the width of some creeks has been altered.

The geomorphological changes in the margin of the delta are most significant near the present day mouth of the river. There appears to be more coastal erosion in between the Turshian River and Kharak Creek than in any other part of the coast over the past 15 years; Kharak Creek itself appears to be silting up, possibly with the sediments swept south-eastwards with the monsoon currents. Both these processes conform to the predictions of Wells and Coleman (1984) that the shoreline of the delta front will tend to be reworked and straightened. In this scenario, the "discharge effectiveness" will further decrease, implying that the ratio of discharge per unit width of the river mouth to the near shore wave power will diminish from its present value of 1.1×10^{-2} (Wells and Coleman, 1984). The mangrove forests contribute to soil stabilisation and erosion control and therefore minimise the degree of disequilibrium between the input and outflow of the sediments.

The Indus Delta has always had a very dynamic coastline, as shown by the changes since 1848 in a small portion of the area near Karachi (Fig. 8). Even allowing for the inaccuracies of the earlier surveys, it is evident that the shape of Bundal Island at the mouth of the Korangi Phitti Creeks, has altered dramatically. Indeed, the small island which appeared to the south-west of Bundal Island in the 1968 survey has now disappeared. The highwater mark on Khand and Miran Islands also appears to have moved steadily eastwards over the last 150 years.

It is difficult to separate out the effects of reduced flows down the Indus and sea level rise, but if both trends persist as predicted, the net result over the next few decades will be

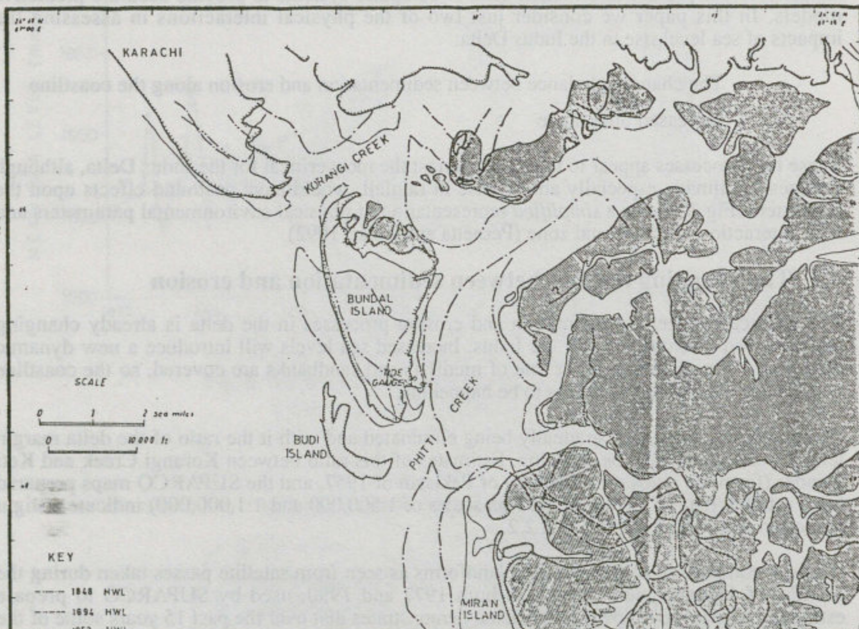


FIG. 8 — EXAMPLES OF REGRESSIVE COAST—LINE NEAR KARACHI 1848—1958
SOURCE :— PORT GASIM AUTHORITY

Fig. 8. Example of changes in the regressive coast line near Karachi since 1848 — 1968.

Source: Port Qasim Authority

cessation of deltaic processes and domination of wave erosion on a coast which already receives the full force of the south-west monsoon. This scenario will be characterised by degradation of the estuarine regime, loss of subaerial and subaqueous delta, and loss of marshy land and vegetation including mangrove forests.

With less silt being introduced into the system from the river, any sedimentation that does occur will either have to come from the mangroves themselves or from marine sources. Sediments from marine sources will tend to be more sandy. Increased proportions of sand in the muds will make the substrate harder and less suitable for mangrove growth. This process is already noticeable in areas where mangroves were clear felled by the Port Qasim Authority some years ago and where the mud has been replaced by a higher, more sandy substrate. These areas will become more difficult for mangrove recolonisation, particularly when less regularly inundated.

The changes in mangrove cover appear to be quite dramatic, although some of the differences between 1977 and 1990 can be attributed to varied interpretation of the satellite images. The 1977 images were the first attempt at visual interpretation using Landsat with a resolution of 80 metres; by contrast the 1990 image used SPOT with a resolution of 20 metres. The greatest losses of mangroves appear to have taken place near the present mouth of the Indus, but it is difficult to quantify the extent to which they have been lost because of these differences in interpretation. Even the 1990 figures (worked out on a scale of 1:250,000) are probably an overestimate, as more detailed studies on 1:50,000 enlargements of the northern part of the delta show lower coverage than the 1:250,000 interpretation. The obvious losses in mangrove cover in the active delta are probably due to a combination of human cutting and changes in the river regime.

Table 1. Differences in mangrove cover estimated from satellite interpretation in 1977 and 1990.

Type of coverage	1977 ha.	1990 ha.
Dense mangroves	52,600	68,100
Medium cover mangroves	not recorded	58,500
Normal mangroves	210,500	not recorded
Sparse cover mangroves	not recorded	31,900
Total mangrove areas	263,100	158,500
% mangrove cover	43.3%	23.8%
Sparse/no vegetation/mudflats	137,600	382,700
Sand	44,500	29,300
Creek areas	162,000	94,508
Salt pans	not recorded	1,100
TOTAL	607,200	666,100

Differences in creek size, mudflats and sand can be explained by the tidal state - the 1990 image being taken at low tide, compared to the higher tide for the 1977 image, which would enlarge the creek cover and reduce the mudflat areas considerably. Figure 9 shows the coverage of mangroves according to the 1990 interpretation.

4.2 Changes in the tidal range

The profile of mangroves fringing the creeks shows that the strongest growth occurs where the roots are inundated regularly for 2-3 hours in each tidal cycle. As the sea level rises so will the duration of inundation until the roots become permanently inundated. Well-established mangroves may be able to survive under these conditions provided that the depths

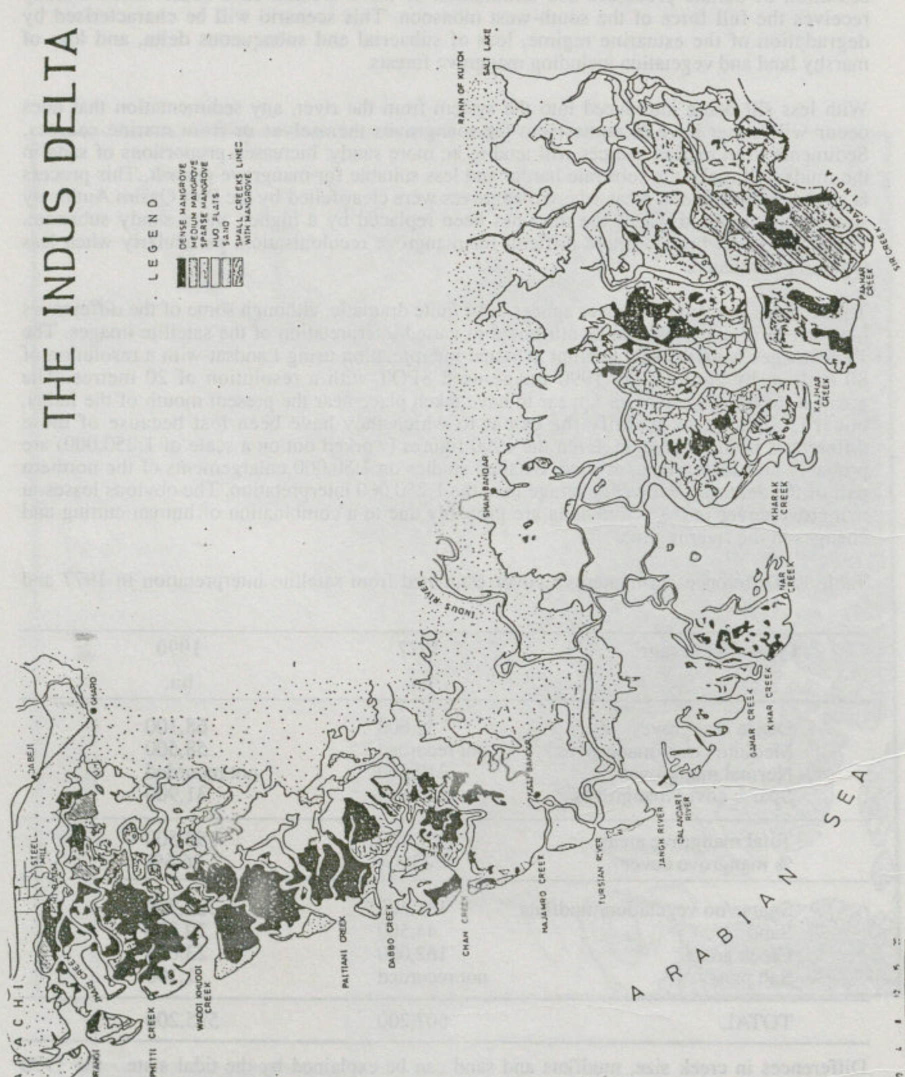


Fig. 9. Mangrove Cover in the Indus Delta interpreted from 1990 SPOT imagery.

of permanent water are not too deep (a few centimetres) and metabolic gas exchange is not restricted (Snedaker, 1990, quoting Lahmann, 1988). However, new seedlings would not become established and so, after a period of several decades, the inundated mangroves would die out.

In order to survive rises in sea level, mangroves have to raise the level of the substrate in which they are growing at an equivalent rate. They maintain the substrate in which they live by allowing silt in the water to deposit around the root structures. The mainly inorganic fraction of the silt generally comes from outside the mangrove ecosystem i.e. the allocthonous sediment from the river, whilst the mainly organic fraction results from the breakdown of leaves and other plant and animal material inside the ecosystem.

In a very generalised tenor, Ellison (1989) has commented that "without significant allocthonous sediment input, mangrove ecosystems can keep up with a rising sea level of 8 cm/100 years and are under stress at rates between 8 and 12 cm/100 years". Where there is more sediment being derived from the land, mangrove ecosystems are better able to keep pace with sea level rises of up to 25 cm/100 years.

The previous rise in sea level of 11 cm over the last 100 years is well within these limits for an ecosystem which received silt from the Indus. With the reduction of this silt discharge, the capacity of the mangroves to maintain themselves over such a wide area as the Indus Delta may now be severely restricted. It is possible that apart from some areas in the immediate vicinity of the one remaining mouth of the Indus, the present ecosystem does not receive significant allocthonous discharge. These areas would therefore be under stress even if the previous relatively low rate of sea level rise (1.1 mm/yr) is maintained.

If the mangroves are to survive sea level rise, they will need to colonise new areas which will become more regularly inundated. The first such areas are those below the maximum high water mark which at present may be inundated only once or twice a month. These sometimes contain stunted mangroves and other halophytic grasses. With greater regularity of tidal inundation the younger stunted mangroves will grow more profusely and the possibilities for colonistion will be enhanced. The extent of such areas within the Indus Delta has not been estimated, since ground levels of the delta region have not been measured.

As the level of maximum high tide increases, so the areas open to mangrove colonisation will increase. However, the soils may not be immediately suitable for mangroves to establish themselves, for without silt from the river, they will tend to be sandy. This has implications for management measures to encourage colonisation as the sea level rises.

Around Shah Bundar in the most southern part of the Indus Delta, the combined impact of reduced freshwater and silt flow and of sea levels increasing may be already noticeable. In this area land, which was used for red rice production during the flood season, now forms part of the inter-tidal zone. Indeed the plots used by Sindh Forest Department to establish plantations of *Rhizophora mucronata* have been used for red rice cultivation within living memory. In addition the villagers of Shah Bundar are now unable to walk to Ibrahim Shah some hours away across the delta without crossing recently formed tidal creeks.

It is possible that sea level rise may force differential survival and establishment of particular types of mangrove, especially those species with large propagules, e.g. *Rhizophora spp.* (Snedaker, 1990). The larger propagule species are able to become established in significantly deeper water than the smaller propagule species such as *Avicennia spp.* According to Snedaker's prediction, as the sea level rises the habitats currently occupied by *Avicennia spp.* may be taken over by *Rhizophora spp.,* whilst the *Avicennia spp.* will remain dominant in the newly inundated tidal areas. In this context the management strategy adopted by IUCN and the Sindh Forestry Department of inter-planting *Rhizophora mucronata* in blank areas between stands of *Avicennia marina* is sound. *Rhizophora mucronata* had virtually died out in the Indus Delta due to a combination of preferential overcutting for fuelwood and high salinities. The new plantations use propagules taken from the Makran Coast where the *Rhizophora spp.* is considered to be of a more salt tolerant strain because they receive no riverine freshwater and only occasional rainfall. Once established these plantations will provide a supply of propagules for further reforestation in years to come.

The zonation and differential survival of particular types of mangroves has been the subject of much controversy over the years with theories of the succession ranging from physiological adaptation, effects of geomorphological conditions, propagule size and differential predation by crabs (See Snedaker 1982 for a full discussion). The classical zonation for New World mangroves of *Rhizophora spp., Avicennia spp.* and *Laguncularia spp.* is not generally found in South and South East Asia, although in Sonmiani on the Makran Coast of Baluchistan a similar pattern of zonation is observed naturally, with *Rhizophora mucronata* on the front of the creeks followed by *Avicennia marina* followed by *Ceriops tagal* towards the landward side (Tahir Qureshi, personal communication).

The exact reasons for particular zonations are probably due to a combination of all these factors with different emphases according to the situation. If sea levels continue to rise without corresponding deposition of silt to raise ground levels, then Snedaker's theory that larger propagule species are able to become established in significantly deeper water may take on greater importance.

However, it should be emphasised that the disruption of 'established' intertidal vegetation, its relocation and retreat towards land when a greater part of the intertidal zone becomes permanently inundated is a complex process. The process is modified by the interaction of a number of geological and oceanographic factors which include the deposition of silt, the freshwater runoff and rainfall.

5. SCENARIO PREDICTIONS

If we consider three scenarios - the existing rate of 1.1 mm/yr, 2 mm/yr and 6 mm/yr - for the rate of sea level rise, this will entail the following rises over the next 50 and 100 years.

Rate of rise	After 50 yrs	After 100 yrs
1.1 mm/yr	5.5 cm	11 cm
2.0 mm/yr	10 cm	20 cm
6.0 mm/yr	30 cm	60 cm

5.1 Impacts upon the mangrove areas

The first scenario assumes that the sea level will continue to rise at the present rate. This is slow enough for most mangroves with some discharge of silt from the river to build up the soils at a similar rate. It is probable that the ecosystem would survive in much the present state assuming that there are no further reductions in the flow of freshwater and silt down the Indus. If there are further reductions, the forces of erosion and sedimentation would readjust to a new balance point depending on the final flow.

An 11 cm rise in 100 years would not inundate any mangroves permanently, and the effect upon the higher-lying areas would be minimal; not many new areas would be opened up for colonisation.

A similar situation would arise after 50 years at a Mean Sea Level (MSL) rise rate of 2.0 mm/yr. Initially a slow and steady rise of sea level will not make any perceptible impact on the Indus Delta and mangrove habitats over the next fifty years. A total rise of 10 cms after 50 years may effect the outermost fringe of the islands which do not support any mangrove growth. On coastal islands on which mangroves do grow, the outermost part of the protuberances will be vulnerable and subject to attack by marine processes.

Beyond a 10 cm rise in MSL the process of removal of vegetative detritus and scouring of sediments holding the mangrove trees will set in. The detrimental effect of this process will perhaps be manifested after a period of one hundred years through further erosion of island protrubrances and the loss of some of the mangrove plants.

However, as the rise continues between 10 and 20 cms in the second half of the century, the frequency of inundation of the fringing mangroves and the total area inundated regularly will increase. Even with a 20 cm rise the existing mangrove roots will not be permanently covered with water, and provided that the soil remains stable, the creek edge sites should remain suitable for seedlings to survive. The net effect will be an overall increase in the potential mangrove area, especially on the landward side. In 100 years at least two generations of mangrove trees (each surviving 40 - 60 yrs) will have adequate time to colonise the areas regularly inundated, especially with an active replanting programme. This scenario is tenable assuming that the coastline remains safe from episodic catastrophes such as severe and frequent storm surges, which might have a more significant effect upon the mangroves than gradual sea level rise. In the past the Indus Delta has not been as prone to such catastrophes as the Bay of Bengal.

Between 20 - 30 cm and up to 60 cm rise in MSL over 100 years, the pressure on the mangroves will intensify. There could be substantial loss of low lands and their mangrove growth in the Indus Delta, as happened elsewhere during the early part of the Holocene period when sea level rose over 12 cms in 100 years (Ellison, 1990). Also the eustatic sea level rise will exacerbate the existing human stresses on mangroves including cutting for fuelwood and fodder, camel grazing and changes in conditions due to pollution from Karachi. The wash from the increasing shipping traffic entering the Phitti/Kadiro creeks Port Qasim is beginning to erode some of the banks.

These human forces could considerably strain the tolerance of the mangrove ecosystem in specific parts of the delta leading to its decline. Management of the ecosystem must focus on reducing the impact of these human induced stresses if the ecosystem is to be able to withstand natural forces such as sea-level rise.

The present levels of the semi-diurnal tides in the creeks at Port Qasim and the projected levels after 100 years at a 6.0 mm/yr rise are as follows:-

Tidal state	Present level (metres)	Projected level (metres)
Lowest Astronomical Tide	- 0.49	+ 0.11
Mean Lower Low Water	+ 0.97	+ 1.57
Mean Higher Low Water	+ 1.43	+ 2.03
Mean Sea Level	+ 2.04	+ 2.64
Mean Lower High Water	+ 2.65	+ 3.25
Mean Higher High Water	+ 3.38	+ 3.98
Highest Astronomical Tide	+ 3.84	+ 4.44

N.B. These figures relate to the Chart datum at Port Qasim, 4.67 metres below a bench mark close to the HW line in Gharo creek about 2.4. Km south-west of Goth Mahmood Shah.

With a 60 cm rise, the projected mean sea level will be close to the present Mean Lower High Water mark. It is probable that this is the lowest point at which the mangroves are presently growing, so that with this magnitude of rise the roots of the outer trees will be permanently inundated. With a rapid rate of rise in sea level, wave action will flush out organic material and sediments away from the roots of mangrove trees and there will be disorganised and patchy growth on the seaward side of the mudflats. Almost all of the protuberances will be eroded away and the rate of coastline flattening will increase.

If this rate of rise persists over 100 years there will be a pronounced effect on the physiographic features of the estuary. With declining runoff and sediments from the Indus, the sea waves will prevail and obliterate the crenulations in the delta, and the salinity gradient will be pushed landward.

With the generally very low land gradients found in the Indus Delta, losses due to erosion at the front edges of the creeks may be balanced by the more regular inundation of the higher-lying areas towards the land. However, the rate of change may be too rapid for natural colonisation processes and for differential species selection. Since *Avicennia marina* predominates in the Indus Delta, natural species selection is unlikely to occur; assisted colonisation may be the only way to ensure that the ecosystem survives in conditions of rapid sea level rise.

5.2 Coastal Inundation

The northern edge of the delta is characterised by a sandstone escarpment with a low-lying coastal strip up to half a kilometre wide with very sparse vegetation. The eastern edge is very low-lying, extending for many kilometres inland. This land is heavily cultivated, but with a tendency towards salinisation and waterlogging.

Using the figure of 0.1^{o} for the slope of the delta lands assumed by Wells and Coleman (1984) the encroachment by the sea level rise can be calculated. The present highwater line is very approximately 370 km long.

Based on these figures the encroachment of the sea in 100 years at the predicted rates would be:-

Rate of MSL rise (mm/yr)	Distance encroached (m)	Area Encroached (sq. km.)
1.1	64	24
2.0	116	43
6.0	346	128

Most of the people immediately affected by such rises would be fishermen and camel herders. Along the northern edge of the creeks about 80,000 people live in the low-lying strip near to Karachi. These coastal villages would be at risk.

On the eastern edge of the delta, the 1981 census figures show that about 300,000 people live in the coastal areas of Thatta district. Only a relatively small proportion of these people would be immediately affected by sea encroachment, although further saline intrusion would make the adjacent agricultural lands less fertile. An estimate of the population from the numbers of fishing boats in the areas around Gharo, Keti Bundar, Karo Chan and Shah Bundar suggests that perhaps 20,000 people may be affected directly.

6. DISCUSSION AND CONCLUSIONS

It is considered that sea level rises up to 2 mm/yr for the next 100 years may favour mangrove survival and growth by opening up the less regularly inundated areas in the Indus Delta for colonisation by mangroves. Above this rate of sea level rise the balance of erosion by marine processes over sedimentation will cut back the mangrove areas at a faster rate than colonisation can occur.

However, the fundamental question in the discussion of the impact of sea level rise on mangrove habitat is:- " What is the threshold rate of sea level rise above which mangroves cannot sustain themselves?"

It is an intricate issue particularly in an estuarine regime where shoreline features, sedimentation and salinity gradient have been influenced by changing fluvial processes. The microtopography, the rate of sedimentation and the salinity in the creeks control the distribution and density of different species of mangrove. The few examples given in this paper have shown how dynamic the Indus Delta is - sea level rise is superimposed on this pattern of change and it is almost impossible to differentiate between the various influences.

Large deviations from any theoretical threshold are possible because a number of factors contribute towards the performance of mangrove ecosytems during sea level rise. In the case of the Indus Delta with a reducing allochthonous sediment input (below 30 million tons/year in the future) from the Indus river and its distributaries, the mangrove ecosystem has been able to survive a rise of 11 cm/100 years which is the observed rate at Karachi. At greater rates of MSL rise the extensive survival of the Indus mangroves may be questionable. Rapid sea level rises will effect the differential survival and establishment of large propagule species. As such the stategic replanting of *Rhizophora mucronata* and *Avicennia marina* in the Indus Delta may be a key to ensuring continued extensive coverage of the mangroves.

Another pertinent question on the subject of sea level rise and mangrove ecosystems is whether there is a stratigraphic sequence of the mangrove substrate in the Indus Delta estuary. If mangrove peat (formed a few thousand years ago) is found at a level lower than the present mangrove substrate, this would indicate that the MSL in the past was also lower. Radiometric dating of the peat sample, if found in the Indus Delta, will provide a definite indicator to the magnitude of sea level rise during the past few thousand years as has been found in several other areas e.g. Cayman Islands, South Florida, Australia, Fiji, Western Samoa etc. (Ellison, 1990).

There is a likelihood that in the Indus Delta, mangrove peat was not formed and that as the delta sediments moved out into the Arabian Sea they were colonised by the mangroves. As the land at the rear edge of the delta became, raised the mangroves died out and were replaced by inland vegetation. The accumulated vegetative detritus in situ is thus ecologically modern. The existing growth is perhaps the first generation growth that has adapted and established itself to the present estuarine physiography, salinity, and elevation of the substrate over the past few hundred years. Ellison (1990) suggests that as in earlier periods elswhere, very fast shoreline progradation of fluvial/deltaic sediments at rates of up to 30 m/year inhibited the development of mangrove forest. The sustained establishment of the mangrove species in the Indus Delta may be limited to locations of optimal environmental conditions of calm water, a very gentle gradient of the substrate in the intertidal zone and a relatively stable sea level. Apart from the the last point, these are the conditions in the areas to the north and east of the active delta which currently show the greatest density of mangrove growth.

Thirdly, Snedaker (1990) makes the point that mangrove responses to global changes may be more directly related to regional precipitation than to sea level rise. In the case of the Indus Delta, which has very little rainfall, any change which increases the freshwater addition to the creeks, either directly or from runoff can only be beneficial to the mangroves. If global warming means greater precipitation in the area, with a lowering of the creek salinity and an increase in the allocthonous sediment, the mangroves will be able to withstand most sea level rises.

7. RECOMMENDATIONS

In order to work out a long term policy and programme for the protection and conservation of the mangrove ecosystem the quantum of environmental stresses in the Indus Delta should be studied in greater detail.

I. In the realm of geology and oceanography the subjects of study are:

- Analysis of sediment distribution in the Indus Delta and its correlation with the health of mangrove growth
- Rate of sedimentation through fluvial processes
- Correlation of topography with distribution of mangrove trees, particularly the lowest and highest levels at which mangroves grow.
- Stratigraphy of mangrove peat, if found
- Pollen analysis which provides a good indicator for determining ancient marine strandlines, and floristic changes in the mangrove area.
- Dynamics of the estuarine regime.

II. Synthesis of geological, hydrological and ecological information in the selection of sites for monitoring the changes occuring over time.

- The monitoring sites would give a clear indication of what is happening.
- The monitored sites would be used to develop different management strategies according to varied uses and threats to the ecosystem e.g. sea-level rise.

III. In the realm of management, six fronts need immediate attention:

- Plantation of more saline tolerant species or strains of mangrove in addition to *Avicennia marina*.
- Plantation of larger propagule species e.g. *Rhizophora mucronata* in lower-lying areas and interplanting of blank areas between existing stands of *Avicennia marina*.
- Experimentation of planting slightly higher areas which are irregularly inundated with species more tolerant to these conditions, e.g. smaller propagules, salt tolerant.
- Experimentation of various methods of stabilising eroding mangrove substrates, and encouraging increased rates of deposition of autochthonous sediment.
- Strict control on removal of mangrove trees for which community participation is intrinsic.
- Carrying out a topographical survey of coastal and mangrove areas to identify areas most at risk from sea level rise, and those suitable for different management options.

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