Sedimentary Geology, 80 (1992) 233–246
Elsevier Science Publishers B.V., Amsterdam

Geologic and human factors in the decline of the tidal salt marsh lithosome: the Delaware estuary and Atlantic coastal zone

John C. Kraft, Hi-Il Yi and Md. Khalequzzaman

Department of Geology, University of Delaware, Newark, DE 19716-2544, USA

Received October 15, 1991; revised version accepted April 10, 1992

ABSTRACT

Kraft, J.C., Yi, H.-I. and Khalequzzaman, Md., 1992. Geologic and human factors in the decline of the tidal salt marsh lithosome: the Delaware estuary and Atlantic coastal zone. In: J.F. Donoghue, R.A. Davis, C.H. Fletcher and J.R. Suter (Editors), Quaternary Coastal Evolution. Sediment. Geol., 80: 233–246.

Two to three thousand years ago, the fringing tidal salt marsh wetlands (including brackish and freshwater marsh) of the Delaware coastal zone were three to four times wider than at present. Observed variations in rates of marsh surface aggradation suggest that some areas are undergoing inundation whereas many other areas are undergoing aggradation at rates greater than sea-level rise as measured by a local tidal gauge (average 33 cm/century based on a 70-year record) and may be undergoing floral succession. Accompanying these sedimentary processes are coastal erosion rates up to 6.9 m/yr along the Delaware estuary, up to 2.8 m/yr along the Delaware Atlantic coast, and ranging from 0.1 m/yr to 0.6 m/yr along the Delaware Atlantic coastal lagoons. Human development has destroyed nearly 9% of Delaware's fringing salt marshes between 1938 and 1975. The rapidly growing trend toward hardening the edge of the adjacent landward uplands leads us to the conclusion that much of the fringing salt marsh of Delaware will disappear over the next two to three centuries with only small remnants declining to extinction ca. 1500–1700 years into the future. Impacts on the State of Delaware, comprised of 13% fringing salt marshes 1/4 century ago, will be profound in terms of destruction of a large segment of the Atlantic coastal or eastern North American migratory bird flyway, and an eventual forced accommodation of the inhabitants of Delaware to these naturally ongoing geological processes.

Introduction

The nature of human occupation of the Delaware coastal zone has rapidly changed to a "hardening" of the landward edge of the marshes against future transgression. Nearly all tributary tidal streams in the Delaware coastal zone had mill dams constructed across the tidal creeks in colonial times. Thus, extension of salt marsh environments inland along the axes of most major tidal streams has stopped. With increasing pressures on farmlands along the landward fringe of the salt marsh, it appears that the next century will include aggressive human actions to further stop the natural encroachment of salt marsh facies driven by the rise in local relative sea levels. Indeed, many farmers already direct their plows towards the marsh fringe to create a higher berm, while a relative few farmers construct dikes or polders to halt the transgressing marine waters (i.e. SW New Jersey).

The main concern of this study is the rate of destruction of the coastal marshes, apparently accelerating with the rapid increase in rate of local relative sea-level rise as documented during the past 150 years. The results included herein are based on our analyses of 20 cores of the upper marsh lithosome surface in which aggradation rates are determined by the use of radionuclide analysis of ^{210}Pb and ^{137}Cs. Rates from two cores of lagoonal sediments previously reported by Chrzastowski (1986) are also noted. Compar-

Correspondence to: J.C. Kraft, Department of Geology, University of Delaware, Newark, DE 19716-2544, USA.

isons are made with other studies in the surrounding regions of the upper Delaware estuary (New Jersey), the lower Chesapeake Bay region and the back barrier marshes of the eastern shore of Virginia.

Coastal erosion and marsh evolution studies

In this paper we present results of several decades of study of salt marsh evolution, coastal erosion, Holocene Epoch paleogeographies and projections of possible future Delaware coastlines. Regardless of the varied greenhouse-effect projections, it is much more important that we address presently extant geological processes. The rates and nature of coastal erosion over the past 150 years are known and we can project them into the near future with reasonable assurance. Similarly, studies show the nature of the evolution of the marsh surface to be highly varied within the Delaware coastal zone. These studies plus the results of the intrusion of human development into the natural evolution of our coastal system form the rationale for this paper.

Holocene epoch sea-level rise (fluctuation): the driving force

Concurrent with the late Wisconsinan Age glacial sea-level low at approximately 130 m below present sea level ca. 18,000 years ago, the Delaware coastal zone lay approximately 75 to 100 km seaward of its present location. Both logic and sparse geological evidence from the outer shelf (Whitmore et al., 1967; Swift, 1973) suggest that coastal and estuarine environments similar to those of present-day Delaware have moved ever landward and upward throughout the Holocene Epoch (Kraft, 1971, 1988; Kraft and John, 1976; Kraft et al., 1979; Belknap and Kraft, 1985; Chrzastowski, 1986; Knebel et al., 1988; Fletcher et al., 1990, 1992). With this inundation along the axis of the ancestral Delaware River and its many tributaries, coastal environments, including the great estuarine and lagoonal fringing marshes as well as back barrier marshes, moved ever landward. The problem of defining the history of sea-level change is one of both world eustasy as well as local and regional tectonism, sediment compaction, water withdrawal from subsurface aquifers, climate-driven deglaciation and variations in the shape of the geoid, amongst others. Within these constraints, using local relative sea-level data, we can engage in studies of evolving sedimentary environments and their resultant lithosomes with considerable precision.

In the past 2000 years, local relative sea level has risen on average 0.12 cm/yr (Belknap and Kraft, 1977; Kraft and Belknap, 1986). There is a problem, however, with these "longer-term" rates of change in sea levels. As they are based on limited ^{14}C data (ca. 100 ^{14}C dates), they may present a blurred image of steady-state rise or an

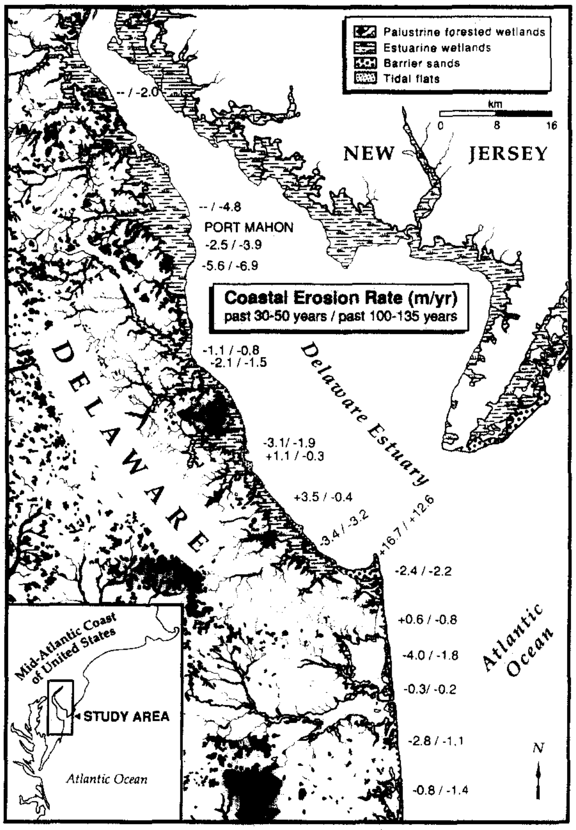

Fig. 1. Map showing the salt marshes of the Delaware estuary and Atlantic coastal lagoons with the rates of shoreline erosion in ca. the past 30–60 years (various map ages 1915–1977) and in ca. 100–135 years (various map ages 1842–1977, and aerial photos of ca. 1935–1977). Shoreline erosion rates were calculated from map and aerial photograph data by courtesy of the Department of Natural Resources and Environmental Control, State of Delaware, Mr. Robert Henry, Manager, Beach Preservation Section. Base map from Tiner (1985).

average of many short-term sea-level fluctuations (C.H. Fletcher III, unpublished data; Thomas and Varekamp, 1991; van de Plassche, 1991). Acceleration in rates of coastal erosion over the past 70 years (1920–1991) are accompanied by a sharp rise in sea level of 0.33 cm/yr at the tidal gauge at Breakwater Harbor, Delaware (Fig. 1). This rise is three times the average rate over the

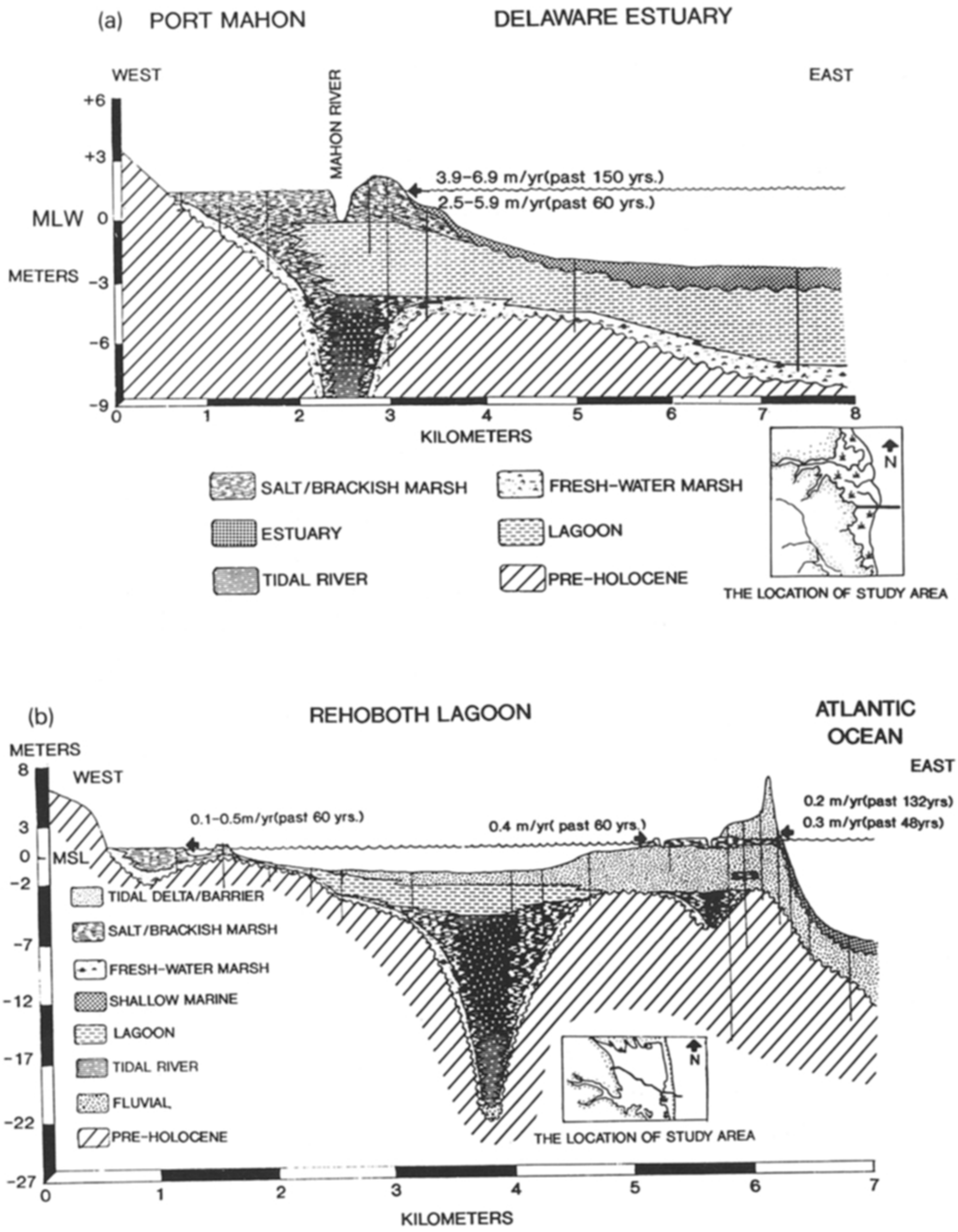

Fig. 2. Geological cross-sections showing the present salt marsh environment correlated with the subsurface extension of the Holocene Epoch salt marsh lithosome and other paralic stratigraphic units. (a) The broad fringing salt marsh of the Delaware estuary at Port Mahon; (b) the fringing and back barrier marshes of the Atlantic coastal lagoon, Rehoboth Bay. Rates of coastal erosion based on data from the Department of Natural Resources and Environmental Control of the State of Delaware, Mr. Robert Henry, and from Swisher (1982). Cross-section (b) after Chrzastowski (1986).

TABLE 1

Sediment aggradation rates and shoreline erosion rates

Location Name	Core number	Core depth (cm)	Regression equation	r^2	Sed. rate (cm/yr) based on ^{210}Pb		Sed. rate (cm/yr) based on ^{137}Cs	Shoreline erosion	
					±50 yrs	±100 yrs		short-term ~30–60 yrs	long-term ~100–135 yrs
Woodland Beach marsh	1	0–18	$Y = -0.149X + 1.547$	0.77	0.21	–	–		
		0–38	$Y = -0.046X + 0.739$	0.29		0.68	–		
Duck Creek marsh	2	0–16	$Y = -0.098X + 1.231$	0.71	0.32	–	0.32		
		0–40	$Y = -0.091X + 1.126$	0.94	–	0.34	–		
Port Mahon marsh	3	0–16	$Y = -0.016X + 1.011$	0.04	1.91	–	–	2.5–5.6 m/yr	3.9–6.9 m/yr
		0–38	$Y = -0.052X + 1.361$	0.70	–	0.59	–	(1910–1977)	(1842–1977)
	4	0–18	$Y = -0.053X + 1.079$	0.75	0.58	–	0.36		
		0–38	$Y = -0.083X + 1.187$	0.61	–	0.37	–		
	5	0–18	$Y = -0.059X + 1.462$	0.81	0.52	–	0.60		
		0–42	$Y = -0.074X + 1.599$	0.94	–	0.42	–		
	6	0–20	$Y = -0.053X + 1.810$	0.90	0.59	–	0.60		
		0–62	$Y = -0.082X + 2.032$	0.77	–	0.38	–		
	7	0–22	$Y = -0.064X + 1.807$	0.95	0.49	–	0.60		
		0–42	$Y = -0.073X + 1.925$	0.92	–	0.43	–		
	8	0– 9	$Y = -0.085X + 2.003$	0.93	0.37	–	0.38		
		0–21	$Y = -0.076X + 1.936$	0.94	–	0.41	–		
	9	0–14	$Y = -0.085X + 1.169$	0.39	0.37	–	0.20		
		0–30	$Y = -0.126X + 1.545$	0.83	–	0.25	–		
South Bowers marsh	10	0–16	$Y = -0.072X + 0.847$	0.33	0.43	–	0.18	2.1 m/yr	1.5 m/yr
		0–38	$Y = -0.154X + 1.368$	0.78	–	0.20	–	(1910–1977)	(1842–1977)

Mispillion River	11	0–20	$Y = -0.058X + 1.230$	0.46	0.53	–	0.36	1.1 m/yr	0.3 m/yr
marsh		0–38	$Y = -0.084X + 1.462$	0.75	–	0.37	–	(1946–1977)	(1884–1977)
Great Marsh	12	0–19	$Y = -0.038X + 0.865$	0.29	0.82	–	–	3.4 m/yr	3.2 m/yr
		0–38	$Y = -0.092X + 1.419$	0.64	–	0.34	–	(1946–1977)	(1884–1977)
	13	0–16	$Y = -0.064X + 1.551$	0.77	0.49	–	0.44		
		0–34	$Y = -0.101X + 1.792$	0.94	–	0.31	–		
	14	0–12	$Y = -0.109X - 0.520$	0.73	0.29	–	0.50		
		0–22	$Y = -0.040X + 5.661$	0.44	–	0.77	–		
Lewes Creek	15	0–20	$Y = -0.156X + 1.763$	0.39	0.20	–	0.36	2.4 m/yr	2.2 m/yr
marsh		0–38	$Y = -0.115X + 0.386$	0.31	–	0.27	–	(1929–1977)	(1845–1977)
Rehoboth Bay	16	0–18	$Y = -0.053X + 0.259$	0.35	(0.59)	–	–	4.0 m/yr	1.8 m/yr
Lagoonal mud		0–26	$Y = -0.133X + 0.974$	0.76	–	(0.23)	–	(1944–1977)	(1845–1977)
Rehoboth Bay	17	0–20	$Y = -0.056X + 1.085$	0.43	0.56	–	0.41		
		0–38	$Y = -0.093X + 1.582$	0.76	–	0.33	–		
Indian River	18	0–20	$Y = -0.108X + 2.073$	0.97	0.23	–	0.24	to	to
Bay		0–32	$Y = -0.045X + 0.946$	0.15	–	0.69	–		
Indian River Bay	19	0–28	$Y = -0.044X + 0.126$	0.57	(0.69)	–	(0.50)		
Lagoonal mud		0–38	$Y = -0.061X + 0.289$	0.54	–	(0.51)	–		
Indian River	20	0–14	$Y = -0.029X + 0.981$	0.98	1.07			0.3 m/yr	0.2 m/yr
Bay		0–22	$Y = -0.050X + 1.130$	0.95	–	0.69		(1929–1977)	(1845–1977)
Little Lagoon	21	0–18	$Y = -0.049X + 1.824$	1.00	0.63	–	0.36	0.8 m/yr	1.4 m/yr
marsh		0–38	$Y = -0.112X + 2.421$	0.96	–	0.28	–	(1929–1977)	(1850–1977)
Assawoman Bay	22	0–22	$Y = -0.038X + 1.411$	0.34	0.82	–			
Lagoon marsh		0–38	$Y = -0.088X + 1.960$	0.84	–	0.35	–		
					Average aggradation rates				
					0.57	0.42	0.39		

past 2000 years and could, in part, be attributed to an initial greenhouse effect evolving from the industrial revolution.

Environmental sequences

We have carried out many studies of the various sedimentary environments including morphology, floral, faunal, sediment size, and lateral and vertical facies relationships in coastal Delaware (Fig. 2). In optimal areas, the lateral order of environmental sequence from land to sea is precisely duplicated in the subsurface vertical stratigraphic record, as predicted in Walther's Law of Correlation of Facies (Kraft, 1971; Kraft and John, 1976; Kraft et al., 1979, 1987a; Fletcher et al., 1990). These studies have shown that predictability of time and space of sedimentologic and stratigraphic events is excellent and in continuity with presently ongoing processes. The ultimate preservation of these stratigraphic sequences is of course subject to erosion in the ravinement surface to variable depths as noted by Belknap and Kraft (1985) and Kraft et al. (1987b).

The greenhouse effect

Over the past decade, much has been said in regard to the greenhouse effect (Hoffman et al., 1983; Revelle, 1983; Titus et al., 1984). Predictions are made of sea-level rise of the world's oceans over the next century of 0.60 m ($\pm$3–10 mm/yr) (IPCC, 1990). Meier (1990) suggested that previous "... estimates may be too high." However, "With an almost certain rise of a half-meter by the year 2100 and even with all currently developed areas protected from inundation and erosion, more than 4000 mi^2 (10,870 km^2) of vegetated wetlands will be lost. With a probable rise of 1 m by the year 2100, 6441 mi^2 (16,687 km^2), or approximately 65%, of the coastal marsh and swamps of the contiguous United States could be lost" (Park et al., 1991). Although science cannot be done by consensus, many scientists agree that there will be a significant increase in the world's sea levels as a result of increased global warming due to the greenhouse effect. Meier (1990) further noted that "even a 30-cm (by 2050 A.D.) rise will cause social and economic problems in low-lying areas ... correspond(ing) to a retreated shoreline of 30 m or more ... ". Delaware's coastal zone is already undergoing far greater rates of coastal erosion than those envisaged above.

Kana et al. (1988a, b) noted the high potentials for near future development of the adjacent edge of the coastal plain upland and resultant inhibition of marsh succession and major loss of coastal marshes. In general, Kana et al.'s studies in South Carolina and New Jersey suggested that a 1-m rise in sea level by 2100 A.D. (0.9 cm/yr) would destroy up to 50% of the present wetlands, whereas, a 2-m (1.8 cm/yr) rise would destroy 80% of the coastal marshes. Such figures are, of course, much dependent upon development practices along the edges of the adjacent uplands, which could approach 100% in future centuries.

Methods and area of study

Area studied

The area studied includes the broad fringing marshes of the Delaware estuary (Delaware Bay) and the fringing and back barrier marshes of the Atlantic coastal lagoons of Delaware, presently transgressing landward and upward over the low-lying coastal plain. Studies were concentrated on the low-marsh (*Spartina alterniflora*) regions in an attempt to determine whether or not the relationships between sea-level rise and fluctuation of rates of marsh surface aggradation could be segregated and identified (see Pethick, 1981). Attempts were made to observe possible floral succession in the cores. However, we did not study the major floral succession elements so well described by Allen (1978).

Rates of coastal erosion

Coastal erosion rates were originally studied in detail by Maurmeyer (1978) for the Atlantic Ocean and Delaware estuary coastlines and Swisher (1982) for Delaware's coastal lagoons also known as Delaware's "inland bays". In this study, coastal erosion rates were determined from boat sheets of the U.S. Coastal Survey and U.S. Coast and Geodetic Survey, and aerial photo data from the U.S. Department of Agriculture and U.S. Coast and Geodetic Survey. Basic concepts of Delaware's coastal erosion were delineated in Kraft et al., 1979.

Radionuclide analyses

Radionuclide analyses of ^{210}Pb and ^{137}Cs were used as dating methods for marsh surface aggradation in the salt marsh environment. Salt marsh sediments were obtained by an extensive vibracoring program using irrigation pipe of 7 cm in diameter with standard vibration equipment, and an Eijkelkamp gouge auger (2 cm in diameter). Some of the samples for radionuclide analysis were isolated into sterile metal containers in the field; other samples were removed directly from sealed cores in the laboratory. Floral elements at the marsh surface as well as in the sediments were easily identified by visual means. The depth profiles of radionuclides in three cores were measured using a nondestructive technique with a germium detector coupled with a multichannel analyzer in Dr. T.M. Church's laboratory, University of Delaware (Khalequzzaman, 1989). The other nineteen cores were analyzed by Teledyne Isotopes, Westwood, New Jersey.

Results

Salt marsh surface aggradation

Calculated rates of marsh surface aggradation using radionuclide analyses varied from a low of 0.20 cm/yr to an extreme of 1.91 cm/yr with average rates of 0.42 cm/yr (over the past 150 years) and 0.57 cm/yr (over the past 50 years) as based on 20 cores taken from a varied set of fringing marsh conditions of the Delaware estuary coastal zone as well as the fringing and back barrier marshes of the Atlantic coastal lagoons. Aggradation rates determined for the upper parts of most of the cores compared favorably with those calculated using the ^{137}Cs method of identifying the "Cesium spike" of 1963 A.D. (Table 1).

Sediment accumulation rates varied widely across a broad spectrum of marsh settings. Further, on an empirical basis, more recent aggradation rates appear to be higher than those of the longer-term rates of marsh surface aggradation over the past 150 years. A number of factors may be involved in the wide divergence of marsh surface aggradation rates. Certainly the marsh surface elevations over the entire Delaware coastal zone vary. Geomorphic factors include: highly variable tidal flow distance from the estuary or ocean; local geomorphic features that may shelter or divert tidal flow such as "islands" or "necks" of the coastal plain protruding into the marsh; mosquito-ditching programs, and variants of spit and barrier morphology. Human development of the barriers, engineering of inlets, and dredging of tidal rivers alter the nature and frequency of storm overwash and marsh-flooding events and thus change marsh sediment deposition in its many varied back barrier settings. In addition, Delaware's policy of raising the coastal dune line in undeveloped areas "starves" the back barrier region of sand size sediment from previously frequent storm overwash processes, thus leading to acceleration of rates of back barrier marsh erosion and narrowing of the coastal barrier (Kraft et al., 1991).

The few low *Spartina alterniflora* marshes with low rates of marsh surface aggradation occur in protected back barrier settings, at long distances from tidal inlets, or adjacent to sand-starved shorelines. In general, the higher rates of marsh aggradation closer to the estuarine shoreline may be attributed to overwash events in which the marsh muds include a higher silt–sand content (Pethick, 1981; Khalequzzaman, 1989; Oertel et al., 1989). At Brockenberry fringe marsh, near Oyster, Virginia, Oertel et al. (1989) noted that overwash sand lenses were a dominant factor in the higher average marsh sedimentation rates observed on the outer barriers of Virginia. Similar back barrier marsh mud–overwash sand intercalations are observed and may be a major factor in the high variability of aggradation rates observed in the Delaware coastal marshes.

Kearney and Stevenson (1991) observed aggradation rates of 0.78 cm/yr after the 1963 ^{137}Cs spike in several cores taken on islands in the southeastern portion of the Chesapeake Bay. Based on a combination of evidence from ragweed ratios contrasted with later ^{210}Pb and ^{137}Cs dates, Kearney and Stevenson (1991) noted that "accretion rates appear to have more than doubled between 1790 (the approximate date of the (a) marker horizon) and the last quarter-century defined by the ^{137}Cs isotope record." Their studies were made on islands with large rates of "land loss ... principally due to shore erosion and not just simple submergence", a situation similar to the rapid rates of loss of coastal fringing marshes along the Delaware estuary. In a nearby study in a tidal freshwater marsh in the New Jersey portion of the Delaware estuary to the north, Orson et al. (1990) noted aggradation rates in a marsh at 0.04 cm/yr prior to the 1600's increasing to 0.12 cm/yr ca. 1940 based on ^{14}RC and pollen studies, with a sharp acceleration over the past 50 years to accumulation rates between 1.04 and 1.38 cm/yr, based on ^{210}Pb and ^{137}Cs -studies. They (Orson et al., 1990) conclude that tidal freshwater marsh sediment accumulation as measured by ^{210}Pb and ^{137}Cs methodologies has been four to six times the rate of local sea-level rise suggesting a large number of factors in marsh-swamp sedimentation rates.

The apparent increases in rate of marsh surface aggradation over the recent past as observed in our studies appear compatible with studies in nearby areas. An important "unknown" is when and at what rates did relative sea-level rise begin to increase over the 2000 years average (0.12 cm/yr) in our study area. Tidal gauge records start about 1920 A.D., whereas the abrupt upward trend in sea-level rise may be a phenomenon of the 19th century industrial revolution. Thomas and Varekamp (1991) clearly show other times of abrupt rise in relative sea level over the past several thousand years. Some of these events are correlated with the climatic record (i.e. the "little warm"), whereas others bear no apparent correlation. As carefully noted by Oertel et al. (1989) variations in tidal ranges are also an important factor in determining marsh surface aggradation rates. In our studies, we have not been able to establish clear criteria for the segregation of these factors in their control of marsh surface aggradation rates as contrasted with the evolution of marsh floral and elevation variants. Clearly, tidal ranges in the salt marshes of our study area are varying with the ever changing coastal landforms of the ongoing coastal transgression (Kraft et al., 1979).

The leading edge of the Holocene Epoch marine transgression

Although the study area is only approximately one hundred kilometers long, in fact, the leading edge of the Holocene Epoch marine transgression, or the line between the fringing salt marsh and the coastal plain uplands (Pleistocene Epoch sediments), is highly crenulated, extending inland along tributary valleys and possibly several thousand kilometers in length. It is along this interface that encroaching salt marsh facies continue the evolutionary processes of transgression and formation of new salt marsh facies. The line of contact varies from vertical bluffs along tidal creeks and lagoons (cf. northwest Indian River lagoon) with no fringing marsh to extremely low-angle continuation of an almost horizontal surface between upland (fastland) and marsh (cf. the Murderkill marsh near Bowers). In most places the Holocene/Pleistocene contact has a "scarp-like" nature, the residual limit of peak Wisconsinan erosion and valley incision. Thus, as least 1 to 2 m of local relative sea-level rise will be required to create areas of large-scale landward extensions of the transgressing coastal fringing marsh. To date, this inundation problem has been described only in a preliminary mode in terms of slope, versus area to be covered, versus local relative sea-level rise (Yi and Kraft, 1989). However, simple observation shows that a significant sea-level rise will be required in order to create new fringing marsh equal to the rates of marsh loss due to human intervention into the natural ecosystem and/or to counter the high rates of estuarine and Atlantic coastal shoreline erosion of the past 150 years (Figs. 1–3).

Coastal erosion

Rates of coastal erosion in the Atlantic coastal lagoon, Rehoboth Bay, were taken from Swisher

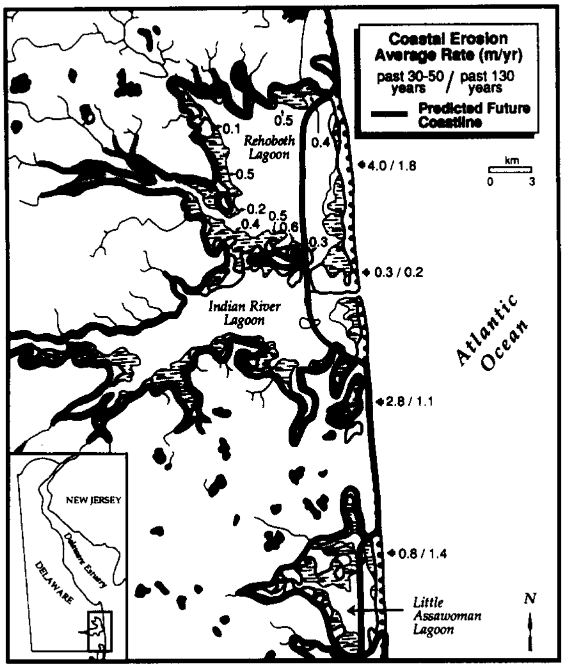

Fig. 3. The salt marshes of the Atlantic coastal lagoons of Delaware showing rates of shoreline erosion over the past 100 years (based on Swisher, 1982). Heavy lines indicate projected shorelines 200 years into the future, with possible small remnants of the back barrier marsh remaining over the next millennium.

(1982). Swishėr determined these rates by profiling fifteen shoreline sites on a monthly basis during 1981 and 1982. Swisher also used aerial photo interpretations that indicated that "long-term trends in historical shoreline changes are extremely variable, ranging from −9 m/yr to +13 m/yr." She further attributed the great majority of coastal erosion in Rehoboth Bay to storm wave activity undercutting both the marsh edge and bulkheaded areas and thereby reintroducing both comminuted floral debris and inorganic materials into the turbid bay waters. Long-term average rates of erosion varied from 0.1 m/yr to 0.6 m/yr, averaging 0.4 m/yr along the marsh fringe of Rehoboth Bay.

One of the more precise measures of long-term coastal erosion may be obtained from the survey records of the Cape Henlopen lighthouse. Built in 1763 on a 35-foot high Atlantic coast parallel dune on a cuspate headland, the lighthouse was originally located 480 m from the Atlantic coast (Kraft and Caulk, 1973; Kraft et al., 1978). From the start, lighthouse keepers noted continual coastal erosion over its 163-year life span. In 1926, the lighthouse fell into the sea, having served as a baseline for an average rate of coastal erosion of 2.9 m/yr. Precision-surveying of the Delaware Atlantic coast began in 1842–1845 by the U.S. Coast Survey. Successive surveys by that agency, followed by surveys of the successor U.S. Coast and Geodetic Survey into the latter part of the twentieth century, plus the advent of repetitive aerial photography from the decade of the 1930s by the U.S. Department of Agriculture, and on an irregular basis, the U.S. Coast and Geodetic Survey, provide a plethora of data on coastal erosion rates.

In this study we have used updated formats of the above sources to calculate average rates of coastal erosion for Atlantic coastal Delaware and the Delaware estuary (Figs. 1 and 3). On average, the rates of erosion shown are greater over the past 60 ± years than over the longer-term $1\frac{1}{2}$ centuries. This acceleration of erosion rates may well be related to the sharp increase in rate of local relative sea-level rise in the twentieth century. We also know that most of the erosion observed is related to the high-intensity events of storm waves of northeasters and hurricanes (Kraft, 1971; Belknap and Kraft, 1977; Maurmeyer, 1978; Kraft et al., 1979, 1987b). Studies of the boat sheets and aerial photos of the U.S. government surveys clearly show that the rates of coastal erosion or retreat are not smoothly incremental, but are a series of halts, small progradation events and highly variable erosion rates so typical of storm-driven erosion.

Galgano (1989) and French (1990) emphasize the irregularity of the process of coastal erosion as well as the fact of stormwave-based erosion as the dominant process. Galgano summarized Delaware Atlantic coastal erosion as "event related phenomena" averaging 0.82 m/yr (2.71 ft/yr) over a 132-yr record, while French averaged Delaware's estuarine coastal erosion at 1.4 m/yr (4.51 ft/yr) over a 135-yr record. French further noted that the Port Mahon marsh, of import to our study, could be completely lost to coastal erosion in as little as 500 years, or 100 years under certain greenhouse-effect conditions.

Human factors and wetland losses

Human factors must be considered. Dahl (1990) noted that Delaware lost 54% of its palustrine and estuarine wetlands between the 1780s and the 1980s. Daiber et al. (1976) showed that the 37,099 ha (91,672 acres) of tidal wetlands extant in Delaware in 1938 were reduced to 33,960 ha (83,420 acres) by 1975, a loss of 3340 ha (8252 acres) or roughly 9% of our tidal wetlands in the 37-year period. This time span coincides with widespread dredging and filling of lands peripheral to the Atlantic coastal lagoons and selected regions along the Delaware estuary. Such rates of wetland loss, had they continued, would have led to complete destruction of Delaware's tidal wetlands in three to four centuries. With the passage of Delaware's Wetlands Act in 1973, a significant reduction of wetland losses due to human activities occurred (Tiner, 1985). Hardisky and Klemas (1983) determined a lower rate of net loss of 57 ha (141 acres) of tidal wetlands between 1973 and 1979. From this, one might tend to conclude that "the problem of wetlands loss is solved." However, simple arithmetic will show that this greatly diminished rate of loss of tidal wetlands is in reality 951 ha (2350 acres) per century. One might then say that we shall have 36 centuries to the time of complete extinction of our tidal wetlands. In fact, this most certainly would not be the case. There has been a moratorium on the infill and development of wetlands but the hardening of the fringe of the wetlands by humans has not ceased and it is actually accelerating.

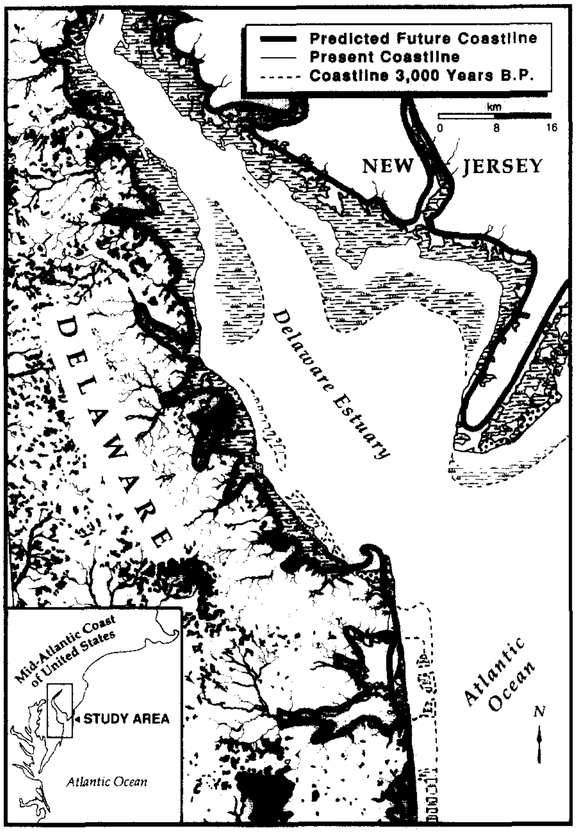

Fig. 4. Fringing marshes of the Delaware estuary and Atlantic coastal lagoons are shown as related to the greater marsh expanse of 3000 years before present. The heavy black line shows future projected coast lines at varied times, assuming public defense of only the developed portions of the Atlantic coastline by means of engineering structures and continued beach nourishment over the forthcoming centuries. Delaware estuary communities may remain as bulkheaded ramps extending from the mainland. Based on data from Kraft and John (1976), Kraft et al. (1981), Marx (1982), Maley (1982). Base map from Tiner (1985).

For the successful long-term existence of the fringing salt marsh environments in the State of Delaware, the geological transgression must continue at a landward rate of inundation of the coastal plain equal to the annual rates of coastal erosion along the Delaware estuary and the Atlantic coastal lagoons. Along our Delaware coastal lagoons it is clear that coastal structures will prevent a landward expansion of the fringing marshes as sea-level rise continues. Further, the last several decades have shown a tendency to begin to harden or develop the coastal plain edges of the fringing marshes of the Delaware estuary, potentially a far greater problem than that of the marsh-fringed lagoons.

Our tendency is to think in terms of years or decades at the most. However, we must remember that any solutions to problems in "our times" have only little meaning if they allow for a continued diminution of the fringing marsh areas of the coastal zone of Delaware. Under present practices and geological processes in the longer-term geological sense of centuries and millennia, the Delaware marsh environment is doomed. Figure 4 illustrates the problem. A moving coastline at apparently accelerating rates (Figs. 1–3) is eroding towards the west. Further, a number of marsh surface aggradation rates in coastal Delaware are less than present rates of sea-level rise measured at the Breakwater Harbor tidal gauge. These areas will undergo continuous inundation. Many other areas have aggradation rates significantly above the rate of sea-level rise at Breakwater Harbor. These surfaces, assuming they continue to aggrade at present rates, may undergo floral succession away from the *Spartina alterniflora* marshes, first to high marsh *Spartina patens* and *Distichlis spicata*, and ultimately to *Baccharis* or *Iva* shrub zones. All of this assumes, of course, that the entire region will not be completely colonized by *Phragmites australis*, the fields of tall reeds that have for yet unknown reasons rapidly accelerated in rates of floral succession (particularly in areas disturbed by humans) over the past 20 years.

Conclusions

The above-stated human and natural processes appear inevitable. Following the dramatic erosion of the salt marsh facies of the Delaware estuary over the past 3000 years and the present high rates of coastal erosion (attributed mainly to storminess or storm wave activity), we may indeed be approaching the twilight or "Götterdämmerung" of the fringing salt marsh of the Delaware estuary and the Atlantic coastal lagoons (Fig. 4). Only the time and rates are in question. A naturally evolving environmental expansion of the fringing marshes landward will be blocked by a "wall of human resistance" accompanied by ongoing massive rates of coastal erosion, resulting in the end of an evolutionary geological process and the coastal salt marsh facies extant over the past 15,000 + years.

Although many engineering and beach nourishment actions are underway to halt coastal erosion along the Atlantic coast, the processes continue. Thus, we can envisage a scenario in which the geological lives of the fringing marshes in our coastal lagoons will end in approximately 200 to 300 years while the broader fringing marshes of the Delaware estuary will decline to minimal remnants over a time span of 300 to 1700 years. Unlikely alternatives to this scenario of destruction of the salt marsh environment and the surficial portion of its sedimentary lithosome include: (1) a rapid drop in relative sea levels in a neo-glacial episode; (2) a major lowering of frequencies of storminess and therefore rates of coastal erosion; (3) human agreement to a massive movement of their occupancy structures landward from the edge of the transgressing fringing marsh; and/or (4) yet unknown engineering solutions that will check the rates of barrier and marsh erosion and yet allow continued salt marsh aggradation within the constraints of presently extant floral sequences.

Finally, we note that we have not called upon accelerative factors such as the greenhouse effect in making these projections. Should the greenhouse effect result in an acceleration of sea-level rise in the next century, as discussed herein, we are left with a great many unknowns in terms of rate of change of the morphologies of Delaware's coastal zone. An inherent factor of an acceleration above and beyond the present rate of local relative sea-level rise is that the final extinction of coastal Delaware's fringing salt marshes will be reduced to as low as one or two centuries. We can only speculate on such matters. However, we can measure the actual rates of coastal erosion and study the potentials and rates of westward transgression of the fringing salt marsh across the coastal plain of Delaware. The situation is indeed quite gloomy. We present map Fig. 4 as a realistic projection of the future.

Delaware citizens (and elsewhere in the nation) might wish to halt this process. To do so will require innovative land management methodologies and costs far beyond those that are now applied toward solutions to the problems of Delaware's (and the nation's) coastal erosion and salt marsh wetlands loss. A comprehensive rethinking of the matter is certainly in order!

It is clear from our experiences with a large number of ^{210}Pb and ^{137}Cs data and with high salt marsh sedimentation rates, that future studies utilizing these techniques must address problems of micro-marsh morphology, problems of deposition and source of sediment and variants as related to the larger geomorphological setting. When only small numbers of cores are analyzed in studies of this type, they must be interpreted with great caution and not be used as regional indicators of marsh sedimentation aggradation rates or patterns.

Acknowledgements

This research has been supported by grants from the National Oceanic and Atmospheric Agency, Office of Sea Grant, Department of Commerce (Project Numbers R/G10-NA85AA-D-SG033 and R/G12-NA86AA-D-SG040) and the Department of Natural Resources and Environmental Control of the State of Delaware. The U.S. Government is authorized to produce and distribute reprints for governmental purposes, notwithstanding any copyright notation that may appear here on. Field and laboratory facilities of the Department of Geology and the College of Marine Studies at the University of Delaware were used in this research. We wish to thank Dr. Michael J. Chrzastowski and Ms. Susan-Marie Stedman for their help in obtaining many of the core samples upon which this research was based. In addition, they contributed significantly to the success of this project in their dissertation and thesis research studies. A number of other graduate student colleagues' research from past years have been important in developing concepts and the data base used in this paper. Radionuclide data used in this study were analyzed from core samples by Teledyne Isotopes, Inc. and the University of Delaware, College of Marine Studies, laboratory of Prof. T.M. Church. Finally, we thank Mr. Robert Henry, Manger of the Beach Preservation Section and Mr. William Moyer, Manager of the Wetland and Aquatic Protection Branch of the Department of Natural Resources and Environmental Control, State of Delaware, for their continuing support in supplying data and other information of import to this research.

References

Allen, E.A., 1978. Petrology and Stratigraphy of Holocene Coastal Marsh Deposits along the Western Shore of Delaware Bay. Ph.D. dissertation, Department of Geology, University of Delaware, Newark, 287 pp.

Belknap, D.F. and Kraft, J.C., 1977. Holocene relative sea level changes and coastal stratigraphic units on to the northeast flank of Baltimore Canyon trough geosyncline. J. Sediment. Petrol., 47: 60–79.

Belknap, D.F. and Kraft, J.C., 1985. Influence of antecedent topography on stratigraphic preservation potential and evolution of Delaware's barrier systems. Mar. Geol., 63: 235–262.

Chrzastowski, M.J., 1986. Stratigraphy and Geologic History of a Holocene Lagoon System: Rehoboth Bay and Indian River Bay, Delaware. Ph.D. dissertation, Department of Geology, University of Delaware, Newark, 444 pp.

Dahl, T.E., 1990. Wetland Losses in the United States. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C., 21 pp.

Daiber, F.C., Thornton, L.L., Bolster, K.A., Campbell, O.W., Crichton, G.L., Esposito, G.L., Jones, D.R. and Tyrawski, J.M., 1976. An Atlas of Delaware's Wetlands and Estuarine Resources. University of Delaware, College of Marine Studies, Newark, Del., and Delaware's Coastal Management Program, Tech. Rep., 2, 528 pp.

Fletcher, C.H., III, Knebel, J.F. and Kraft, J.C., 1990. Holocene evolution of an estuarine coast and tidal wetlands. Geol. Soc. Am. Bull., 102: 283–297.

Fletcher, C.H., III, Knebel, H.J. and Kraft, J.C., 1992. Holocene Depocenter migration and sediment accumulation in Delaware Bay: a submerging marginal marine sedimentary basin. Mar. Geol., 102: 165–183.

French, G.T., 1990. Historical Shoreline Changes in Response to Environmental Conditions in West Delaware Bay. M.S. Thesis, Department of Geography, University of Maryland, College Park, Md., 240 pp.

Galgano, F.A., 1989. Shoreline Recession and Nearshore Response: The Atlantic Coast of Delaware, 1845–1987. M.S. Thesis, Department of Geography, University of Maryland, College Park, Md., 161 pp.

Hardisky, M.A. and Klemas, V., 1983. Tidal wetlands—natural and human-made changes from 1973 to 1979 in Delaware: mapping techniques and results. Environ. Manage., 7 (4): 339–344.

Hoffman, J.S., Keyes, D. and Titus, J.G., 1983. Projecting Future Sea Level Rise, Methodology, Estimates to the Year 2100, and Research Needs. U.S. Environmental Protection Agency, Office of Policy and Resources Management, Washington, D.C.

Intergovernmental Panel on Climate Change (UNEP), 1990. Policy makers summary of the scientific assessment of climate change. Report to IPCC from Working Group 1. Executive Summary. EarthQuest, 4 (2): 3–4.

Kana, T.W., Baca, B.J. and Williams, M.L., 1988a. Charlestown case study. In: J.G. Titus (Editor), Greenhouse Effect, Sea-Level Rise and Coastal Wetlands. U.S. Environmental Protection Agency, Washington, D.C., pp. 37–54.

Kana, T.W., Eiser, W.E., Baca, B.J. and Williams, M.L., 1988b. New Jersey case study. In: J.G. Titus (Editor), Greenhouse Effect, Sea-Level Rise and Coastal Wetlands. U.S. Environmental Protection Agency, Washington, D.C., pp. 61–86.

Kearney, M.S. and Stevenson, J.C., 1991. Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. J. Coastal Res., 7: 403–415.

Khalequzzaman, Md., 1989. Nature of Sedimentary Deposition in a Salt Marsh: Port Mahon, Delaware. M.S. Thesis, Department of Geology, University of Delaware, Newark, Del., 158 pp.

Knebel, H.J., Fletcher, C.H., III and Kraft, J.C., 1988. Late Wisconsinan–Holocene paleogeography of Delaware Bay; a large coastal plain estuary. Mar. Geol., 83: 115–133.

Kraft, J.C., 1971. Sedimentary facies patterns and geologic history of Holocene marine transgression. Geol. Soc. Am. Bull., 82: 2131–2158.

Kraft, J.C., 1988. Geology. In: T.L. Bryant and J.R. Pennock (Editors), The Delaware Estuary; Rediscovering a Forgotten Resource. University of Delaware Sea Grant College Program, Newark, pp. 30–41.

Kraft, J.C. and Belknap, D.F., 1986. Holocene Epoch coastal geomorphologies based on local relative sea-level data and stratigraphic interpretation of paralic sediments. J. Coastal Res., 1: 53–59.

Kraft, J.C. and Caulk, R.L., 1973. The evolution of Lewes harbor. In: J.C. Kraft and R.L. Salsbury (Editors). Transactions of the Delaware Academy of Science, 2: 79–125.

Kraft, J.C. and John, C.J., 1976. The Geological Structure of the Shoreline of Delaware. Newark, Delaware, College of Marine Studies, Delaware Sea Grant-Del-SG-14-76, Tech. Rep., 107 pp.

Kraft, J.C., Allen, E.A. and Maurmeyer, E.M., 1978. The geological and paleogeomorphological evolution of a spit system and its associated coastal environments: Cape Henlopen spit, Delaware. J. Sediment. Petrol., 48: 211–226.

Kraft, J.C., Allen, E.A., Belknap, D.F., John, C.J. and Maurmeyer, E.M., 1979. Processes and morphologic evolution of an estuarine and coastal barrier system. In: S.P. Leatherman (Editor), Barrier Islands from the Gulf of St. Lawrence to Mexico. Academic Press, New York, N.Y., pp. 149–183.

Kraft, J.C., John, C.J. and Marx, P.R., 1981. Clastic depositional strata in a transgressive coastal environment: Holocene Epoch. Northeastern Geol., 3: 268–277.

Kraft, J.C., Belknap, D.F. and Demarest, J.M., 1987b. Prediction of effects of sea level changes from paralic and inner shelf stratigraphic sequences. In: M.R. Rampino, J.E. Sanders, W.S. Newman and L.K. Königsson (Editors), Climate, History, Periodicity, and Predictability. Van Nostrand Reinhold, New York, N.Y., pp. 166–192.

Kraft, J.C., Chrzastowski, M.J., Belknap, D.F., Toscano, M.S. and Fletcher, C.H., III, 1987a. Morphostratigraphy, sedimentary sequences and responses to a relative rise in sea level along the Delaware coast. In: D. Nummedal, O.H. Pilkey and J.D. Howard (Editors), Sea Level Rise and Coastal Evolution. SEPM Spec. Publ., 41: 129–144.

Kraft, J.C., Yi, Hi-Il and Khalequzzaman, Md., 1991. Geologic and human factors in the decline of the salt marsh lithosome: the Delaware estuary and Atlantic coastal zone. The Society of Economic Paleontologists and Mineralogists and Internal Geological Correlation Project 274 Research Conference: Quaternary Coastal Evolution, Wakula Springs, Fla., Progr. Abstr.

Maley, K.F., 1982. A Transgressive Facies Model for a Shallow Estuarine Environment: The Delaware Bay Nearshore Zone from Beach Plum Island to Fowler Beach, Delaware. M.S. Thesis, Department of Geology, University of Delaware, Newark, 184 pp.

Marx, P.R., 1982. A Dynamic Model for an Estuarine Transgression Based on Facies Variants in the Nearshore of Western Delaware Bay. M.S. Thesis, Department of Geology, University of Delaware, Newark, 183 pp.

Maurmeyer, E.M., 1978. Geomorphology and Evolution of Transgressive Estuarine Washover Barriers Along the Western Shore of Delaware Bay. Ph.D. dissertation, Department of Geology, University of Delaware, Newark, 174 pp.

Meier, M.F., 1990. Reduced rise in sea level. Nature, 343: 115–116.

Oertel, G.R., Wong, G.T.F. and Conway, J.D., 1989. Sediment accumulation of a fringe marsh during transgression, Oyster, Virginia. Estuaries, 1: 18–25.

Orson, R.A., Simpson, R.L. and Good, R.E., 1990. Rates of sediment accumulation in a tidal freshwater marsh. J. Sediment. Petrol., 60 (6): 859–869.

Park, B.A., Trehan, M.S., Mausel, P.W. and Howe, R.C., 1991. The Effects of Sea Level Rise on U.S. Coastal Wetlands. Cooperative Agreement CR814578-01 (with) the U.S. Environmental Protection Agency, 1-1 to 1-55.

Pethick, J.S., 1981. Long-term accretion rates on tidal salt marshes. J. Sediment. Petrol., 51: 571–579.

Revelle, R.R., 1983. Probable future changes in sea level resulting from increased atmospheric carbon dioxide. In: W.A. Nierenberg (Chair), Changing Climate, Report of Carbon Dioxide Assessment Committee, National Research Council. National Academy Press, Washington, D.C., pp. 443–448.

Swift, D.J.P., 1973. Delaware shelf valley: estuary retreat path, not drowned river valley. Geol. Soc. Am. Bull., 84: 2743–2748.

Swisher, M., 1982. The Rates and Causes of Coastal Erosion, Rehoboth Bay, Delaware. M.S. Thesis, College of Marine Studies, University of Delaware, Newark, 210 pp.

Thomas, E. and Varekamp, J.C., 1991. Paleo-environmental analyses of marsh sequences (Clinton, Connecticut): evidence for punctuated rise in relative sea level during the latest Holocene. J. Coastal Res., SI 11: 125–158.

Tiner, R.W., Jr., 1985. Wetlands of Delaware. U.S. Fish and Wildlife Survey, Newton Corner, Mass. and Delaware Department of Natural Resources and Environmental Control, Wetlands Section, Dover, Del., Cooperative Publication, 77 pp.

Titus, J.G., Barth, M.C., Gibbs, M.J., Hoffman, J.S. and

Kenny, M., 1984. An overview of the causes and effects of sea level rise. In: M.C. Barth and J.G. Titus (Editors). Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold, New York, N.Y., pp. 1–56.
Van de Plassche, O., 1991. Late Holocene sea-level fluctuations on the shore of Connecticut inferred from transgressive and regressive overlap boundaries in salt-marsh deposits. J. Coastal Res., SI, 77: 159–179.
Whitmore, F.C., Emery, K.O., Cooke, H.B.S. and Swift, D.J.B., 1967. Elephant teeth from the Atlantic continental shelf. Science, 156: 1477–1481.
Yi, Hi-Il and Kraft, J.C., 1989. A subtle variation of marsh environments in the Delaware Estuary with respect to local relative sea-level rise. Geol. Soc. Am., Abstr. Progr., 101: A213.