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Sea-level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi delta plain

Denise J. Reed *

Department of Geology and Geophysics, University of New Orleans, New Orleans, LA 70148, USA

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Abstract

Chronostratigraphic approaches to coastal geomorphology frequently include consideration of salt marsh deposits as indicators of past sea-level positions. Continuous horizons of such deposits can be used to infer that salt marshes were keeping pace with local rates of relative sea-level rise (RSLR). Rates of past accumulation, estimated using dating techniques, are then used to hindcast the rate of sea-level rise in that area. Estimates of contemporary sea-level rise rates are often derived from tide gauge records. This approach allows identification of subdecadal variations in mean water level. Accumulation rates of both organic and inorganic sediments can also be derived at these time scales and studies from many coastal marshes demonstrate the episodic nature of inorganic sediment deposition. The frequency and spacing of these events does not necessarily coincide with periods of increased local sea level. In addition, short-term increases in sea level could result in marsh deterioration as soils become excessively waterlogged. A conceptual model of changes in geomorphic and ecological processes contributing to marsh sustainability during the Holocene has been developed for the Mississippi delta plain (MDP). The survival of some marshes in this area, despite high rates of subsidence, indicates that the combined effect of organic and inorganic accumulation processes can be adequate to sustain coastal marshes in the face of sea-level rise.

Keywords: Marsh sedimentation; Mississippi Delta Plain; Sea-level rise; Subsidence

1. Introduction

Understanding the combined effects of sea-level rise on coastal ecosystems is frequently constrained by a lack of existing information on the way in which ecosystem functions respond to environmental changes. For coastal marshes, the effects of changes in sea-level rise rates caused by global climate change must be combined with potential concurrent alterations in inputs of freshwater and sediments from the watershed to the coastal zone (Boesch et al., 1994; Brinson et al., 1995). Despite this difficulty, the challenge of predicting the future of coastal wetlands becomes an increasingly significant problem as coastal areas become heavily populated. Today, over half of the nation's peoples live and work within coastal communities that encompass less than 10% of the US land mass (Watzin and Gosselink, 1992). This population density and the intense development that accompanies it has resulted in direct and indirect deterioration and destruction of wetlands.

* Tel.: +1-504-280-7395; fax: +1-504-280-7396.
E-mail address: djreed@uno.edu (D.J. Reed).

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The need to understand interactions between sea-level change and coastal wetland sustainability is nowhere more immediate than in large deltaic systems that experience both eustatic sea-level rise and land subsidence. Even where natural subsidence is not exacerbated by groundwater withdrawals (e.g., in the Yellow River) (Wang, 1998), rates of relative sea-level rise (RSLR) can exceed 1 cm/year (Penland and Ramsey, 1990). The exploitation of oil and gas can also result in increased submergence of coastal wetlands (White and Tremblay, 1995; Dijkema, 1997). Despite concerns about our ability to explain contemporary sea-level rise (Baltuck et al., 1996), when even the most conservative future sea-level rise scenarios (Titus and Narayanan, 1995) are added to these existing rates, it is clear that coastal marshes are threatened by submergence.

Many studies of coastal marshes have addressed the ability of coastal marshes to keep pace with sea-level rise (Orson et al., 1985; Stevenson et al., 1986; Gehrels and Leatherman, 1989; Reed, 1990, 1995). In general, contemporary rates of elevation change in nondeltaic coastal marshes of the Atlantic and Gulf coasts of the US appear to be in balance with contemporary sea-level rise rates (Stevenson et al., 1986). Most of these assessments, however, are based upon measures of marsh accretion or elevation change at decadal or shorter time scales and sea-level rise rates derived from several decades of tide gauge measurements (e.g., Penland and Ramsey, 1990). Roman et al. (1997) have recently called for assessments of coastal system response to sea-level rise to integrate marsh sedimentation over at least decadal time scales. This results from their study of New England marshes, which showed differences in sedimentation rate based upon the use of short-term marker horizons and longer-term ^{210}Pb dating techniques. Such an approach allows for the comparison of two data sets (sedimentation rate and tide gauge records) averaged over the same time scale and this may be appropriate for estimating the rate at which the marsh landform keeps pace with rising sea level. Such an approach has also been suggested by Kearney et al. (1994). However, the ultimate control on wetland survival in sheltered or interior marsh areas, such as the back barrier system examined by Roman et al. (1997), is the survival of the vegetation. When local conditions cause plants to die, the lack of live roots binding the marsh soil results in erosion of the remaining sediments by tidal flows (Gosselink and Sasser, 1995). Thus, an understanding of the ecological response of the marsh vegetation to sea-level rise, and the time scale on which it occurs, must be incorporated into assessments of whether marshes can keep pace with future changes in sea level.

This paper seeks to mesh recent advances in understanding of coastal marsh geomorphology and ecology to elucidate the factors controlling long-term sustainability. This will include summary of (1) recent chronostratigraphic approaches to coastal geomorphology that frequently include consideration of salt marsh deposits as indicators of past sea-level positions and (2) the use of tide gauge records to determine sea-level rise rates and the rate of submergence of coastal marshes. Studies of marsh sedimentation and plant ecology will be assessed to determine the temporal response of geomorphic and ecological factors to water level increases. A conceptual model of coastal marsh evolution during the Holocene in the Mississippi delta plain (MDP) will be presented which incorporates a biogeomorphic approach to understanding landform development meshing short-term processes with long-term landscape drainage. The goal is to ensure that projections of coastal marsh response to future sea-level rise include consideration of ecological as well as geomorphic processes.

2. Chronostratigraphic approaches

Chronostratigraphic approaches to coastal geomorphology frequently include consideration of salt marsh deposits as indicators of past sea-level positions. Continuous horizons of such deposits can thus be used to infer that salt marshes were keeping pace with local rates of relative sea-level rise. Rates of past accumulation, estimated using dating techniques, are then used to hindcast the rate of sea-level rise in that area.

The estimation of sedimentation rates based upon dating of cores can be problematic. In very long cores, encompassing thousands of years of sedimentary record and diverse environmental conditions, radiocarbon-derived sedimentation rates for different parts of the core can vary by an order of magnitude (e.g., Liu et al., 1992). Even some of the most widely accepted chronologies of coastal development, such as that of Fisk (1944) in the Mississippi delta plain, have been recently questioned, because of sampling over large vertical intervals, and then revised using new dating techniques and more precise sampling of cores (Tornqzist et al., 1996). The constraints of relating a dated deposit to a specific tidal datum are widely recognized and cause some workers to term their sea-level reconstruction efforts as "tentative" (Hesp et al., 1998). Scott et al. (1995) recognize that their identification of a mid-Holocene sea level high in South Carolina may be limited by low numbers of preserved foraminifera, even though their vertical sampling interval is small. The problem of autocompaction of peat (Kaye and Barghoorn, 1964; Pizzuto and Schwendt, 1997) may also confound the elevation of Scott et al.'s (1995) high sea-level event because peat sequences may have formed at higher elevations than they are found within cores. The compaction of peats should mean that sedimentation rates based upon their elevation and date would be underestimates. Similarly, Kearney (1996) notes that sedimentation rates for Chesapeake Bay marshes derived from dating basal peats are still much lower than rates based upon contemporary process studies.

While some of the problems in identifying a reference tidal datum for dated material can be overcome by using plant macrofossils rather than bulk peat samples (e.g., Tornqzist et al., 1996; van Heteren and van de Plassche, 1997), the elevational range over which salt marsh plants occur can be great and varies with latitude (McKee and Patrick, 1988). In addition, Chmura et al. (1997) have shown how disturbance and competition effects in coastal marshes can influence the elevational range for some dominant salt marsh species. Thus, the ecology of coastal systems needs to be considered in chronostratigraphic studies, which seek to reconstruct sea-level histories, as well as those that infer long-term sedimentation rates for coastal marshes.

3. Contemporary process studies

Analysis of tide gauge records reveals not only long-term trends in sea level (e.g., Gornitz, 1995) but also the magnitude of short-term (i.e., subdecadal) variations. Tsimplis and Spencer (1997) analyzed low-frequency variability in long-term tide gauge data from the Mediterranean, obtained from the Permanent Service for Mean Sea Level (PSMSL), and note a 2–5-year oscillation event, which is in phase across all stations. In addition, the period 1955–1965 shows higher sea level than the decade before or the decade after. Despite the limitations of using PSMSL records to derive global trends in sea level (Groger and Plag, 1993), it can be used to detect local and regional changes of this type. Similarly, Swenson and Swarzenski (1995) analyzed tide gauge records for part of coastal Louisiana and found that between 1969 and 1972 trends in water level for a number of stations showed increases in excess of 6 cm/year while long-term trends for these stations were less than 1.5 cm/year. Unless accretionary processes also vary at the same time scale, such increases in water level must result in increased flooding of the marsh surface. The challenge these water level studies present for understanding marsh response is in determining the time scale and magnitude of the stress (increased flooding) vs. the time scale and potential of marsh building processes.

Interactions between tidal imports, vegetation, and depositional processes in salt marshes influence elevation change of the marsh surface. These processes are going on simultaneously with compaction and dewatering of sediments both within and beneath the root zone. The accumulation of inorganic material is directly mediated by marsh hydrology and the local availability of suspended sediments. Day et al. (1995) have noted the importance of episodic events in sustaining deltaic marshes, largely through their control of sediment inputs. Detailed field studies of sediment deposition in coastal marshes by Stumpf (1983), Reed (1989a), Hutchinson et al. (1995) and Leonard et al. (1995) and among others have shown the importance of meteorological forcing in mobilizing sediment for delivery to coastal marshes. These studies examined storms with frequencies of several per year—the effect is even more dramatic during events such as hurricanes (Chmura and Kosters, 1994; Cahoon et al., 1995). Even in systems where nonstorm tidal processes are thought to dominate sediment inputs (e.g., Stoddart et al., 1989; Bartholdy, 1997), sediment delivery is enhanced during storm events. However, Orford et al. (1996) found a negative correlation between storm surge activity, assessed from tide gauge records at Newlyn, and marsh deposition at Bracky Bridge in western Ireland between 1916 and 1994. In their study, deposition was positively correlated with offshore wave height for a shorter period of record (1975–1988). Orford et al. (1996) suggest that extreme surges import coarser material to the marsh and can remove finer material, which may be transported back to the marsh during fair-weather conditions. This "stripping" appears to be similar to that documented by Pethick (1992) on the Dengie Peninsula in Essex.

Advances in modeling sediment deposition in tidal marshes (Woolnough et al., 1995) combined with existing accretionary models (e.g., French, 1993) may allow the temporal variability of sediment deposition to be incorporated into projections of coastal marsh response to future sea-level rise using probabilistic approaches to sediment supply terms. However, projections are made more tenuous by shorter-term variations in water level forcing, as described above, both through their direct effects on inundation and their indirect influence on many aspects of vegetative growth. Manipulative experiments have shown that sudden and large increases in submergence of saline marsh plants (e.g., surface lowering relative to mean tide level) can lead to severe plant stress and reduced growth because of soil waterlogging and the generation of soil phytotoxins (Mendelssohn and McKee, 1988; Koch et al., 1990). These experiments include a step function change in hydrology, which does not simulate a gradual increase in flooding associated with long-term sea-level rise. However, they may simulate vegetative response to short-term increases in water level such as those identified by Swenson and Swarzenski (1995)—more than 6 cm/year for a 3-year period.

Morris and Haskin (1990) showed that annual production of *Spartina alterniflora* was positively related to interannual variations in July and August sea level in South Carolina. They attributed the lower production during lower water years to higher soil salinities, which inhibited plant growth. Teal and Howes (1996), however, showed poor correlations between biomass of *Spartina* and regional environmental variables for a 20-year study of Massachusetts marshes. They did note increased root and rhizome biomass during years when positive deviations from the long-term sea-level trend were greatest. The mechanism here appears to be an allocation of more plant resources to roots during periods of greater flooding, with the allocation changing in subsequent years as water levels changed. Portnoy and Valiela (1997) found in a 2-year experimental study that permanent waterlogging of marsh soil reduced *S. alterniflora* production. Similarly, in a 1-year field experiment, Webb et al. (1995) concluded that plant dieback and lack of plant recruitment in deteriorating Louisiana salt marshes was due to excessive plant submergence and association soil conditions. While different plant species are found in association with different hydrologic and chemical conditions (Hackney et al., 1996), laboratory studies show that different populations of the same species can have different growth responses to flooding (Lessman et al., 1997).

Unfortunately, most of these vegetation studies fail to simulate either long-term sea-level rise or extreme subdecadal variations in water level over the length of time necessary to ascertain the growth response of the plants. However, they do provide evidence to indicate that *S. alterniflora*, although one of the most flood tolerant of salt marsh plants, decreased productivity during prolonged flooding. How much flooding plants can tolerate, and for how long, is likely to be determined by characteristics of the local population and other environmental conditions, such as salinity. However, it is likely that a threshold exists beyond which plant dieback occurs (Mendelssohn and McKee, 1988).

The amount of flooding that vegetation experiences is determined by the net balance between relative sea-level rise and marsh elevation increase. Both inorganic and organic accumulation contribute to marsh elevation. Net organic accumulation is the result of both production and decomposition. Blum (1993) has found in Virginia salt marshes that differences in organic matter accumulation between high and low marshes are due to differences in root production rather than root decomposition. These measures represent the response to tidal conditions over several years rather than response the interannual variations identified by Teal and Howes (1996). Root production in Blum's study appears to be influenced by variations in tidal inundation conditions, suggesting a sensitivity of the plant below-ground development to elevation change to sea-level rise even under conditions not sufficiently severe to result in plant death. If the relative elevation of the marsh surface is to be maintained, and submergence is prevented, then inorganic accumulation must increase during such periods of low below-ground organic accumulation. However, in microtidal systems (e.g., Cahoon and Reed, 1995) or in subsiding deltas where storms or other pulsed events control sediment inputs (Day et al., 1995), this may not occur.

Short-term imbalances between marsh elevation change and extreme water level conditions may be one of the factors controlling changes in the rate of land loss in coastal Louisiana (Britsch and Dunbar, 1993). The time of highest land loss, between mid-1950s and 1974, includes the period when Swenson and Swarzenski (1995) identified a short period of extremely high water level trends (>6 cm/year for 1969–1972) in the Barataria and Terrebonne basins of coastal Louisiana. There were no hurricanes or major storms recorded for this period in those areas, which could have contributed significant inorganic sediment inputs (Rejmanek et al., 1988; Nyman et al., 1995; Cahoon et al., 1995). Any "elevation capital," which marshes in the Mississippi delta plain manage to accumulate during periods of increased sediment supply or organic matter accumulation, may be used up by the additive effects of continued subsidence and these subdecadal increases in water level. Improved understanding of the dynamics of both marsh flooding and marsh vertical accretion is critical to both predicting future loss in these systems and designing effective long-term restoration measures.

4. Changing contributions to marsh accretion in the Mississippi delta plain

Understanding inorganic and organic contributions to marsh accretionary processes and their dynamics provides a new perspective on chronostratigraphic interpretations of how marshes keep pace with sea-level rise. Over the last several 1000 years, the natural cycle of delta growth and deterioration in the Mississippi delta plain has resulted in major changes in the coastal landscape (Roberts, 1997), including both land building and land loss. The resulting coastal landscape includes deltas of different ages subject to varying degrees of deterioration (Fig. 1). For example, Chandeleur Sound, and the barrier islands and marshes bounding it, has been formed as the St. Bernard delta was abandoned by the river and marine processes became dominant. Subsidence is an accepted component of the delta cycle (Roberts et al., 1994) and has long been viewed as one of the underlying factors influencing marsh deterioration in coastal Louisiana. Delta building and degradation occurred during the Holocene over periods of 1000–2000 years (Roberts, 1997).

Assessments of coastal land loss between 1930s and 1990s in MDP show rates of conversion to open water of over 50 km^2/year (Gagliano et al., 1981; Britsch and Kemp 1990)—rates that if sustained would result on total degradation of the system in centuries rather than millennia. Workers frequently attribute much of this more recent loss to the underlying problem of subsidence and the resulting high rates of relative sea-level rise (e.g., Baumann et al., 1984; Walker et al., 1987; Boesch et al., 1994). Coastal marsh submergence is assumed to occur when rates of relative sea-level rise exceed marsh surface accretion rates. In MDP, contemporary rates of relative sea-level rise exceed 1 cm/year (Penland and Ramsey, 1990) and are greatly influenced by substrate subsidence. In other areas, marshes subject to these rates of sea-level rise would have transgressed to cover adjacent uplands. In MDP, the relatively steep slope of the Pleistocene terrace to the north (in the vicinity of Baton Rouge and the north side of Lake Pontchartrain on Fig. 1) prevents the maintenance of coastal marsh area by transgression. Subsidence has been a factor influencing coastal marshes in MDP throughout the Holocene. Were coastal marshes fundamentally unable to cope with this average rate of rise, submergence would have "consumed" MDP marshes already. Understanding how coastal marshes maintain elevation in MDP can elucidate how marsh in other coastal systems might respond to future sea-level rise and changing coastal conditions.

Existing models of Mississippi delta growth and decay largely focus on either the evolution of stratigraphic sequences (Frazier, 1967) or the geomorphic development of the barrier islands (Penland et al., 1988). The gradual loss of marsh over time is an essential component of barrier island arc development (Penland et al., 1988) and is fundamental to the way we understand the Holocene evolution of the MDP (e.g., Roberts, 1997), but these studies do not consider the system dynamics, that result in marsh deteriora-

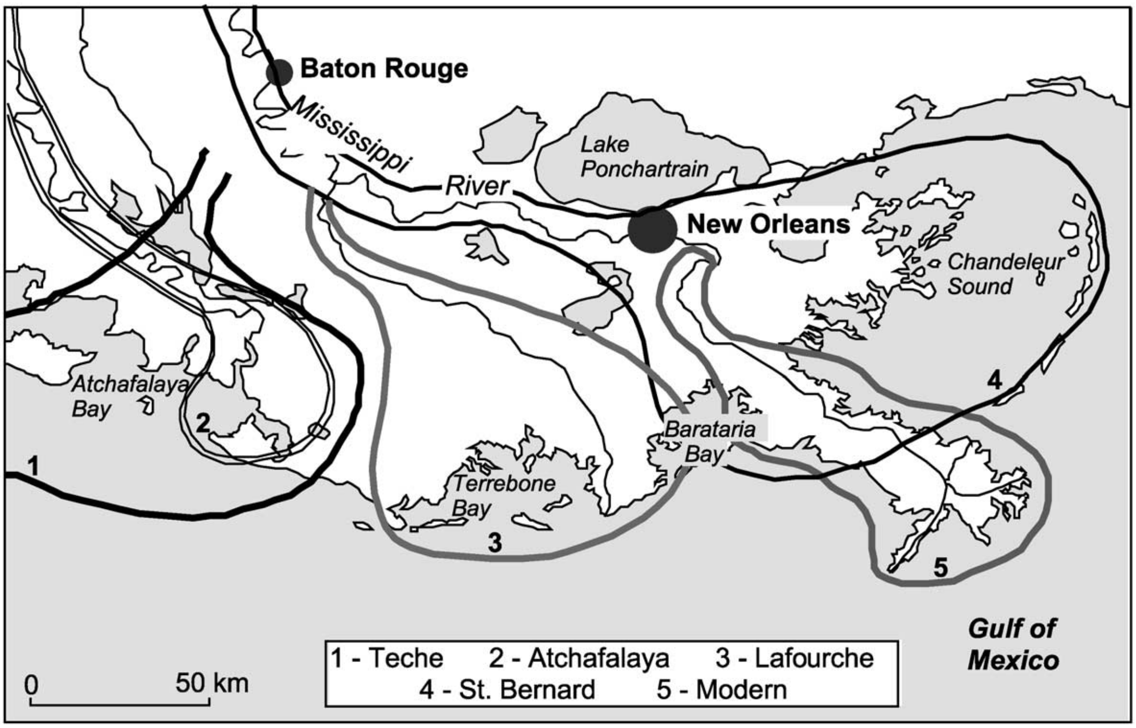

Fig. 1. Plan view of contemporary MDP showing Holocene deltas (after Frazier, 1967) and type locations for components of the model shown in Fig. 2 and referred to in text. Approximate periods of delta building are Teche 5700–3925 years BP, St. Bernard 4650–1850 years BP and Lafourche 3475–250 years BP. Deposition in the Modern delta began approximately 800 years BP and the Atchafalaya delta became substantially emergent in Atchafalaya Bay in 1973 (Roberts, 1997).

tion. Roberts' (1997) review of the delta cycle includes detailed discussion of both lacustrine and shelf phases of delta building and acknowledges that the deterioration or transgressive phases of the delta cycle may be prolonged. However, the only process described in relation to marsh deterioration is subsidence with no regard to the accretionary processes that continue to maintain marsh surface elevation during transgression.

To redress this imbalance, a conceptual model has been developed which incorporates both geomorphological and ecological processes affecting accretion. Fig. 2 shows changing bay–marsh configurations during the delta cycle including changes in vegetation type and the nature of the marsh substrate. The scheme of the model is based on Penland et al.'s (1988) transgressive depositional model of barrier island development. It includes one regressive component, during which the delta progrades, and three transgressive stages that are associated with marsh loss and bay expansion.

During active delta building (upper left panel on Fig. 2), supplies of freshwater and suspended sediments are high because of the direct influence of the river. Freshwater marshes are highly productive. Both organic and inorganic accumulation rates are high contributing to delta progradation and marsh soil development. Subsidence rates are also high within the marshes due to rapid consolidation of fine sediments and autocompaction of the organic materials combined with regional deep subsidence and downwashing (Roberts, 1997). However, the net balance is for accretion to exceed subsidence. Coastal bays are small during this phase and diminishing in size as the delta builds. The analogues for marsh soils–bay configuration in this component of the model are the Atchafalaya delta (van Heerden and Roberts, 1980a,b), recent subdeltas of the modern Mississippi

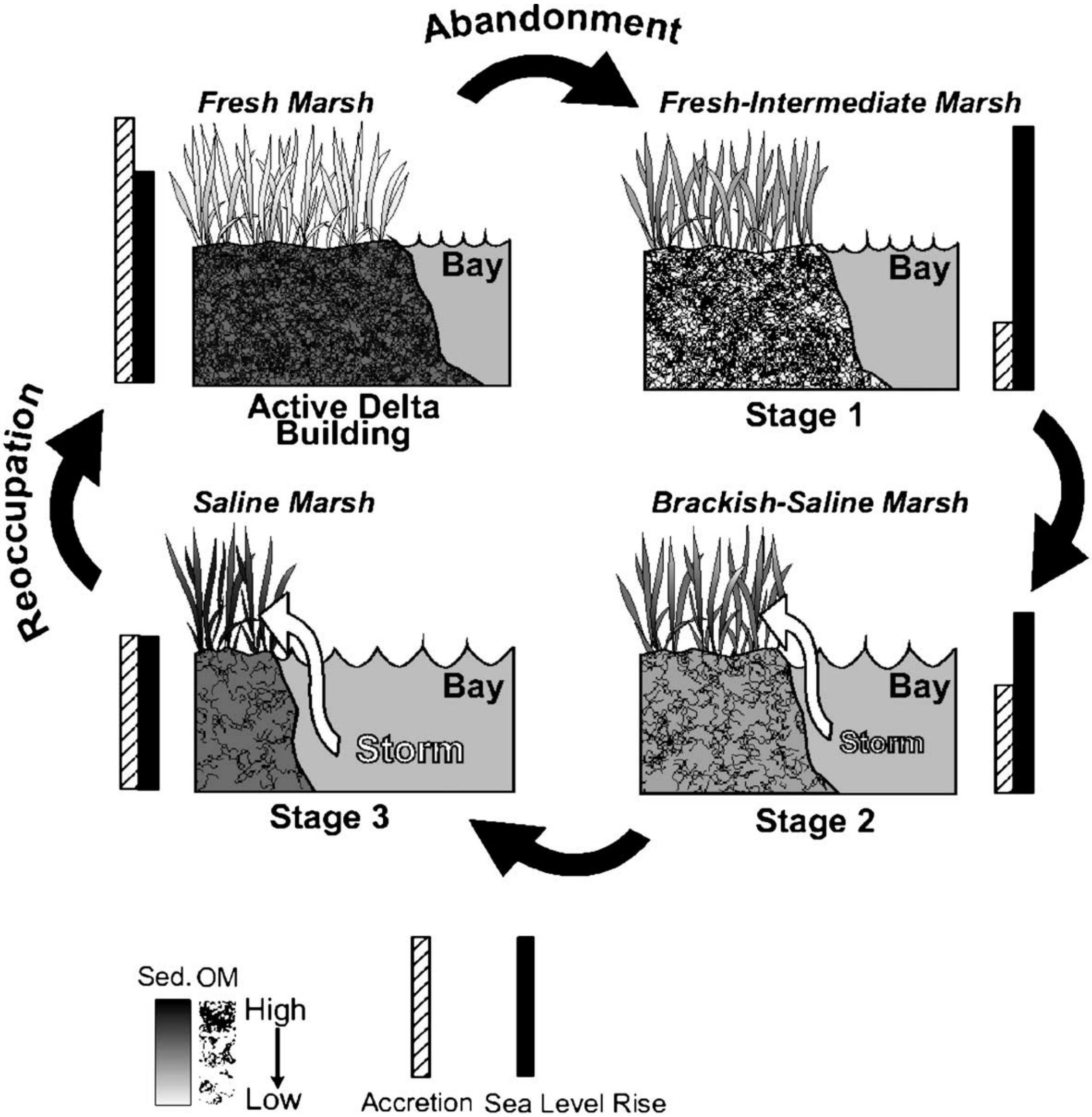

Fig. 2. A conceptual model of geomorphic and vegetative processes contributing to marsh sustainability during both regressive (active delta building) and transgressive (Stages 1–3) phases of the Holocene delta cycle in the Mississippi delta plain. Accretion bars represent the relative rate of accumulation of material in and on the marsh soil. Sea-level rise bars represent relative rates of subsidence combined with eustatic rise. Shading of the marsh substrate shows the combination of inorganic sediment (Sed.) and the organic material (OM) composing the marsh soil (with ~ 0.5 m of the surface). White arrows indicate resuspension of sediments from the bay and their movements onto the marsh surface (see text for more detailed discussion).

(Wells, 1996) and some small active crevasses in the modern delta of the Mississippi (Boyer et al., 1997). Fig. 1 shows the locations of these actively prograding areas.

After the depocenter of the River has moved and the delta lobe is largely abandoned by the Mississippi River, Stage 1 of the model shows a system, which is still dominated by freshwater inputs but has limited supply of suspended sediments (upper right panel in Fig. 2). During these early transgressive phases, marine processes begin to rework delta sediments at the coastline (Penland et al., 1988) but the integrity of both the shoreline and the marshes prevent saltwater penetration into interior basins. Consolidation and compaction of the delta sediments continue, resulting in high rates of relative sea-level rise, but accretion rates are much diminished and largely limited to the accumulation of organic material. Nyman et al. (1990) showed how fresh MDP marsh soils remote from fluvial input had high organic content, a condition similar to that noted by Stevenson et al. (1985) for Chesapeake Bay marshes. Gradual deterioration of marshes through submergence results in expansion of ponds and interdistributary bays and the gradual opening up of the marsh–bay system. The last distributary channel of the Lafourche delta was effectively abandoned approximately 300 years ago, although some river flow was present until the early 1900s. This distributary, Bayou Lafourche, built the eastern margin of the Lafourche delta (Fig. 1) and the fresh marshes in the vicinity of Lake Salvador are the type example for this stage of the model. The soils are highly organic (Hatton et al., 1983), subsidence rates are high and open water bodies like Lake Salvador and Little Lake have relatively limited fetch for wave development and sediment resuspension.

As the lakes and bays expand and tidal inlets become more pronounced at the coastline, such as in the older parts of the Lafourche delta in Terrebonne and Timbalier Bays (Fig. 1), the processes influencing the marshes change. Higher salinities can penetrate into coastal bays and into interior marshes as breakup proceeds. Stage 2 of the model (Fig. 2) shows that increased salinities result in a transition to brackish and saline marshes. The opening of coastal bays and increased fetch allows fine sediment reworked during storms to contribute to marsh accretion (e.g., Reed, 1989a). This increased mineral sediment input to the marsh soil counters a decrease in organic accumulation in brackish marshes (Nyman et al., 1990). Overall, subsidence rates decrease as contributions from initial dewatering and compaction of deltaic sediments decline (Roberts et al., 1994), and less organic material results in less autocompaction. Submergence still occurs in areas of locally high subsidence or limited sediment input. Bay expansion occurs both through submergence of marshes surrounding the bays and through erosion of the bay margin marshes by waves (Reed, 1989b). The contemporary analogue for marshes in this stage of the model is the west and central Lafourche delta complex where a fringing barrier island arc (Penland et al., 1988) fronts Terrebonne and Timbalier Bays and extensive saline and brackish marshes.

Fig. 2 shows the final stage of the model as a system with a large bay system from which sediment is reworked during storms and deposited in adjacent marshes in amounts sufficient for the marsh to maintain elevation vs. relative sea-level rise. The open coastal system allows saline water to penetrate far into the marshes, so salt marsh is the dominant vegetative type. Bays are large relative to remaining marsh area. Marsh soils are dominantly inorganic by this stage. Early consolidation and settlement of the highly organic and clay-rich delta deposits has diminished in importance (Kuecher, 1994) and subsidence rates are low as subsidence under load (delta scale) and downwarping (basin scale) remain as the main surface lowering factors (Roberts, 1997). Some organic accumulation and delivery of sediments from the coastal bays during storms maintain marsh elevation. Thus, land loss rates are low. The current analogue for this stage of the model is the remaining marshes of the St. Bernard delta, fronted by Chandeleur Sound (Fig. 1).

Under ideal conditions, the cycle begins anew when the river reoccupies its former location and begins land building once more by rejuvenating the remaining marshes and building land into the large open bay (DeLaune et al., 1987; Roberts, 1997). However, control of the Mississippi River in the twentieth century to prevent coastal flooding and aid navigation (Kesel and Reed, 1995) has interrupted the natural cycle such that natural delta switching no longer occurs. Recent increases in land loss rates are largely attributed to human modifications to the system, such as levees of the Mississippi River and the construction of numerous canals and small levees throughout the coastal marshes, which limit the ability of the marshes to sustain elevation in the face of high rates of relative sea-level rise (Gosselink and Sasser, 1995). Understanding how both ecological and geological factors combine in various ways through time and across coastal landscapes to maintain marshes in areas where hydrology is largely unaltered informs not only our understanding of coastal geomorphic development but also our efforts to restore and sustain these marshes in the future.

5. Conclusions

Chronostratigraphic studies of coastal marsh landscapes usually focus on long time scales (greater than 500 years). Examination at this large a scale, both in time and in space, confounds our understanding of the processes, which have operated to maintain coastal marshes against Holocene sea-level rise and which must also be appreciated for effective coastal management under future sea-level rise conditions. Those processes occur at a smaller temporal and spatial scale and are essentially biogeomorphic in nature. This paper has shown how short-term (subdecadal) changes in water level or sediment supply can affect vegetative vigor and ultimately marsh survival. The continued presence of marshes in rapidly subsiding coastal landscapes such as the Mississippi delta plain is testament to the ability of the short-term dynamic processes to maintain the marsh surface at an elevation necessary for marsh plants to survive. This does not mean that the rate of elevation change or the contributing processes are continuous. The apparent importance of storm deposits in contributing sediment and the changes in vegetative communities, which occur through time, suggest that the rate of marsh vertical building can be high for short time periods, resulting in an "elevation capital." This "capital" is then used up as subsidence proceeds during periods of low vertical building. The conceptual model proposed here for the Mississippi delta plain incorporates changes in landscape-scale process, such as sediment supply, as well as local contributions to marsh elevation from autochthonous plant production. The ultimate submergence of coastal marshes occurs when there is insufficient elevation to prevent excessive waterlogging of the marsh soil leading to plant deterioration. If even some of the marshes, which were built by the Mississippi River during the Holocene, can survive relative sea-level rise rates in excess of 1 cm/year, they have been sustained by the geomorphological and ecological processes described here. Effective management of coastal marshes under future sea-level rise conditions requires a more detailed understanding of these processes and the time scales on which they operate.

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