Coastal Lowlands

Geology and Geotechnology

Edited by

W. J. M. van der Linden, S. A. P. L. Cloetingh, J. P. K. Kaasschieter,

W. J. E. van de Graaff, J. Vandenberghe and J. A. M. van der Gun

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Edited by

W.J.M. van der Linden
Institute of Earth Sciences, University of Utrecht, The Netherlands

S.A.P.L. Cloetingh
Institute of Earth Sciences, Free University, Amsterdam, The Netherlands

J.P.K. Kaasschieter
Nijverdal, The Netherlands

W.J.E. van de Graaff
KSEPL, Rijswijk (ZH), The Netherlands

J. Vandenberghe
Institute of Earth Sciences, Free University, Amsterdam, The Netherlands

J.A.M. van der Gun
TNO-DGV, Institute of Applied Geoscience, Delft, The Netherlands

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Preface

Coastal Lowlands by virtue of their position across the boundary of land and sea belong to the earth's most dynamic systems. This is true in the physical, i.e. geological and biological, as much as in the cultural and social sense. Although the nearness to the sea was and still is fraught with danger coastal lowlands have always attracted human interest, providing challenging opportunity, holding the promise of profitable enterprise. Coastal lowlands, especially where rivers enter the region, are the cradles of great civilisations and there, of old, populations reached highest densities. As an example, Dutch history is a tale of human struggle and endeavour with and against the sea. Dutch 'lowlanders' wrestled their land from the sea, in turn the sea forged a nation of independent fishermen, navigators, farmers and traders who built their towns and ships at the borders of the North and Zuyder Seas.

As lowlands subside and sea level rises, apparently these days at an increasing rate, concern about this environment world-wide is also rising. It certainly was appropriate and timely for the Royal Geological and Mining Society of the Netherlands when celebrating its 75th birthday to organize and call together a symposium, focussing attention on the geology and geotechnology of coastal lowlands; geology to better understand their formation and evolution, geotechnology to better manage and harvest resources as much as protect a unique and crucial environment.

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Utrecht, Summer 1988
The Editors

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Deltaic coastal wetlands

James M. Coleman & H.H. Roberts
School of Geoscience, Coastal Studies Institute, Louisiana State University, Bâton Rouge, Louisiana, U.S.A.

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Key words: Deltas, coastal wetlands, landloss, subsidence, sealevel

Abstract

Modern-day deltas exist in a wide variety of settings. Despite the various environmental contrasts, all actively prograding deltas have at least one common attribute: a river supplies clastic sediment to the coast and inner shelf more rapidly than it can be removed by marine processes. The most important processes controlling the geometry and landforms in deltas are climate, water and sediment discharge and its variability, river mouth processes, nearshore wave power, tides and tidal regime, nearshore currents, shelf slope, tectonics of the receiving basin, and receiving basin geometry.

Many present-day deltas are experiencing relatively large coastal landloss; this results from the complex interaction of many physical, chemical, and biological processes that operate in the natural environment and, in more recent times, the processes induced by man's utilization of this environment. All of these processes operate at different scales and magnitudes, in both time and space; some are amenable to manipulation by man, while others are essentially out of his control. Natural processes include sea level changes, subsidence and compaction, changes in deltaic sites of deposition, catastrophic events such as hurricanes, and biologically-induced factors. Man-induced factors include dams and levees, canal dredging, and fluid withdrawal.

Introduction

Since ancient times, river delta lowlands have been of fundamental importance to civilization. Owing to their early significance as agricultural lands, deltas received considerable attention from scholars such as Homer, Herodotus, Plato, and Aristotle. The term delta was first applied by the Greek historian Herodotus, approximately 450 B.C., to the triangular alluvial deposits at the mouth of the Nile River. In broader terms, deltas can be defined as those deposits, both subaerial and subaqueous, derived from riverborne sediments and dispersed by distributary channels. Because the different processes which control delta development vary considerably in relative intensity on a global scale, delta plain landforms span nearly the entire spectrum of coastal features and include distributary channels, river mouth bars, interdistributary bays, tidal flats, tidal ridges, beaches, dunes, dune fields, swamps, marshes, and evaporite flats.

River systems have been in existence throughout geologic times; the only major prerequisites are a partially elevated land mass, a depositional basin, rainfall, and chemical and physical degradation processes. River size and overall morphologies, however, have varied through time and are dependent on tectonic episodes, size of continents, basinal tectonics, climate, severity of weathering processes, sea level changes, and similar global processes. Today's modern river systems occur in a wide variety of geologic settings with associated environmental processes. A knowledge of these variations is helpful in defining present trends in coastal regions, as well as attempting to predict future trends in these important wetlands. Coleman (1976) showed, in a study of numerous modern worldwide deltas, that only a few major processes are responsible for the major variations seen in modern deltas. These processes are: climate, water and sediment discharge and its variability, sediment type, river mouth processes, nearshore wave power, tides and tidal regime, nearshore currents, shelf slope, and tectonics and geometry of receiving basin. This paper is a review of the variations displayed by modern day river systems and a discussion of the processes responsible for landloss as illustrated by the Mississippi River coastal wetlands.

Delta attributes

Previous research has shown that deltaic facies associations are a function of numerous process variables. Attempts to incorporate some or all of these process variables into models for discriminating delta types have resulted in at least three classification themes. Fisher et al. (1969) proposed high constructive and high destructive delta types based on relative intensity of fluvial and marine processes. Coleman & Wright (1971) and Wright et al. (1974), using a broad range of parameters, quantified the process variables, then used statistical techniques to cluster deltas into discrete groupings. More recently, Elliott (1978) proposed a classification scheme based on the earlier work of Galloway (1975) wherein deltas were plotted on a ternary diagram to define general fields of fluvial, wave, and tide dominance. The most significant aspect of these studies is the recognition of the role of physical processes in producing specific and predictable responses.

Examination of a few major attributes of modern world river systems indicates that although a large number of variations exists, there are generalized trends and most exceptions can be logically ex-

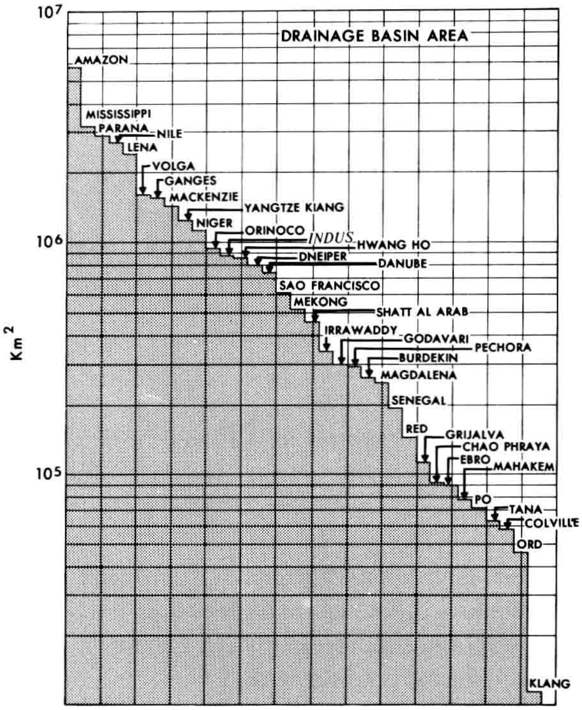

Fig. 1. Drainage basin areas of selected major river systems.

plained. Figure 1 shows the drainage basin area of some 34 major world river systems. Note that these river systems span the climatic zones and represent deposition in a wide variety of depositional settings. Today's basin drainage areas span nearly three orders of magnitude, from less than $1 \times 10^4\,km^2$ to greater than $4 \times 10^6\,km^2$. Figure 2 illustrates the delta plain area of modern world deltas and shows a variation of approximately three orders of magnitude. Plotting only these two parameters gives the result shown in Figure 3, that is, as the drainage basin area increases, so does the delta plain area. However, there is a very wide variation in delta size for any given size of a drainage basin. Plotting of any two parameters shows similar results, general trends, but wide variation within those trends, illustrating that deltaic facies display variability because of numerous interacting parameters. For example, the San Francisco delta of Brazil is relatively small for the size of its drainage basin; this delta is characterized by extremely high wave action, and most of the fine-grained

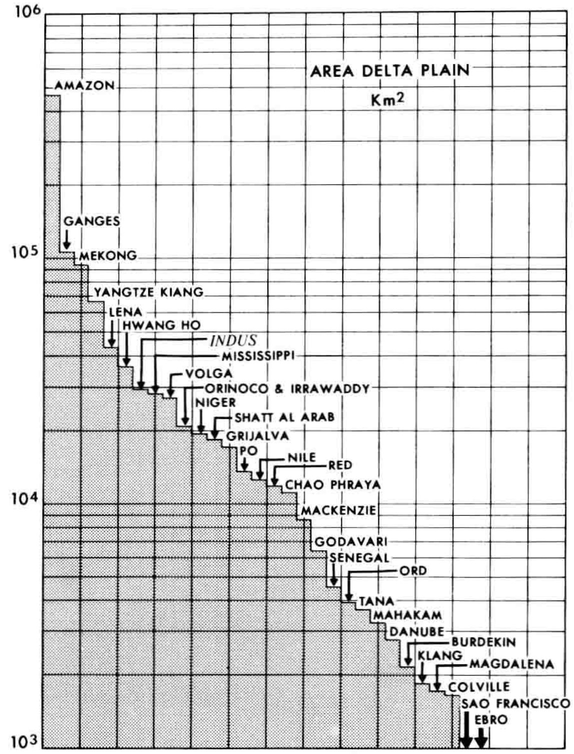

Fig. 2. Delta plain areas of selected major river systems (includes the subaqueous delta).

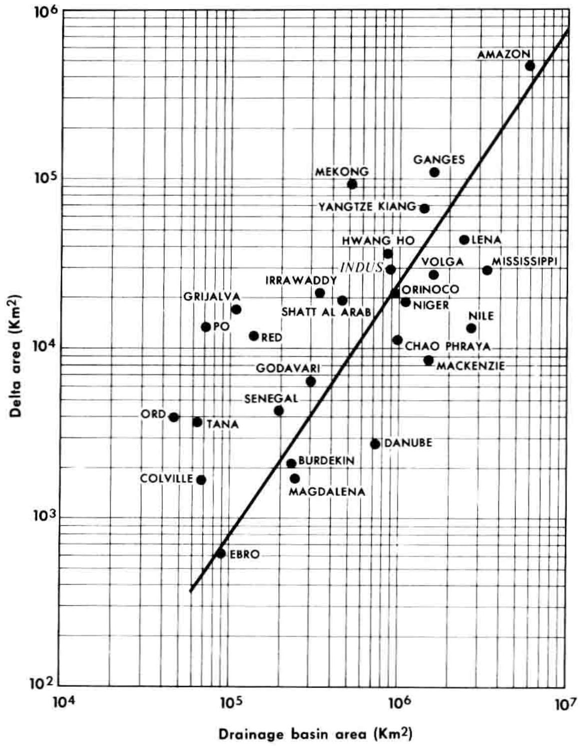

Fig. 3. Plot of drainage basin area against delta plain area. Sloping line is line of best fit.

sediment delivered to the basin is advected seaward by wave action and marine currents, while sands are concentrated at the shoreline as well as transported landward by eolian transgressive processes. In contrast, the Mekong delta of Vietnam is relatively large for the size of its drainage basin. The delta is rather stable (little subsidence) and is significantly influenced by tidal processes, which tend to laterally spread the deltaic facies associations.

Figure 4 illustrates river system discharge (m^3/sec) for several modern world deltas. Once again, there is nearly a three-fold magnitude in discharge among the rivers analyzed. Plotting discharge against delta area (Fig. 5) indicates that as discharge increases, delta area increases. Variations exist, but in the larger discharge river systems, this variation becomes minimal; it is the smaller discharge rivers which tend to show the highest variation primarily because of sediment load and sediment characteristics.

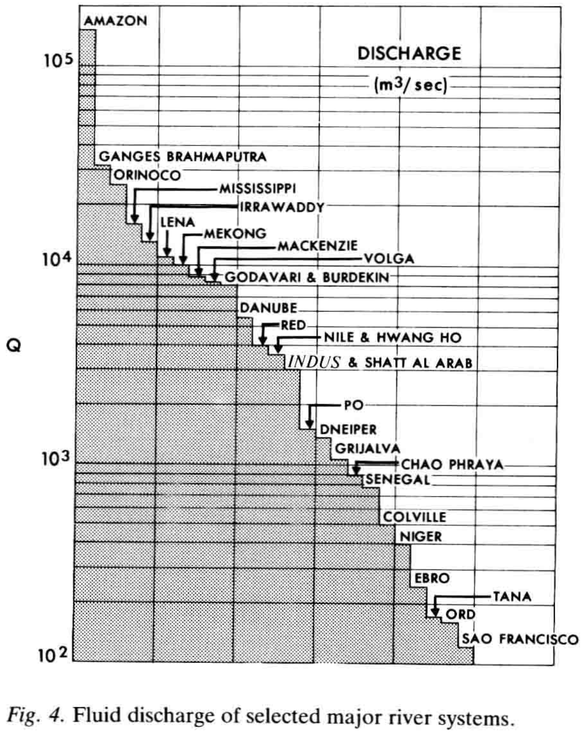

Fig. 4. Fluid discharge of selected major river systems.

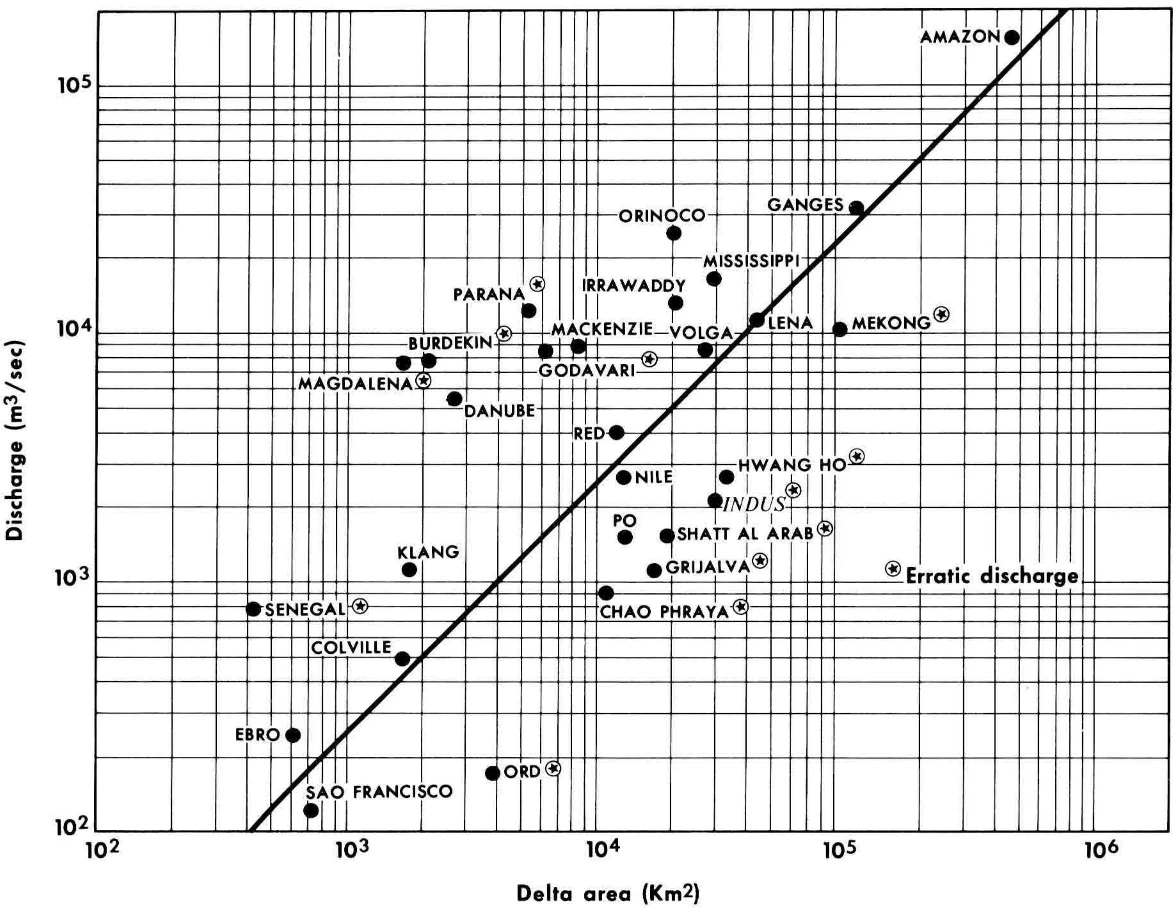

Fig. 5. Fluid discharge plotted as a function of delta area.

A quantitative evaluation of wave power ($\times 10^7$ ergs/sec/m of coast) for seventeen river systems is shown in Figure 6. This parameter shows extremely wide variation; the Senegal experiences nearly 1000 times more wave energy than the Mississippi. In other words, the Senegal receives more wave power along its coast in a little over two hours than the Mississippi River does all year. Such wave energy tends to smooth out the delta coast, preventing the development of protruding river mouths. Figure 7 plots delta shoreline length to straight-line width of the delta. Low wave energy deltas such as the Mississippi, Ganges, and Volga have high shoreline length to width ratios (approximately 4 : 1), whereas high wave energy deltas such as the Senegal, San Francisco, and Magdalena tend to show low ratios, generally 2 : 1 or less (Fig. 7). Although wave energy is highly dependent on the marine climate, one of the major controlling factors is the slope of the continental shelf fronting the delta. Figure 8 plots continental shelf angle against wave power. Those deltas having extremely low offshore slopes display relatively low shoreline wave energy, whereas those deltas displaying higher offshore slopes generally show much higher wave energy.

Tidal processes control the spatial relationships and geometries of deltaic facies. Three important characteristics of tidally dominated rivers can be identified: a) water-mass mixing by tidal activity destroys vertical density stratification, so that effects of buoyancy at river mouths are negligible; b) for part of the year tides account for the highest percentage of the sediment-transport energy, and

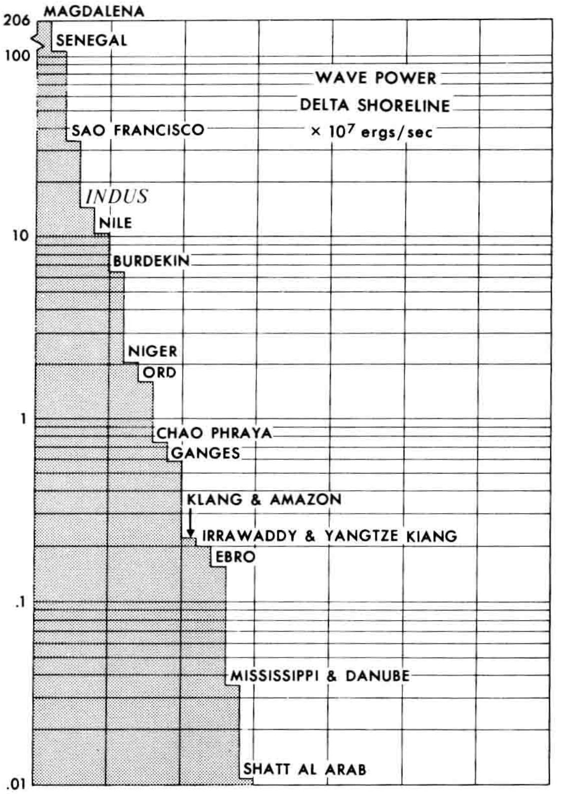

Fig. 6. Wave power ($\times 10^7$ ergs/sec) of selected delta shorelines.

flow both in and seaward of the river mouths is subjected to reversals over a tidal cycle; and c) the zone of marine-riverine interactions is greatly extended both vertically and horizontally. These effects result in widely differing geometries for the sand bodies that develop at the river mouth. Tidal processes are difficult to quantify, but Fig. 9 shows the average tidal range (in m) for 27 river deltas. The morphology of a low tide river delta such as the Nile or the Mississippi would be drastically altered in a short period of time if it was subjected to tidal inundation of nearly 6 m, as in the case of the Ord River delta of Australia.

Other factors are just as important as those discussed above, but many are very difficult to quantify. For example, the rate of subsidence controls the thickness of individual sand bodies and the stacking of the deltaic facies through time. However, this factor is virtually impossible to quantify because data on relative subsidence rates in modern world deltas do not exist. A more lengthy discussion of other factors that control deltaic facies development can be found in Coleman (1976), Coleman & Wright (1971), and Wright et al. (1974).

An alarming aspect of present-day deltaic lowlands is the rapid loss of subaerial wetlands. This is occurring on a worldwide basis; nearly all coastal deltaic plains have suffered extensive landloss within the past several centuries. The reasons are complex, yet an understanding of the major processes responsible for this loss is critical if mitigation measures are to be successful in slowing down this trend. Landloss is especially rapid in coastal Louisiana, the site of one of the world's major river deltas, the Mississippi River. In the third and fourth decades of this century, Russell (1936) and Fisk (1944) reported that Louisiana was losing its wetlands and that the state's coastal marshes were rapidly changing composition. Since that time, a considerable amount of research has been conducted to document and explain this wetland loss.

Wetland loss in the Mississippi River delta plain

The Mississippi River, the largest river system in North America, drains an area of 3,344,560 km^2 (Coleman, 1976) and has formed the largest coastal wetlands in North America. When De Soto found and named the Rio del Esperitu Santo, now the Mississippi River, in 1543, the Indians had been living in and utilizing its coastal zone for nearly 12,000 years (Gosselink, 1984). By the late 1800's industrial development had begun in the wetlands, and the construction of levees along the river accelerated this trend. The discovery of petroleum resulted in dredging of canals through the coastal wetlands for access to drilling sites. Geological and biological investigations of the delta began in the late 1800's (Lerch et al. 1892), but the most important studies of geomorphology and geology were concentrated in the middle to late 1900's. Significant studies include those by Russell (1936), Fisk (1944, 1952), and Kolb & Van Lopik (1958). Articles dealing with marsh ecology were published by Hathaway & Penfound (1936), Penfound & Hatha-

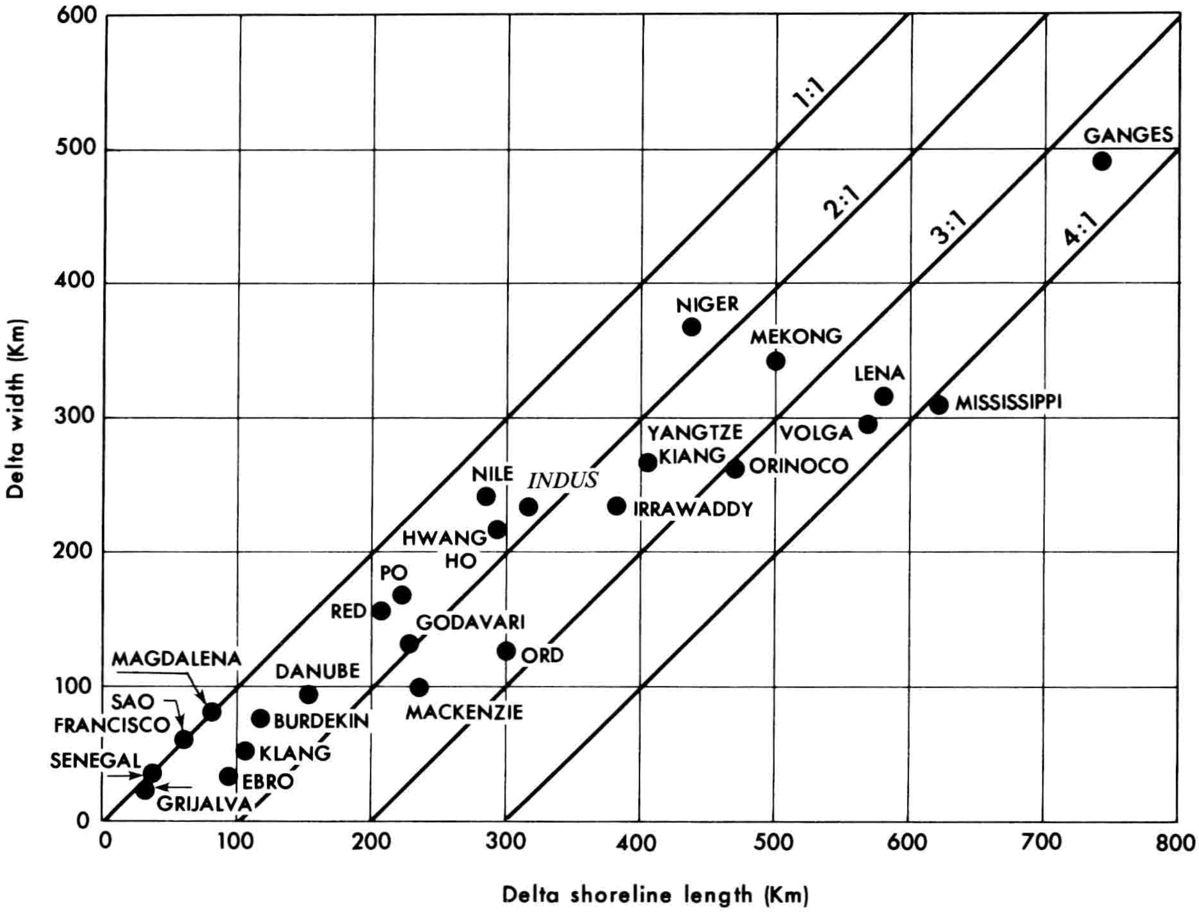

Fig. 7. Plot of delta shoreline length to straightline of delta width. Several ratio lines are shown for reference.

way (1938), and Brown (1944). More recent articles have extended the details of these early workers, and the advent of the Coastal Studies Institute and Sea Grant Program at Louisiana State University has expanded this field of study considerably.

The coastal area of Louisiana is a unique and valuable economic and environmental resource to the state and its citizens. Although early workers, especially Russell (1936) and Fisk (1944), called attention to the fact that Louisiana was losing its wetlands and that the coastal marshes were undergoing rapid change, little attention was paid to these predictions. Research by Gagliano & Van Beek (1970) and Gagliano et al. (1981) focused on this problem, and within a few years both the public and government agencies were acutely aware of the magnitude of the problem. Documented wetland loss rates averaging 0.8% per year (Gagliano et al., 1981; Turner et al., 1982) have caused major concerns about the future of the coastal parishes, state boundaries and hence oil and gas revenues, and renewable resources such as shrimp, crabs, and menhaden. Figure 10 shows the magnitude of this loss across Louisiana's wetlands. In some areas, especially the modern Mississippi River delta, the rates are exceptionally high; Figure 11 shows the accelerating rate of land loss in the Mississippi deltaic plain. Although various investigators differ as to the causes for rates of land loss, the numerous studies all indicate that the wetlands of Louisiana are being lost and undergoing rapid changes.

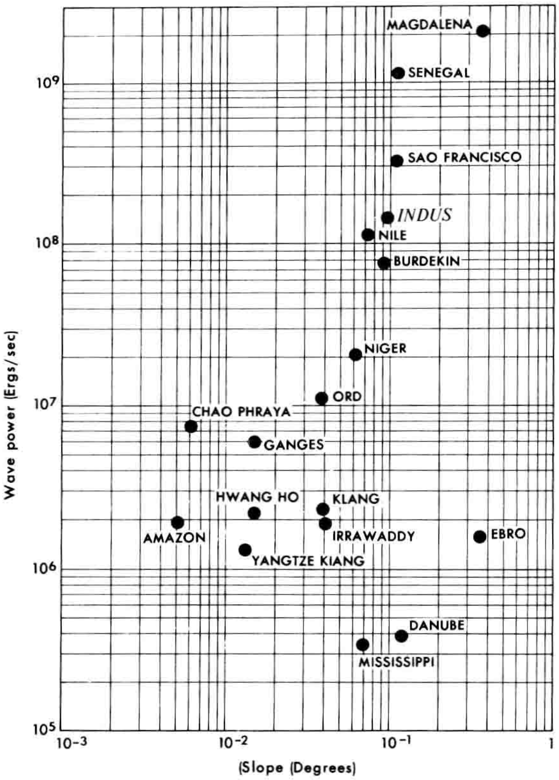

Fig. 8. Plot of wave power (ergs/sec) against offshore slope (degrees).

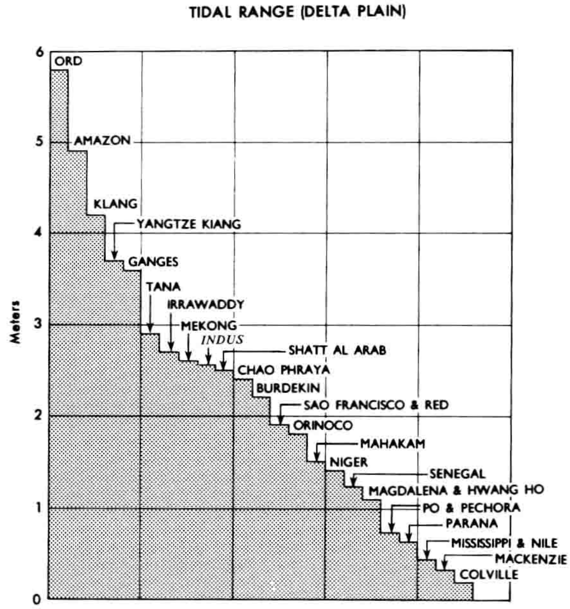

Fig. 9. Average tidal range of selected river deltas.

Causes of Louisiana's wetland loss

Rapid degradation of the wetlands is cause for considerable alarm. Wetland loss results from the complex interaction of many physical, chemical, and biological processes that operate in the natural environment and, in more recent times, the processes induced by man's utilization of this environment. All of these processes operate at different scales, in both time and space; some are amenable to manipulation by man, while others are essentially out of his control. In order to better understand some of these processes, it is helpful to view the development of the Gulf Coastal Plain over a long period of geological time so that present conditions can be placed in proper perspective.

The Mississippi River has had pronounced influence on the development of the northern Gulf of Mexico throughout a long period of geological time. Since the beginning of the Tertiary Period (some 65 million years ago), thermal cooling and the delivery of large volumes of sediment brought down by coastal rivers, especially the ancestral Mississippi Rivers, have created a major subsiding sedimentary basin, the Gulf Coast Geosyncline. Many of the ancient subsurface sedimentary sequences were laid down in localized depocentres, the prolific hydrocarbon-producing horizons that have formed the basis for Louisiana's recent economy. Geologists have documented that throughout this long period of geological time, there were major changes in the position of the shoreline and in the presence of large, extensive coastal plains that have been developed and subsequently lost by coastal inundation. Overall, however, the coastal plain has experienced a net gain in sediments, and the long-term pattern has been shoreline progradation and continued buildout of coastal environments. Causes of the 'cyclic' patterns of coastal retreat and loss are complex; they result from such processes as changes in the sediment yield, climate, sea level (both eustatic and subsidence), and patterns or sites of sediment deposition. In the Quaternary, changing sea levels associated with the

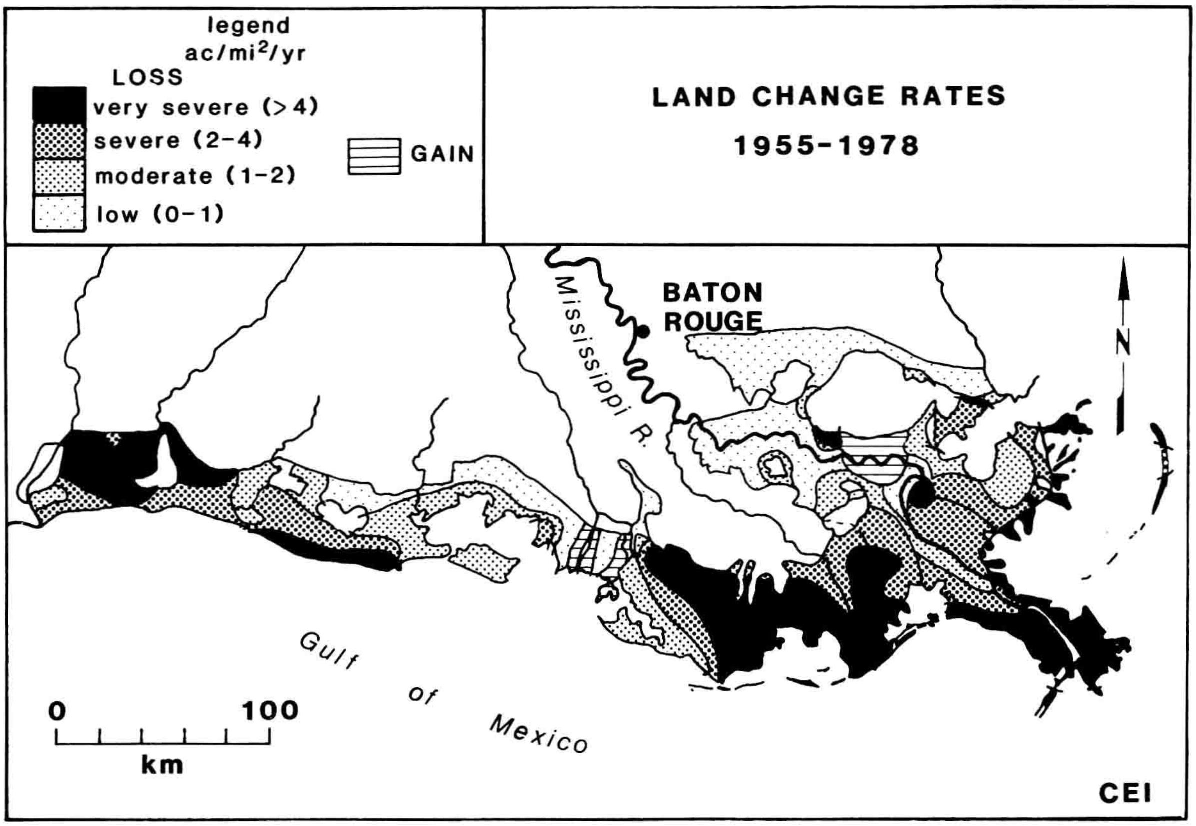

Fig. 10. Rates of land loss in the coastal wetlands of Louisiana (after Van Beek & Meyer-Arendt, 1982).

advance and retreat of inland glaciers have strongly influenced the near-surface sedimentary patterns of coastal wetland development. Numerous times during this period, extensive coastal advances and retreats have taken place. Freshwater marsh deposits (representing older wetlands) have been documented from cores taken in offshore Louisiana and Texas in water depths of 200 m and at distances several hundred kilometres from the present shoreline.

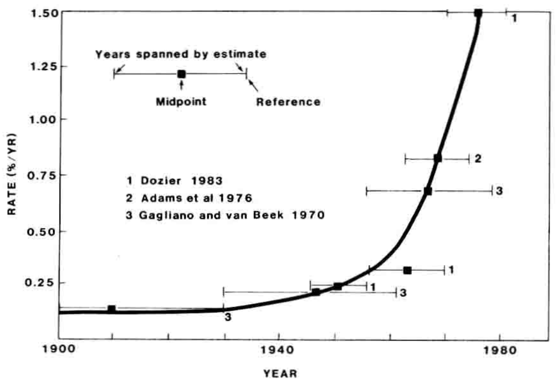

Fig. 11. Accelerated rate of land loss from 1900 to late 1980's. After Dozier, 1983.

In order to understand the changes in the coastal marshes that comprise our present-day wetlands, it is necessary to examine briefly some of the major factors, both natural and man-induced, that contribute to wetland loss. The following sections describe some of these major processes; it should be mentioned that there are second- and third- order processes not included in this compilation. However, we consider the factors listed below as the most important in contributing to wetland loss:

I. Geological factors
   A. Sea level changes
   B. Subsidence and compaction

C. Changes in deltaic sites of deposition
II. Catastrophic factors: (hurricanes)
III. Biological factors
IV. Man-induced factors
A. Dams and levees
B. Canal dredging
C. Fluid withdrawal

Geological factors

Sea level changes

Controls on sea level. The total volume of water in the ocean basins is believed to have remained fairly constant throughout the earth's evolution. The interplay of such processes as plate tectonics and climate has produced a variable and sometimes erratic record of sea level changes throughout geological time. Plate tectonics and climate control sea level position on a worldwide or 'eustatic' scale, whereas the regional influences of geology, climate, and hydrology interact to affect sea level on a local scale. Commonly, the local processes can override the global trend in sea level, resulting in regional sea level 'highs' or 'lows'.

Vail et al. (1977) have derived a global sea level curve showing relative high and low stands from the Precambrian (575 M.a. B.P.) to the present. Vail et al. (1977) curves indicate that the average position of sea level during geological time was higher than present sea level. Response of the oceans to climatic changes is the most important factor influencing short-term sea level positions. Five major sequences of glacial advance occurred during the 2.1 million years of Pleistocene time.

The most recent of the glacial advances (17,000 years B.P.) depressed sea level approximately 110 m below its present stand (Fig. 12; Nummedal, 1983). The subsequent rise in sea level following glacial retreat 15,000 years B.P. has been termed the Holocene transgression. Although the Holocene transgression is depicted as a smoothly increasing rise in sea level, Brooks et al. (1979) have shown that on a local scale, the rate of rise can be highly erratic (Fig. 13). Worldwide climate and local tectonic changes are probably responsible for the irregular Holocene sea level curve.

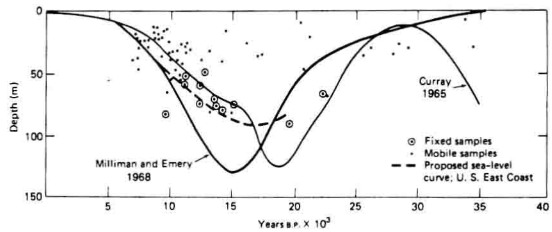

Fig. 12. Sea level curves for the Late Quaternary from sites on the east coast of the U.S. From Nummedal, 1983.

Coastal Louisiana is highly vulnerable to short-term changes in water level caused by hurricanes, cold-front passage, and flood waters. Increases in sea level produced by these processes may range from a few centimetres to several metres, and from a few hours to weeks in duration.

Recent sea level. Numerous attempts have been made to quantify the present rate of sea level rise, but, owing to the highly variable regional controls on sea level and the inability to acquire a reliable and representative data base, estimates of the eu-

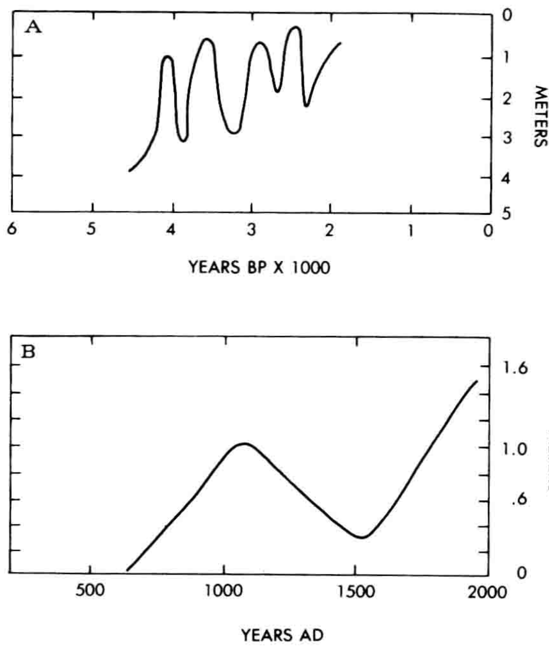

Fig. 13. Sea level fluctuations on (A) the South Carolina coast over the past 4000 years and (B) on the North Sea Coast of Germany since the year 650 AD. From Nummedal, 1983.

static sea level rise range from 1.2 to 3.0 mm/year (Kraft, 1971; Nummedal, 1983). A eustatic rise of 1.2 mm/year is generally accepted, and is the value used in computing subsidence rates in Louisiana.

This rate of sea level rise is apparently due to glacial melting and expansion of the oceanic water (Nummedal, 1983). Hoffman et al. (1983) have postulated a series of accelerated sea level rise scenarios based on climatic warming trends and projections of the greenhouse effect. Values for the medium sea level rise scenario outlined by the Environmental Protection Agency (Hoffman et al., 1983) suggest that sea level will be rising 3.3 mm/yr by the year 2025; 6.6 mm/yr by 2050; and 11.4 mm/yr by 2075. These values do not take subsidence into consideration; so the relative rates of sea level rise in Louisiana could be much higher.

Subsidence in coastal Louisiana

Subsidence occurs naturally in Louisiana on both regional and local scales as a result of processes ranging from downwarping of the earth's crust in response to thermal cooling and excessive sediment loading, to rapid compaction of unconsolidated coastal sediments. Numerous data sets (Trahan, 1982; Holdahl & Morrison, 1974; Swanson & Thurlow, 1973) have shown that there is a general trend toward increasing subsidence to the south and southeast in Louisiana. This increase in regional subsidence reflects both greater sediment thickness and loading of the crust toward the axis of the Gulf Coast Geosyncline as well as compaction/dewatering of vast areas of geologically young sediments deposited by the modern Mississippi River.

Tectonic subsidence. Development of the Gulf Coast Geosyncline was promoted by accumulation of thick, elongate sedimentary masses that were deposited on top of each other as successive delta sequences prograded seaward with time (Murray, 1961). These depocenters are genetically linked to the down-to-the-Gulf fault systems that roughly parallel the present northern Gulf shoreline. Such faults are commonly termed growth faults or contemporaneous faults. As sedimentation and loading continue, many of these faults remain active and thus add to the regional subsidence in Louisiana. Accurate rates of movement along growth faults over short times is not presently known, but offshore seismic data indicate that many of them are experiencing movement today. Much of the regional subsidence can be associated with fault compensation and with deformation of sediments under loading. However, lateral and vertical flowage of thick salt beds (Worzel & Burk, 1979) that underlie deposits of the ancestral Mississippi River, as well as the modern delta, also adds to the regional subsidence. Again, little quantitative data exist on the amount of subsidence that is attributable to salt withdrawal or salt solution at depth. Both crustal downwarping and salt mobilization are long-term components of regional subsidence.

Sediment loading and compaction. Shorter term processes that certainly add to sinking of the land, resulting in wetland loss, involve localized sediment loading, dewatering, and physical/chemical compaction of recently deposited sediments (younger than 6000 years) of the coastal plain. The dominantly fine grained and highly organic sediments of Louisiana's coastal plain are subjected to three processes that add to subsidence immediately after deposition (Terzaghi, 1943):

1. Primary consolidation – a reduction in the volume of the soil mass owing to dewatering under a sustained load. The load is transferred from the interstitial water to the soil particles.
2. Secondary compression – a decrease in soil volume associated with the rearrangement of constituent particles.
3. Oxidation of organic matter – reduction of soil volume as chemical reactions occur that cause organic matter to decompose into its mineral constituents.

These processes are fundamental properties of all sediment deposition. However, in areas where sedimentation rates are high, where the sediments contain high amounts of water, and where organic content is high, these processes are extremely active and contribute significantly to land loss. When viewed in a short period of time, for example the last 5000 years, it is apparent that sedimentation and accompanying compactional processes are not uniformly distributed across the coastal plain and

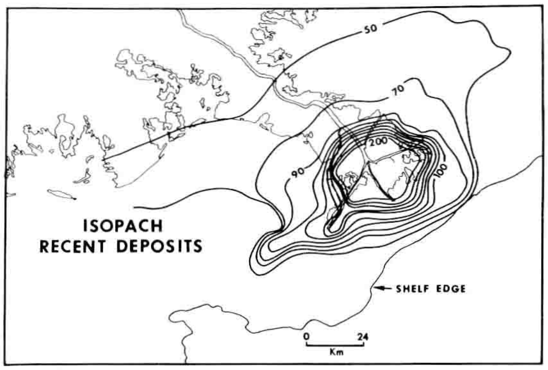

Fig. 14. Isopach of 'Recent' sediments in the modern Mississippi River delta. Contours in metres.

shallow continental shelf. Switching of the site of deposition is the rule rather than the exception in coastal Louisiana. Although each depositional event (delta lobe) takes only about 1000 to 1500 years to complete (Kolb & Van Lopik, 1958; Frazier, 1967), Figure 14 illustrates that sediments in a single delta lobe can be over 100 m thick. A column of dominantly fine grained sediment of this magnitude, deposited in less than 1000 years, suggests that normal processes of compaction have not had time to consolidate the sediments, as would be the case under less rapid sedimentation conditions. Therefore, compaction in areas of thick deposits can be expected to be greater than in areas where sedimentation is slow and recent deposits are thin.

On a regional scale, this point of view can be supported by comparing long-term water level records. In dynamic areas of sedimentation such as the Mississippi delta, compaction causes the mean water level to increase at the gauge site relative to the rate of sea level rise caused by eustatic processes. Thus in areas experiencing high compaction and subsidence, water level rise over even short periods of time are significantly higher than in areas having less subsidence and compaction. Figure 15 compares a water level gauge record from the central coast of Louisiana with one from a much more stable area in western Florida. The major differences in the rate of water level rise can be attributed to subsidence and compaction of deltaic sediments associated with the Louisiana site. This rate of water level rise, 1.61 cm/yr, includes eustatic sea

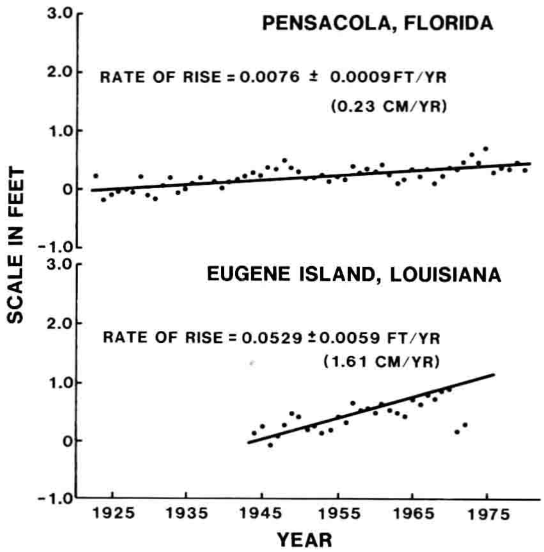

Fig. 15. Water level gauge records from Florida and Louisiana. Data courtesy of Louisiana Geological Survey.

level rise. If eustatic sea level rise is subtracted, the rate of compaction and subsidence at the Louisiana site is 1.59 cm/yr. This figure is significant when compared to the vertical accretion rate of the marsh (Table 1).

On a local scale, the thickness of recently deposited sediments over a more consolidated Pleistocene surface can make a considerable difference in subsidence and compaction rates. Figure 16 illustrates subsidence data calculated from three soil borings across the central Louisiana coastal plain. The borings are located so that they cross the old

Table 1. Accretion Rates in Louisiana Coastal Marshes.

Marsh Type	Accretion Rate (cm/yr)	
	Mean	Range
Fresh – streamside	1.06	–
Fresh – inland	0.65	0.31–0.69
Intermediate – streamside	1.35	1.30–1.40
Intermediate – inland	0.64	0.38–1.06
Brackish – streamside	1.40	1.06–1.69
Brackish – inland	0.59	0.38–0.81
Salt – streamside	1.35	–
Salt – inland	0.75	0.56–0.94