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Sealevel Rise and the Coastal Lowlands in the Developing World

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ABSTRACT

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About two hundred low-lying coastal areas in the developing world were characterized in terms of a range of variables influencing the nature of the effects on each area of a gradual eustatic sealevel rise. The areas were clustered with weightings emphasizing the variables considered most important, and a brief description of the probable effects was given for one area from each of the main clusters. This paper summarizes processes affecting low-lying coastal areas, methods of characterization and clustering, and reports descriptions for examples from three clusters. A sealevel rise does not only affect the coastline and the structures along it, but may also change the hydrology, the soils and the natural vegetation or the potential for agriculture over an appreciable distance inland. The nature and extent of these changes depends on, for example, the length of the dry season, the sediment supply from rivers, and the incidence of tropical cyclones. The basic tabular data set and the transformed one used for clustering are available from the third author for reanalysis on the basis of improvements in data, knowledge or insight. The maps are being entered into a geographic information system and should in due course be available in digital form.

ADDITIONAL INDEX WORDS: *Eustasy, nearshore lands, coastal wetlands, delta, mangroves, land subsidence.*

INTRODUCTION

At the request of the Food and Agriculture Organization (FAO), a study was carried out to characterize the low-lying coastal areas of the developing world with a view to estimating the possible effects on them of a gradual, eustatic sealevel rise, stipulated as one of the consequences of global warming by the Intergovernmental Panel on Climate Change (IPCC). Many of the world's most productive agricultural areas are located in river deltas and coastal plains, as are some of the world's important natural wetland areas.

All the world's coastline will, in principle, be affected by a sealevel rise, but the effects along relatively steep, upland coastlines would be small, except on human-made structures related to the existing sealevel, such as harbours or piers. Major consequences of even a gradual sealevel rise may be expected in low-lying coastal areas, both along the coast and further inland. These consequences may be very different from area to area, depending on climate, sediment load of rivers, and characteristics of the deltas and coastal plains and the adjacent sea. Specifically, the vertical accretion of nearshore land depends on the sediment supply from rivers or from the sea, the width of the shelf or the proximity of a submarine canyon through which turbidity currents remove sediments, the strength of longshore currents and the incidence of cyclones, both of which transport and redistribute sediments along the coast.

The impact of sealevel rise on agriculture is expected to be important, especially in humid tropical climates. Land presently used for dryland crops may be intermittently or seasonally flooded by fresh or brackish water, and deeper or longer-term flooding may impair the yield potential of land presently used for rainfed wetland rice. In arid conditions, periodic seawater flooding may partially desalinize parts of presently barren, hypersaline land with consequent gradual colonization by mangroves.

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There is no consistent indication that tropical cyclones will increase in frequency or intensity with global warming (FOLLAND *et al.*, 1990), but they may reach somewhat higher latitudes if and as the sea-surface temperature increases. The present cyclone incidence has been used in this study.

Estimates of the magnitude of sealevel rise over the next century cover a wide range. The Coastal Zone Management Subgroup of the IPCC in its meeting of August, 1991 stipulated 0.3 and 1 m/century as low and high estimates, close to the 0.3 and 1.1 m shown by WARRICK and OERLEMANS (1990). It should be recognized that the rise would not be linear, but would probably accelerate with time (Figure 1).

A gradual, eustatic sealevel rise will affect the low-lying coastal areas of the world; however, in the large river deltas, this is in addition to the rate of their continual, natural subsidence. Locally, human-induced subsidence caused by drainage or overpumping of water, oil or gas has also been adding to the relative sealevel rise. The human-induced reduction in sediment supply to deltas and shorelines by hydroelectric and irrigation dams on rivers and the exclusion of sediments from low-lying coastal areas by dikes have diminished or eliminated vertical accretion which counteracted the subsidence in the natural landscape.

These various processes are discussed below, as well as the nature and rate of sedimentation association with sealevel rise in the recent geologic past. A range of variables characterizing low-lying coastal areas is used to cluster many coastal areas in the developing world into a small number of groups; the effects of a gradual sealevel rise are then described for examples of such groups on the basis of process knowledge and insights from geologic analogues.

It is well to note the broad scale and the necessarily low spatial resolution of this global study. Although the descriptions do take into account the variations within individual deltas or coastal plains, each of these—large or small—is characterized by a single class value for each variable. The northwestern part of the Guyana coastal plain, for example, is largely peaty while the major central and eastern parts have mainly clayey sediments with locally, some sand ridges; lithology was classified as fine (neglecting the peat and some sand ridges). Different parts of the coast may also have different characteristics: in the Ganges-Brahmaputra delta, for example, from mangrove-covered in the west through diked with tidal creeks to ephemeral tidal flats in the Meghna mouth and more stable, cultivated higher tidal flats in the eastern part.

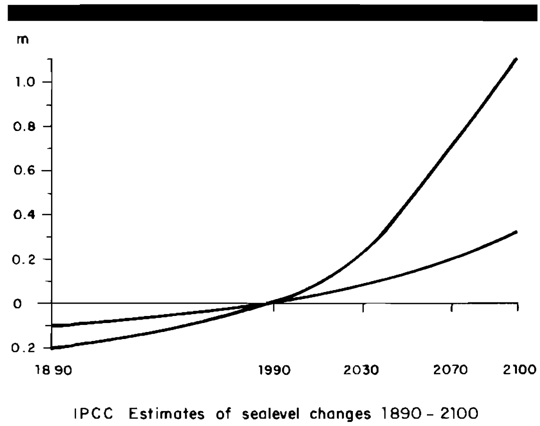

Figure 1. Low and high estimates of sealevel changes 1890–2100. Values from IPCC (1992).

MORPHOLOGY AND PROCESSES IN RIVER SYSTEMS AND DELTAIC PLAINS

The major components of river systems are the drainage basin, the alluvial valley, the deltaic plain and the receiving basin (Figure 2). The deltaic plain is the area where the main river channel reaches base level and branches into multiple distributaries, disposing of and distributing the discharge and the sediment load. The deltaic plain is the resultant of the interaction between these river processes and the marine processes dominating the receiving basin offshore. The main morphological features of the deltaic plain comprise the levees bordering the distributary channels, the interlevee basins or backswamps (topographic depressions), crevasse deposits in the basin margins, coastal ridges, intertidal mud or sand flats and dunes. In some humid tropical lowlands, ombrogenous (rainfed) peat domes may occur in central parts of large backswamps with eustatic peat (at sealevel) in the remainder.

Several studies have shown that the shape and morphology of the deltaic plain and the nature of its sediments are governed by numerous process variables (*e.g.*, MORGAN, 1970; COLEMAN and WRIGHT, 1971; WRIGHT *et al.*, 1974; ELLIOTT, 1978). These variables can be subsumed under four major factors (MORGAN, 1970): river regime,

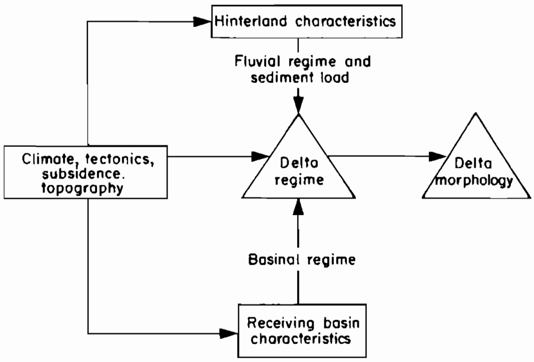

Figure 2. Conceptual framework for the comparative study of deltas. After READING (1986).

structural behaviour (tectonics), coastal processes and climate. The nature of the variables and their relationships should be known if present trends in deltaic and coastal plains are to be explained and if prediction of future changes in these important lowlands is to be attempted.

All of the recent deltaic and coastal plain deposits have accumulated during and after the postglacial sealevel rise. A wedge of recent, soft sedimentary materials is present in all these areas.

LAND SUBSIDENCE IN COASTAL LOWLANDS

Tectonic subsidence must be added to (or emergence subtracted from) eustatic sealevel rise to arrive at an estimate for local, relative sealevel rise; similarly, subsidence due to natural or human-induced compaction of soft sediments should be added. Land subsidence can result from natural near-surface processes and tectonics, or from human activities.

A general overview of the nature of the tectonic instability of the world's coasts is given in Figure 3. In the area influenced by plate tectonics (shaded coastlines), earthquakes trigger sudden vertical and lateral movements of the earth's crust. Slow uplift (+) by isostatic rebound is still continuing in areas formerly covered by ice caps. Most low-lying coastal areas, especially deltas, are subject to slow tectonic subsidence (−), being situated on subsiding sedimentary basins. These basins may have accumulated Cenozoic sediments up to several km thick.

Tectonic subsidence consists of basement subsidence accelerated through loading by the sediment deposited in the basin. Though little is known about the tectonic subsidence rates in sedimentary basins, values are thought to be small: less than 5 cm/century (JELGERSMA, 1992, in press).

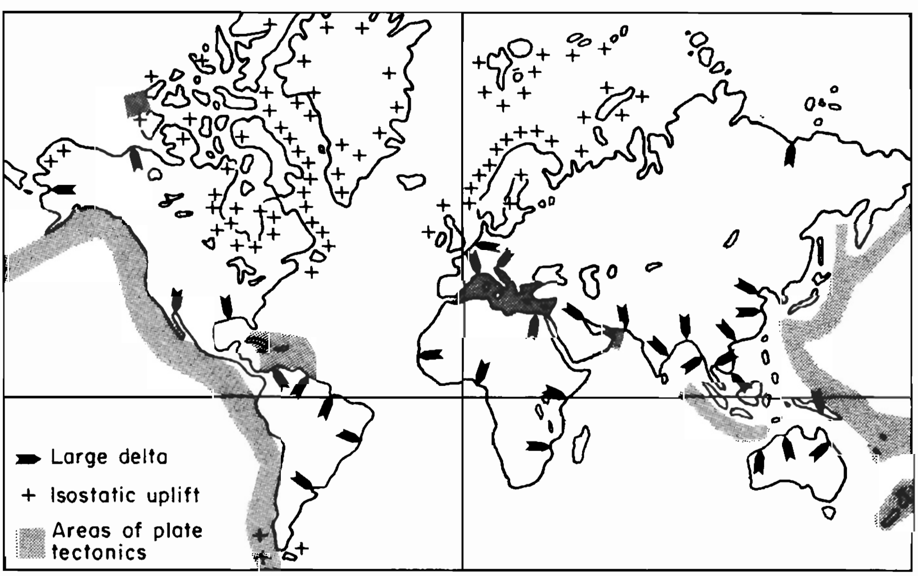

Figure 3. Principal deltas, areas of subsidence and isostatic uplift and areas influenced by plate tectonics. After FAIRBRIDGE and JELGERSMA (1990).

Compaction is also a significant factor in land subsidence, especially in fine-grained sediments: for example, freshly deposited muds with more than 40% clay may have a porosity exceeding 80%. This is very gradually reduced by loading with water being expelled, eventually to about 40% porosity, resulting in a threefold final decrease in volume and increase in density.

Fine-grained sediments can be compacted similarly, but much more abruptly, by vibration during earthquakes. Lowering of the groundwater table during a dry period, or lowering of relative sealevel, causes drainage and consequent compaction of the emerged fine-grained sediments and peat. Oxidation of emerged peat also contributes to lowering of the land surface. The emerged material causes increased loading and consequent further compaction of deeper layers.

Under natural circumstances, sedimentation or peat accumulation (in wet areas far from river channels or the coast) compensates for these processes of land subsidence, albeit with appreciable fluctuations in individual areas over periods of up to several decades.

Human-Induced Subsidence

Human-induced land subsidence can occur by withdrawal of gas, oil or water or by drainage and land reclamation. The processes involved, similar to those mentioned above, are only touched upon here. Detailed information on processes, measurement and modelling can be derived from the Proceedings of the various international symposia on land subsidence of the International Association of Hydrological Sciences (*e.g.*, IAHS, 1977), and from POLAND (1984).

Drainage has lowered the groundwater table in extensive areas of wetlands reclaimed for agriculture or for urban or industrial use, with consequently accelerated compaction and subsidence. After drainage, peat layers are gradually reduced to about one-ninth of their original thickness; clayey muds with about 80% porosity are reduced to about half their original thickness within a century after drainage (BENNEMA *et al.*, 1954; DE GLOPPER, 1986). Subsidence generally varies from place to place in reclaimed areas and may exceed about 2 m. Since reclaimed areas are protected against natural flooding, the subsidence will not be compensated by deposition of sediment or peat accumulation.

Subsidence above oil and gas fields is caused by compaction after a drop in pore pressure by fluid or gas withdrawal from a deep confined reservoir. The amount of subsidence may range over two orders of magnitude: up to some 0.25 m near the centre of the Groningen gas field in the Netherlands (PÖTTGENS, 1986), for example, and up to 9 m between 1928 and 1968 in the Long Beach harbor area above the Wilmington oil field in California (GATES *et al.*, 1977).

Groundwater extraction in areas underlain by Cenozoic basins may also cause severe subsidence. Subsiding basins in coastal areas contain very thick layers of unconsolidated material deposited in alluvial, lacustrine and shallow marine environments. This material generally consists of confined or semiconfined sandy or gravelly aquifers of high permeability and low compressibility alternating with clayey aquitards of low permeability and high compressibility. Groundwater withdrawal causes a decline in hydraulic head resulting in decreased pore pressure. This results in immediate, largely elastic, slight compression of the aquifers, but this is reversible if fluid pressure is restored. The decrease in pore pressure in the aquifer creates a hydraulic gradient from the aquitards to the aquifers, resulting in slow and long-continued expulsion of water from these clayey layers and consequent large and irreversible compaction.

Subsidence by overpumping of groundwater can lead to saltwater intrusion into the aquifers, deterioration or disruption of drainage systems and flooding by tidewater (POLAND, 1984). Parts of Bangkok, for example, have been subsiding by up to 1.6 m between 1933 and 1987, at rates increasing to some 0.12 m/year in recent years (NUTALAYA *et al.*, 1989). In northeastern Tokyo, groundwater levels were lowered by some 60 m and the land subsided by up to 4.6 m between 1920 and 1975; the consequent flood hazard during typhoons had to be countered by a major programme of dike construction and strengthening.

SEDIMENTATION IN DELTAS AND COASTAL PLAINS

Under natural conditions, deposition of sediment from rivers or from the sea counteracts slow natural subsidence and tends to maintain the land surface near river channels or near the coast at high-tide or normal river flood level, or slightly higher. The land surface in the inter-levee basins is generally lower because of the smaller sediment input, but may be maintained at flood level by peat accumulation in permanently wet climates.

Human Impact on Sedimentation in Deltas and Along Coasts

Human interventions in the river system, in the catchment area, the alluvial valley, the delta or the coastal strip itself, may have a major influence on sediment supply to coastal areas, generally aggravating the effects of a sealevel rise. The dynamic near-equilibria between land and sea maintained by sedimentation can be broken by embankments; drainage of wetlands; building reservoirs on rivers upstream; dredging sand from river beds or along the coast; construction of breakwaters or harbours; or converting a natural mangrove belt along the coast into other uses, such as fishponds.

Embankments along river channels or the coast keep out sediment from the adjacent land, thus eliminating the gradual vertical accretion. Drainage and reclamation of wetlands for agriculture or for urban or industrial use causes accelerated subsidence as discussed above.

Construction of reservoirs in upper river courses for flood protection, power supply or irrigation may essentially stop, or strongly decrease, the transport of sediment downstream (MILLIMAN and MEADE, 1983). Successful, very large-scale soil conservation efforts may have similar but less extreme effects, as will the large-scale dredging of sediment from river beds, or the construction of barrages and diversion of river flow into irrigation systems. The Nile delta, for example, has been subject to serious coastal erosion and encroachment of lakes on adjacent land since the completion of the Aswan High Dam in the sixties. The discharge and sediment load in the Indus delta have been reduced to about one fifth by the major dams on the Indus and its tributaries and the large-scale irrigation development (WELLS and COLEMAN, 1984).

The Mississippi delta is another clear example of wetland deterioration by decreased sediment input (DAY and TEMPLET, 1989). Construction of dams and reservoirs and sand mining from upstream stretches of the Mississippi has sharply reduced the amount of sediment reaching the delta. The sediment that does arrive, as well as bay-bottom mud resuspended by storms, is kept from settling in the wetlands by dikes and high spoil banks constructed along distributary channels and canals. The combined effects of subsidence and sealevel rise are thus no longer counteracted by sediment input, and large wetland areas are reverting to open water.

Sand mining from beaches or offshore for land reclamation and construction, as well as the interruption of longshore sediment transport by harbours or breakwaters, can also cause serious coastal erosion downdrift from such activities or structures. Mining of coral from offshore reefs, or dynamiting fish, besides destroying a habitat of great biological diversity, tends to increase wave energy on the coast and thus, coastal erosion.

Clear-cutting of mangrove forest along the coast or tidal channels and its replacement by brackish-water fishponds, wetland rice, or salt pans where there is a long dry season, stops vertical accretion, may increase saltwater intrusion and large-scale saltwater flooding by storm surges in cyclone-prone areas, and also impairs the functions of the mangrove belt as a nursery for local and offshore fish and shellfish.

In contrast to the negative effects on coastal areas of the human activities indicated above, several river deltas and coastal plains are presently expanding because of an increased sediment supply. Deforestation and conversion to agriculture have caused major and extensive erosion in the Rhine basin over the last two millennia, and the resulting sediments have formed much of the surface of the western and northern Netherlands. Erosion has been extensive in the Po and Ebro watersheds since about seven centuries ago (SESTINI, 1989; MARINO, 1989); and presently, in the watersheds of Java and Madagascar, to name just a few examples. The deltas of the Ebro and Po rivers have been mainly formed due to these changes in sediment supply. Before that time, the Ebro had an estuary, and the Po and adjacent rivers had developed modest deltas at their mouths (SESTINI, 1989). These two deltas are presently subject to erosion because much sediment is being trapped in reservoirs. The deltas of North Java and Madagascar are still expanding seaward, in spite of local subsidence due to human activities.

These human-induced changes have greater and more immediate impacts on low-lying coastal areas, both positive and negative, than the expected effects of a gradual sealevel rise over the next half century or so.

PARALLELS FROM THE PAST

The decay of the continental icecaps after the last Glacial has been responsible for a major and rapid sealevel rise. From a lowest level of about 125 m below the present, about 17,000 years ago, at the maximal extent and thickness of the ice caps, the sealevel rose rapidly with the melting of the ice until about 6,000 years ago (FAIRBANKS, 1989). Since then, the generally minor further changes in sealevel have been mainly local or regional, resulting from crustal movements or subsidence through consolidation of soft sediments forming the deltas and coastal plains.

Between 17,000 and 6,000 BP, the sealevel rose at a rate exceeding 1 m/century, tailing off to less than 0.6 m/century near the end. These values correspond with the "high" and "best" estimates of sealevel rise for the next century as a consequence of global warming (WARRICK and OERLEMANS, 1990).

Information on the nature of coastal deposits, the sedimentary environments and the sedimentation rates during the later part of the rapid Holocene sealevel rise, between 9,000 and 6,000 BP, has contributed to understanding of what may happen during future sealevel rise. The sedimentary environments in the past were identified by analysis of physical, chemical and biological characteristics of the accumulated sediment; age determinations were by ^{14}C methods.

There are numerous case studies of coastal development during the postglacial sealevel rise; *e.g.*, the three Guyanas (BRINKMAN and PONS, 1968), the Netherlands (ZAGWIJN, 1986) and north Australia and Papua New Guinea (CHAPPELL, 1990). Three cases are briefly discussed below. These are situated in the humid tropics, with sediment sequences originating during various rates of sealevel rise, with different sediment inputs and under different tidal ranges.

Sedimentation in the coastal plain of the three Guyanas, northern South America, is dominated by the enormous quantities of mud discharged by the Amazon river and transported north and west along the coast by longshore current and wave action. In these coastal plains, extensive pedogeomorphological and sedimentological investigations were carried out on surface and shallow subsurface layers (VAN DER HAMMEN, 1963; BRINKMAN and PONS, 1968; ROELEVELD, 1969).

In the coastal plain of the three Guyanas, two typical facies of clay sedimentation have been encountered: one at a stable sealevel, the other with a rising sealevel. The sediments deposited at a stable sealevel, dated after 6,000–5,500 BP, are characterized by rapid, successive lateral sedimentation of clays low in organic matter and pyrite, colonized by mainly *Avicennia* mangroves, followed by freshwater swamp vegetation as the distance to the sea increased.

The sediments formed under a rising sealevel, before about 6,000 BP, accumulated vertically under an actively growing vegetation of almost pure *Rhizophora* extending many km inland from the coast. They contain large proportions of organic matter from the abundant fine *Rhizophora* roots and of pyrite, formed by reduction of sulphates from the brackish water and iron oxides from the sediment. The vertical accretion must have kept pace with a sealevel rise of about 0.6 m/century for centuries, with the sediment supply maintained by the longshore current from the Amazon mouths: a thickness of some 5 m is quite common, and locally, up to some 40 m of *Rhizophora* clays have been found.

The same two facies as in the Guyanas were observed in tropical riverine lowlands in the Ganges-Brahmaputra and Chao Phraya deltas, Bangladesh and Thailand, the Mekong delta and eastern Sumatra (BRINKMAN and PONS, 1968; BRINKMAN, 1984, 1987). In Bangladesh and Thailand, *Rhizophora* clays are shallowly buried under recent freshwater deposits; areas with *Avicennia* clays occur closer to the coast.

In the South Alligator river plain in North Australia (CHAPPELL, 1990), sediment input from the land is small and the tidal range is large. A large supply of marine mud appears to be available. During the last part of the rapid postglacial sealevel rise, about 12 m between 8,000 and 6,000 BP, mangrove muds up to 10–14 m thick were deposited in the South Alligator plain. These are presently overlain by recent river deposits, as is the case in the Ganges-Brahmaputra and Chao Phraya deltas. Mangrove clay sedimentation throughout the valley must have kept up with the rapid sealevel rise during this period, with a vertical sedimentation rate of 0.6 m/century—probably through the effective redistribution of the abundant marine mud by the strong tidal currents.

The Sepik and Ramu river plains in Papua New Guinea (CHAPPELL, 1990) are characterised by a large discharge and sediment load and a small tidal range, hence insignificant tidal currents. The continental shelf is narrow and much of the river sediment disappears off the shelf into the deep. During the rapid postglacial sealevel rise, the area of the plains was an inland sea; after about 6,000

BP, this was gradually filled in at a rate of about 0.3 m/century. A future sealevel rise exceeding that rate would presumably recreate an inland sea in a millennium, and a perennial swamp, with brackish-water influence in the seaward parts, in one or two centuries.

Where the sediment supply to low-lying coastal areas is very small or nil, for example on coastal limestone platforms, analysis of dated cores of mangrove peat has shown that mangroves can keep up with rates of sealevel rise of about 0.1 m/century, and disappear at more rapid rates of rise (ELLISON and STODDART, 1991).

These parallels from the past show two important facts: if sufficient sediment is available from rivers or from the sea, and with an adequate tidal range, vertical accretion can keep pace even with a rapid sealevel rise, and such a sealevel rise can change the inland freshwater environment of a deltaic plain in the humid tropics into an extensive zone of brackish *Rhizophora* clays. However, where barrage and dam construction has drastically curtailed the sediment supply to a delta, the present situation is not comparable to the past, and much of the sediment that will transform the delta will be derived from erosion of the coastline or from marine mud.

INVENTORY OF COASTAL LOWLANDS

In order to investigate the effects of a gradual rise in sealevel on coastal lowlands of the developing world and efficiently extrapolate the information to homologous areas, a systematic inventory of these areas is essential. Together with the Geological Survey of the Netherlands, the Commission on Quaternary Shorelines of INQUA, the International Union for Quaternary Research had initiated a study and mapped a part of the world's coastal lowlands. On the basis of these results, FAO and the Geological Survey of the Netherlands broadened the scope of the study and extended its coverage to all of the developing world.

Much information could be derived from published studies: particularly important were the data and insights from COLEMAN and WRIGHT (1971) and WRIGHT *et al.* (1974). The former study lists complete data for a range of variables for 24 deltas of the developing world and 10 deltas in industrial countries; the second shows clusters of deltas on the basis of selected variables from one broad factor; *e.g.*, offshore conditions or delta morphology.

A system of multivariate characterization and classification, called OSDA, was developed for the present study to facilitate systematic collection and handling of data for a large number of low-lying coastal areas. Characteristics of 207 areas throughout the developing world were entered into the system in so far as available; the areas were delineated at a scale of 1:5 million, using the FAO-Unesco Soil Map of the World (FAO, 1974–1980) as a base and combining its information with that from geological maps.

Coastal lowlands predominantly comprise deltas or coastal plains. A delta or coastal plain (the latter essentially the compound deltas of many small streams) is the downstream, coastal part of a river system, which reflects the interplay between the river regime, coastal processes, structural behaviour (tectonics) and climate (MORGAN, 1970).

Figure 2 summarizes the main components of a river system and their interactions which control the development of deltas. From the variables describing these components and the delta itself, those variables were selected (Table 1) which were considered most useful for impact analysis of a sealevel rise.

The OSDA System and its Variables

In the OSDA system of characterization and classification, the variables are ordered into four main groups: referring to, or acting through *O*ffshore conditions, the *S*horeline, and the *D*eltaic plain itself (including the fluvial conditions). The system allows space for human *A*ctivities as well, but these have not been elaborated. The OSDA variables are listed in Table 1.

The variables grouped under the category "Offshore" summarize the dynamics of the sea. These strongly influence especially the coastal morphology. The variables characterizing the coastline itself, including a classification of coastal morphology, are grouped under the category "Shoreline". These variables provide information about its vulnerability and its ability to protect the interior of the delta. The variables in the category "Deltaic plain" indicate the composition of the deltaic plain itself, the river conditions, and climate. The fourth category "Activities" allows for the characterization of human factors influencing coastal lowlands. To date, only a general indication of population density has been included.

Table 1. *Offshore, Shoreline, Deltaic and Activities variables used in the OSDA system.*

	Variable		Symbol
	Offshore		
1	Wave energy	low, medium, high	1, 2, 3
2	Tidal range	low, medium, high	1, 2, 3
3	Tidal type	diurnal, mixed, semidiurnal	1, 2, 3
4	Cyclone incidence	low, high	0, 1
5	Longshore transport	weak, prominent	0, 1
6	Shelf width	narrow, wide	1, 2
	Shoreline		
7	Shoreline closed/open	closed, open	0, 1
8	Lithology of shoreline	fine, medium, coarse	1, 2, 3
9	Vegetation	bare, other than mangrove, mangrove	0, 1, 2
10	Subsidence/Tectonics	stable, subsiding, rising	0, 1, 2
11	Exposure	semi-exposed, exposed	1, 2
12	Morphology	muddy, sandy beach/ridges/cheniers with or without mud, beach & dunes, beach & barrier islands, dunes & ditto	0, 1, 2, 3, 4
13	Stability	eroding, stable, prograding	0, 1, 2
	Deltaic Plain		
14	Ratio upper/lower plain	small, large	1, 2
15	Lithology of deltaic plain	fine, medium, coarse, peat	1, 2, 3, 4
16	Length of growing period, days	< 75, 75–179, 180–329, 330–365	1, 2, 3, 4
17	Climate	temperate, subtropical winter rainfall, ditto summer, tropical	1, 2, 3, 4
	Activities		
18	Population density	low, medium, high	1, 2, 3

Data Collection and Analysis

Using the OSDA system, an inventory was made of low-lying coastal areas of the developing world. This was used in the construction of sealevel rise scenarios for different types of low-lying coastal areas.

In order not to have to design a sealevel rise scenario for every area, cluster analysis was used to form groups of areas with similar characteristics and expected reactions to sealevel rise. A sealevel rise scenario for an area for which much information is available can be used for a complete cluster in an indicative way. Thus, impacts of sealevel rise for many areas can be estimated using a limited number of scenarios. Coded data from 35 selected major coastal areas in the developing world (Table 2) were used to test the clustering; the result is shown in Figure 4.

A representative area was selected from each cluster in the database. Each of these areas was briefly described, including the main expected effects of a gradual sealevel rise. Other variables affected by climate change, such as rainfall or evapotranspiration, or frequency of tropical cyclones, were assumed to have their present values. Three contrasting examples are given at the end of this paper: the Indus and Mekong deltas and eastern Sumatra.

Further study provided data for a total of 207 coastal areas throughout the developing world. For many areas, certain variables could not be estimated for various reasons, however.

Some variables of the OSDA system were excluded from the main cluster analysis of the 207 areas because the data were available for too few areas: ratio active/abandoned plain, ratio upper/lower plain, and extent of delta or coastal plain. Their estimation would require the use of large-scale maps which were not readily available for many areas.

For three other variables, river discharge, discharge range and sediment load, few data are available, and these also are liable to be inaccurate. Many rivers are poorly studied and many data have been reported without reference to date of measurement or sampling procedure. Also, dam construction and other major works are still continuing in many river basins, although the number of new works initiated seems to be decreasing.

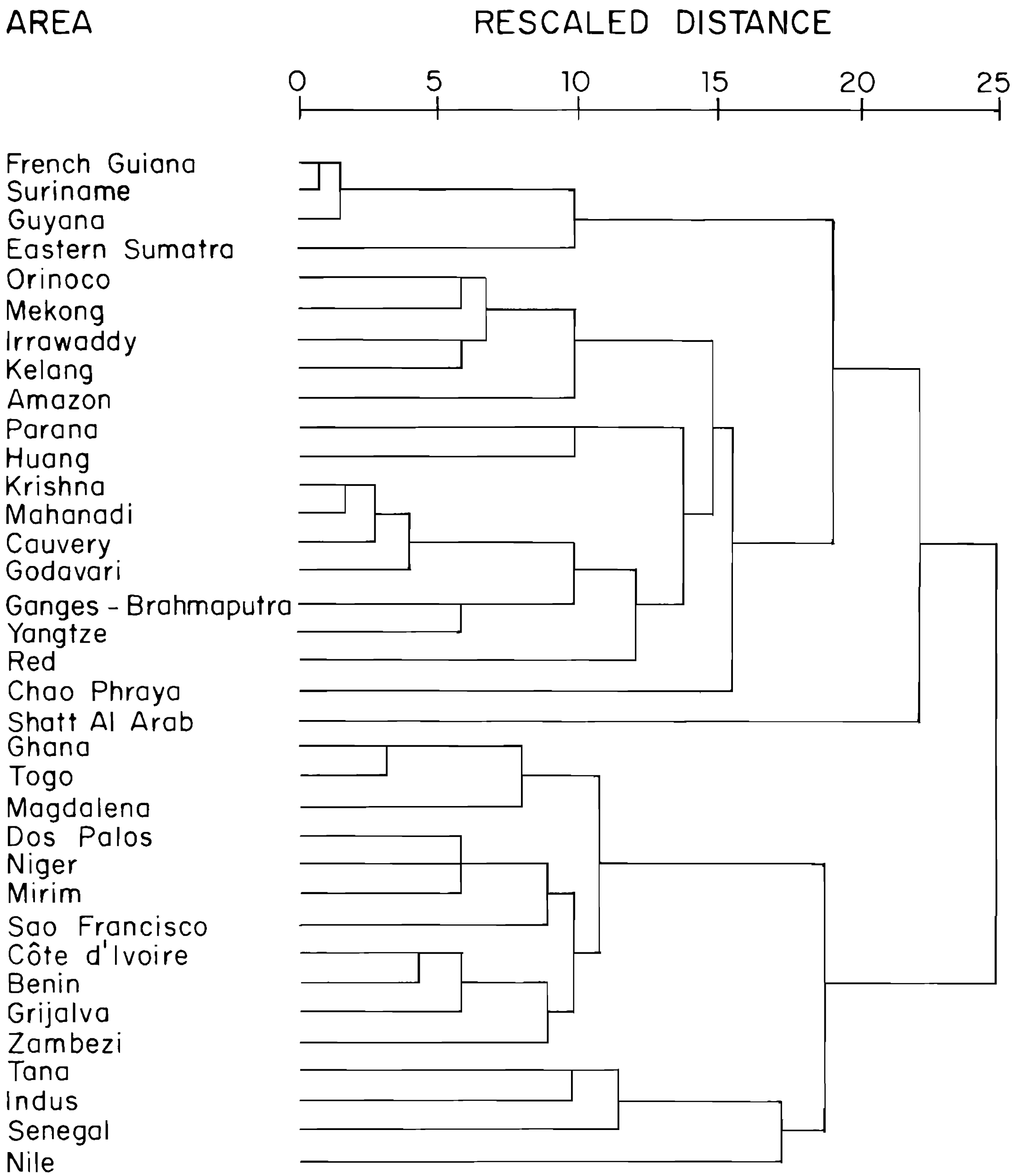

Figure 4. Dendrogram of 35 coastal areas. Euclidean distance, unweighted class differences.

The effects of current construction will be changing river characteristics for several years to come. Although sediment supply has a major influence on low-lying coastal areas, the variable can only be used in combination with an indication of the proportion lost to the sea, for example as turbidity current, and in combination with the extent of the land area over which the sediment is being

Table 2. *Coded classes of variables for 35 of the 207 low-lying coastal areas.*

	Variable																	
Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Grijalva	3	1	2	0	1	2	0	3	1	1	1	3	0	2	2	4	4	2
Amazon	1	3	3	0	1	2	1	2	3	1	2	1	1	2	1	3	4	1
Magdalena	3	1	2	0	0	1	0	2	0	1	2	1	0	2	1	1	4	2
Orinoco	1	2	3	0	0	2	1	1	3	0	2	0	2	1	1	4	4	1
Parana	1	1	2	0	0	2	1	1	1	1	1	0	2	2	1	3	3	2
Sao Francisco	3	1	3	0	0	1	0	3	1	0	2	4	0	2	3	3	4	1
French Guyana	1	2	3	0	1	2	1	1	3	0	2	1	2	2	4	4	4	2
Suriname	1	2	3	0	1	2	1	1	3	0	2	1	2	2	4	4	4	2
Guyana	1	2	3	0	1	2	1	1	3	0	2	1	2	2	4	4	4	2
Mirim	2	1	3	0	1	2	0	3	1	1	2	4	0	2	1	4	3	1
Dos Palos	2	1	3	0	1	2	0	3	1	1	2	4	0	2	3	3	3	1
Niger	2	1	3	0	1	2	1	3	1	1	2	3	0	2	2	3	4	2
Nile	2	1	3	0	1	2	1	3	0	1	1	3	0	2	2	1	2	3
Senegal	3	1	3	0	1	2	0	3	0	0	2	4	0	2	3	1	4	1
Tana	3	2	3	0	1	1	0	3	0	0	2	4	0	2	2	2	4	2
Zambezi	3	2	3	0	0	2	1	3	1	1	1	3	0	2	1	3	4	2
Ghana	3	1	3	0	1	1	0	3	1	1	2	3	0	2	1	2	4	2
Cote d'Ivoire	3	1	3	0	1	1	0	3	1	1	2	3	0	2	3	4	4	3
Togo	3	1	3	0	1	1	0	3	1	1	2	3	0	2	2	2	4	1
Benin	3	1	3	0	1	1	0	3	1	1	2	3	0	2	2	3	4	3
Cauvery	2	1	3	0	0	1	0	3	1	1	2	1	2	2	2	2	4	3
Ganges-Brahmaputra	1	2	3	1	0	1	1	1	3	1	2	0	1	1	2	3	4	3
Godavari	3	1	3	1	0	1	1	3	1	1	2	1	2	2	2	3	4	3
Indus	2	2	2	0	0	2	1	2	0	0	2	3	0	2	2	1	4	1
Krishna	2	1	3	1	0	1	0	2	1	1	2	0	2	2	2	3	4	3
Mahanadi	2	1	3	1	0	1	0	2	1	1	2	3	2	2	2	3	4	3
Shatt Al Arab	1	2	2	0	0	2	1	1	0	1	1	1	2	1	2	1	2	1
Chao Phraya	1	2	1	0	0	2	0	1	3	1	1	0	0	2	1	3	4	3
Huang	1	1	3	0	0	2	1	2	1	1	1	0	2	2	2	3	1	3
Irrawaddy	2	2	3	0	0	2	1	1	3	1	1	0	2	1	2	3	4	2
Kelang	1	3	3	0	1	2	1	1	3	1	1	0	2	1	1	4	4	2
Mekong	1	2	2	0	0	2	1	1	3	0	2	1	2	2	1	3	4	2
Red	2	2	1	1	0	2	1	3	1	0	1	1	2	1	1	3	4	3
Yangtze	1	2	3	0	0	2	1	2	1	1	2	0	2	1	2	3	3	3
Eastern Sumatra	1	2	1	0	1	2	1	1	1	0	1	0	2	2	4	4	4	1

distributed. In view of the above, these variables were excluded as well. The variable stability of the coast was used to infer an insufficiency of sediment where the shoreline is eroding, or sufficient sediment supply, from rivers or from the sea, where the shoreline is stable or prograding.

The variable population density was not included because it does not improve clustering of areas into groups with similar reactions to sealevel rise. Enough variables remained, however, to allow adequate discrimination of areas into clusters.

A few of the variables strongly influence the nature of the response of coastal areas to sealevel rise, as well as their potential for agriculture. Such variables were assigned a double weight in the clustering algorithm finally adopted. These comprise wave energy, tidal range, lithology of deltaic plain and length of growing period. Other selections of weights or more sophisticated clustering algorithms did not improve the results.

For each cluster, the main common features were listed after the type description, as in the three following examples.

INDUS, MEKONG, EASTERN SUMATRA

Indus Delta, Pakistan

The Indus delta has an arid climate and a coastline exposed to medium wave energy particularly during the Southwest monsoon. The longshore current to the southeast transports sediment from the Indus mouth towards the Rann of Kutch. During the summer monsoon period, some of the large basins in the lower deltaic plain are intermittently flooded by fresh or brackish tidewater. Consequently, basin margins are strongly saline.

The Indus river is characterized by a relatively large, but highly erratic discharge and carries a mainly coarse bed load. In the last 30 years, however, the sediment and water discharges have been much reduced because of large-scale irrigation development and construction of upstream reservoirs (MILLIMAN *et al.*, 1984). This has resulted in increased groundwater salinity and settling of coarse sediment in the river bed.

As a consequence of these human interventions the coastline of the Indus delta is subject to erosion, particularly in the northwest near the Indus mouth. There, in contrast to the southeast, the tidal flats are bordered by sand ridges and partly covered with some windblown sand. Former distributary channels are being transformed into tidal creeks and tend to silt up, there is increased saltwater intrusion in the lower deltaic plain, deterioration of the mangrove communities, and an increase in windblown sediments (SNEDAKER, 1984), as the coastal part of the delta is being transformed into a transgressive sand body (WELLS and COLEMAN, 1984).

With a gradual sealevel rise, increased wave energy would result in more rapid shoreline erosion. This would be aggravated by decreased sediment discharge, since the backing up of river water by a higher sealevel would decrease sedimentation near the coast still further.

A higher sealevel would also decrease bottom friction of the tidal flow. The tidal currents would then increase and start to erode the channels (VOLKER, 1989). Enlargement of the tidal channels together with a higher sealevel and upstream sedimentation would cause saltwater to penetrate further inland, and accelerate the change of former distributary channels into tidal creeks. The higher groundwater level in tidal basins and basin margins linked to the rise in sealevel would increase evaporation rates and thus, increase salinization and extend the presently saline basin margins. Any seawater entering the basins would aggravate these processes. The very narrow mangrove fringe, restricted to the strip where regular flushing takes place (SNEDAKER, 1984), would tend to move inland with the change in location of the intertidal strip.

An upstream shift in sedimentation in the riverbed due to a higher sealevel would further back up river water. As a consequence, floods and groundwater levels would be higher, also, in areas more upstream and at higher elevation than expected from the rise in sealevel alone. This rise in river level could entail an increase in height of the levees in the upper part of the delta if sediment is available.

Former abandoned deltaic plain areas may become periodically flooded (active) again, but marsh development or long-term water stagnation would be unlikely due to the arid climate. In those abandoned areas where the predominant effect will be a higher groundwater level, the topsoil may become strongly saline. This would further decrease natural vegetation cover and these areas would become subject to wind erosion.

Presumably, however, such a natural adaptation of the Indus delta to a rise in sealevel will to a large extent be prevented by human interventions, including embankments and drainage.

The common characteristics of the Indus cluster, comprising 11 of the total 207 areas, are:

A wide shelf (all 11 areas)
An arid climate, LGP (length of growing period) 0–74 days (10 areas)
No pronounced longshore transport (9 areas)
Medium lithology of the shoreline (8 areas)
Fine lithology of the deltaic plain (8 areas)
A high tidal range (8 areas)
Low (7 areas) to medium wave energy (4 areas)
A barren shoreline (7 areas) or with vegetation other than mangrove (4 areas).

Mekong Delta, Vietnam

The Mekong has a monsoon related discharge. During the dry season, seawater intrudes into the distributary channels as far as 50 km upstream (GAGLIANO and MCINTIRE, 1968). During the rainy season, with high rainfall and discharge, saltwater is pushed out and only remains in the lowest sections of the distributary channels in the lower deltaic plain. A mangrove vegetation occurs along these lowest sections and along the coastline.

The greater part of the delta surface is less than 2 m above mean sealevel and consists of broad, shallow, poorly drained backswamps. The higher land comprises levees, coastal ridges, and some portions of raised swamps.

The Mekong delta has two very large backswamp areas: the Plain of Reeds and the Trans-Bassac. Such large backswamps are common in deltas where the tidal range is large (MORGAN and MCINTIRE, 1959). During the rainy season, they are natural overflow basins of the Mekong river system. The Trans-Bassac drains to the Gulf of Thailand, but slowly, and water depth during the monsoon season can exceed 3 m. The Plain of Reeds is drained by the East and West Vam-co rivers, which are too small to rapidly evacuate the overflow and local rainfall: large parts are inundated to depths of 1–2 m during the river flood period (Figure 5). During the dry season, the soil in major parts of these backswamps becomes extremely acid because of the prevalence of pyrite-rich sediments (*Rhizophora* clays) at shallow depth (BRINKMAN, 1984; GAGLIANO and MCINTIRE, 1968).

The large difference in elevation between the extensive backswamps and the main river levees is due to the fact that local rainfall fills the backswamps before and during the main rise in river level during the monsoon season: the rainwater prevents sediment-laden river water from moving into the backswamps, and vertical accretion is largely limited to the levees. The remainder of the sediment is carried through to the river mouths.

The Mekong delta is tide-dominated with moderate wave influence. There is a moderate longshore current during the dry season (Northeast monsoon), moving sediment from the Mekong and Bassac mouths to the southwest. This part of the shoreline is prograding; in the extreme southwest, at a rate of 60–80 m/year. The tidal estuary southeast of Ho Chi Minh city (the Saigon river delta), northeast of the Mekong and Bassac, receives little sediment and progrades little if at all. There, the mangrove zone is extensive, particularly along the many tidal creeks. The west coast of the Mekong delta, on the Gulf of Thailand, has low wave energy and a longshore drift towards the south.

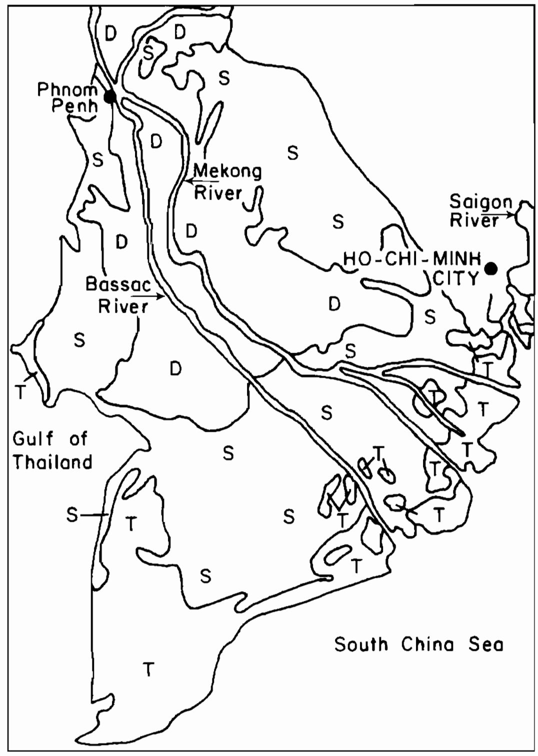

Figure 5. Depths and types of flooding in the Mekong delta. T: tidal flooding; S: shallow, wet-season flooding; D: deep, wet-season flooding. Generalized from NETHERLANDS DELTA DEVELOPMENT TEAM (1974).

With a gradual sealevel rise, the expected shift in sedimentation further upstream—discussed below—would decrease the amount of material brought to the shoreline. Coastal erosion may therefore start or be accelerated; this would be aggravated if in the future, building of dams and reservoirs upstream would decrease the sediment supply. Near the distributary mouths, erosion of the shoreline by the littoral processes is likely to be counteracted by the rate of sediment deposition. The chenier ridges in the lower deltaic plain of the moribund part of the delta will first become wetter due to a rise in groundwater level, but those reached by the sea would be eroded, providing building material for new beaches and cheniers landward, along the eroding coastline.

A rise in sealevel would lessen the bottom friction of the tidal flow. The tidal range would increase, and the inlets would be enlarged and deepend, with consequently increased saltwater penetration inland, especially during storms in the dry season. Especially where little sediment moves along the coast because of a small supply or decreased longshore transport, new tidal creeks may also be formed particularly where deep backswamps or freshwater peat areas occur close to the coast. A deeper penetration of tidewater would cause the formation of tidal levees and extend the mangrove zone and consequently the production of potential acid sulfate soils further inland. However, where inland areas are occupied by agriculture and protected by dikes, the mangrove zone would become narrower by erosion and might even disappear.

Due to sealevel rise and the associated backing up of river water, sedimentation would shift upstream. This would diminish the river gradient, resulting in a decrease in transport capacity thus moving the river bed sedimentation still further upstream. The resulting higher water levels would result in higher river levees. The increase in levee height especially in the lower reaches of the Mekong and Bassac rivers, combined with the continued vertical accretion in the mangrove zone along the coast and the mouths of the Mekong and Bassac, would impair the drainage of the backswamps, thus increasing the depth and duration of flooding in these areas. In the more shallowly flooded parts, largely used for wetland rice cultivation, building of more and larger floodgates in the dikes along the tidal rivers and main canals—which also have a considerable tidal range—would maintain the hydrology of the rice land for several decades.

A rise in river levels will lead to more frequent and deeper flooding of the active floodplain areas and their expansion into part of the abandoned backswamp areas. This will increase the rate of sedimentation. Stagnation and flooding in depressions in other parts would become still deeper and more extensive and persist during longer periods. Usually, the rainy season arrives before the river floods. Therefore, most backswamp areas are more likely to continue to be flooded by clear rain water than by sediment-laden river water.

The common characteristics of the Mekong cluster, comprising 33 of the total 207 areas and also including the Ganges-Brahmaputra and Amazon deltas, are:

- A subhumid to humid climate with a distinct dry season, LGP 180–329 days (31 areas)
- A wide shelf (32 areas)
- No pronounced longshore transport (32 areas)
- A low (26 areas) to medium (7 areas) wave energy
- A medium (24 areas) to high (9 areas) tidal range
- A fine (14 areas) or medium (15 areas) lithology of the deltaic plain.

Eastern Sumatra Coastal Plain, Indonesia

The coastal plain of eastern Sumatra, up to 200 km wide, comprises the deltas of many small streams. It is not influenced by cyclones and only the southern part of the coast is affected by the swell from northeastern monsoon winds.

A major part of this coastal plain, largely fringed by mangroves, is covered by level, topogenous (eustatic) peat deposits overlying potential acid sulphate soils (BRINKMAN, 1987). In areas away from the rivers, there are large rainfed (ombrogenous) dome peats which stand up to about 4 m above mean sealevel near the coast and locally up to about 12 m more inland (ANDRIESSE, 1974). These are perennially wet, and have a plateau-like surface with margins sloping towards broad, flat, topogenous peat areas or low, imperfectly drained clayey river levees. The drainage pattern of the peat domes is radial.

With a gradual sealevel rise, the present shoreline progradation would slow down or erosion would start. Along the eroding shoreline sections, the mangrove vegetation would shift inland at the expense of the topogenous peat, and the outer part of the mangrove belt might change into a tidal flat. Along rivers and tidal creeks, the mangrove vegetation would extend deep inland. The width of the mangrove zone would be inversely related to the rate of vertical sedimentation.

Inland, if the climate remains perhumid, the ombrogenous peat would accumulate at a similar rate as at present. The topogenous peat would accumulate more rapidly because of the gradually rising groundwater level linked with the rising sea and river levels. The areas of topogenous peat would therefore encroach slightly on the edge of the ombrogenous peat domes.

If the climate would become somewhat drier, peat growth may lag behind the sealevel rise; in due course, very broad peat areas may be intermittently flooded by saline or brackish tidewater, which would kill the freshwater swamp vegetation. Then, *Rhizophora* would be expected to colonize large parts of the present topogenous peat areas and if enough sediment is available, a cover of clay with large proportions of organic matter and pyrite might accumulate, as described in the section Parallels from the Past. With little or no sediment supply, mangroves could accumulate peat but slowly, so lagoons or bays might eventually form in that case.

The common characteristics of the Eastern Sumatra cluster, comprising 62 of the total 207 areas and also including the coastal plain of the three Guyanas, are:

- A humid climate without a distinct dry season, LGP 330–365 days (31 areas) or a subhumid to humid climate with a distinct dry season, LGP 180–329 days (29 areas)
- A mangrove (42 areas) or other vegetation (20 areas) along the coastline
- A low wave energy (50 areas)
- No pronounced longshore transport (51 areas)

A fine lithology of the delta (24 areas) or peat (17 areas).

CONCLUSION

It has proved possible and practical to sort about two hundred of the low-lying coastal areas of the developing world into reasonably homogeneous clusters on the basis of a limited number of variables characterizing each delta or coastal plain, its coast, the offshore conditions and climate, and for a selection of them, to describe their main features and the nature of the different changes expected as a consequence of a gradual sealevel rise. Even though the clusters have been made in a relatively crude fashion, descriptions for one area can be taken as indicative for the nature of the changes to be expected in other areas within the cluster.

The descriptions, made on the basis of parallels from the geologic past, information on sedimentology and dynamics of alluvial landscapes, as well as changes taking place in some presently subsiding coastal areas, demonstrate the considerable differences between clusters; *e.g.*, depending on sediment supply or length of dry season, but also between different parts of a coastal plain or delta. They also show that the approach of some authors (*e.g.*, MILLIMAN *et al.*, 1989), estimating land loss simply by comparison of topographic elevation and sealevels, may exaggerate loss and neglects the remodeling of the coastal strip and the deltaic or coastal plain by supply and redistribution of sediment.

Further work along the lines of this study could usefully distinguish between different parts of deltas presently dealt with in a unitary and necessarily global way: for example, the characteristics of the eastern coastal part of the Ganges-Brahmaputra delta (the Mouths of the Ganges) are very different from the western, moribund part (Sunderbans, Khulna, Barisal), and a more detailed study would recognize differences in their expected reaction to sealevel rise.

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