PHYSICAL PROCESSES OF MARSH DETERIORATION

by

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SUMMARY

Openings in the marsh, ponds, begin with vegetation death which can be related to various environmental factors. At the sediment-poor experimental site, Bayou Chitique, waterlogging stress caused vegetation die-back, resulting in pond formation. As marsh root mats decayed, it was found that soil shear strengths decreased dramatically and that physical processes removed surface soils quickly reducing elevation of the site. Pond depth appears to be more related to decay and removal of the marsh root mat material than to wave-related processes. If stress which causes the death of marsh vegetation is localized, then the resulting pond can stabilize if the pond is less than 0.5 ha in area. In ponds this size and smaller waves are too small to physically erode the healthy marsh around the pond's perimeter. Because of wave characteristics in small ponds, sediment erosion by waves is not taking place except under extremely low tide conditions when resuspension of bottom sediments occurs. Small ponds function as sediment sinks under normal tide and wind conditions. This quasi-balance between erosion and deposition seems to be responsible for maintaining a equilibrium form at both the sediment-rich and sediment-poor experimental sites. However, if stress, e.g. water- logging, causes vegetation death along the pond perimeter, a given pond will expand and perhaps merge with adjacent ponds. When a pond attains a size of 1 ha or greater, fetch is large enough to produce erosive waves and the process of pond expansion becomes irreversible. However, if sediment input to the system increases significantly ponds can fill and new marsh will be established. Selected ponds monitored in the sediment-rich study area followed this pattern.

Sediment deposition and erosion in the marsh-pond-tidal channel setting is complexly related to a variety of hydrodynamic forcing events. During normal tides, suspended material is imported from the channel to the pond where most of it settles. There is minimal exchange between the pond and marsh and little sediment deposition on the marsh surface. Frontal passage results in water level set-up and import of higher levels of suspended material to both the pond and marsh surface. Short term deposition is consistently higher during frontal passage. The low water levels and high winds during set-down lead to erosion of pond bottoms and export of material. Drainage under these conditions also promotes consolidation of both pond and marsh sediments. River discharge generates higher total suspended sediment concentrations

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and in conjunction with frontal passages can lead to significant deposition on the marsh surface. During tropical cyclones, channel flow is less important and over marsh flow dominates. The highest deposition rates at both the sediment poor and sediment-rich experimental sites were measured during Hurricane Andrew.

PROJECT SIGNIFICANCE

Background

Vertical accretion is the primary mechanism by which intertidal marshes maintain themselves against apparent sealevel rise (ASLR), which is caused by the combined effects of eustatic sealevel change as well as local subsidence. In 1972, Redfield suggested that tidal marshes are able to maintain their relative elevation during rapid sealevel rise by sediment capture and increased accumulation of *in situ* belowground production (primarily macrophytic). Letzsch and Frey (1980) went further, stating that marsh aggradation rates are actually enhanced by coastal submergence. Stevenson et al. (1985, 1988) challenged Redfield's idea (1972) and concluded that marshes may not maintain the optimum elevation in relation to ASLR, particularly in areas with reduced sediment supply and low tidal amplitudes. On the Chesapeake Bay eastern shore, Stevenson et al. (1985, 1988) report that much of the marsh erosion began with the formation of inland ponds that enlarged by marginal slumping. Decreased sediment supply is one hypothesized reason for the initial formation of these inland ponds.

Through analysis of aerial imagery from three geologic provinces of the Louisiana coast (encompassing 2,174 km^2), Leibowitz and Hill (1987) demonstrated that conversion of land to inland open water accounted for 70 - 93 % of the loss (in Barataria Basin, this includes both pond formation and expansion of portions of Barataria Bay) while shoreline erosion accounted for approximately 3 %. The deterioration of interior marshlands occurs as openings or holes develop in the continuous vegetative cover and marsh substrate, resulting in open water ponds. Turner and Rao (1987) analyzed pond formation in 72 quadrangle maps between 1955/56 and 1978 and determined that > 7800 ponds were formed, representing 38 % of the wetland loss during that time period. Ponds < 20 ha in size were most numerous but ponds > 60 ha in size accounted for most of the pond area.

This evidence illustrates the role of pond enlargement in wetland loss and various hypotheses are being proposed concerning the mechanics of this process. However, field verification is presently lacking. This study aimed to:
1) obtain the first comprehensive field data concerning pond dynamics and enlargement.
2) test hypotheses relating to the specific processes controlling pond enlargement.
3) develop a quantitative model of pond dynamics and enlargement which can be used in the management and restoration of deteriorating marsh areas.

Marsh Ponds

Background. Shallow marsh ponds, or pans, were described in early morphological studies of salt marshes in north-west Europe (Yapp, 1917). Yapp classified pans as either primary, 'contemporaneous with the sward that bounds them', or secondary, when they are formed either by die-back of surface vegetation or the isolation by bank collapse of the upper sections of small marsh channels. Primary pans develop during initial vegetation colonization of a mud flat, when plant distribution is uneven and some areas are left bare but surrounded by plants. These areas, and similar enclosed secondary openings in plant cover, are maintained and enlarged by wavelet erosion which produces a smooth, sometimes circular plan outline, and the ponding up of saline water after the marsh surface as a whole has been drained (Pethick, 1974). Water remaining on the marsh surface will be subjected to high rates of evaporation, increasing salinity of the ponded water and the underlying sediments, and prohibiting colonization of the pan from the surrounding marsh (Steers, 1946).

Pans and pond holes have been identified in north American marshes (Miller and Egler, 1950; Redfield, 1972), but Frey and Basan (1985) note that they are not ordinarily present in Georgia marshes. However, 'barrens' in Georgia marshes have been attributed to the smothering of original grasses under tidal wracks of dead *Spartina*. The wracks block light, increase temperatures at the sediment surface thus increasing the evaporation rate and hence salinity. As the marsh plants die and become ineffective current bafflers or sediment binders, physical processes become more effective and the barren area persists.

Lateral erosion from pond enlargement has been suggested to provide sediment to immediately adjacent marshes in coastal Louisiana. Sediment accumulation rates within the immediate vicinity of an eroding pond have been observed to be higher than surrounding marsh areas (DeLaune et al. 1983) and local rates of ASLR (Cahoon and Turner 1987). This phenomenon has been observed in a limited number of ponds in two widely different environments in coastal Louisiana, the Chenier Plain (3 ponds) and the sediment-poor Barataria marshes of the Deltaic Plain (1 pond). Because the area of a pond increases more rapidly than the length of the pond edge, bed sediments become progressively more important as a sediment source to the marshes.

Definition. Open water bodies in Louisiana coastal marshes are diverse in their characteristics, origin and relationship to the marsh and include bays, bayous, canals, lakes and ponds. Aspects of this study determined characteristics of Louisiana marsh ponds. Our studies concentrated on water bodies with the following characteristics:

- the water column is under normal conditions well mixed with little or no stratification in terms of salinity and temperature.
- the margins and bed of the pond is natural in form and not directly altered by human activities.
- the depth of the pond will not normally exceed 1 m in depth, and the surface area will normally be less than 100 ha.
- the bed of the pond does not normally contain *in situ* root zone material derived from previously healthy marsh vegetation (i.e., the pond bed should not have an elevation equal to the surrounding marsh surface).
- the pond is largely hydrologically isolated with minor connections to the marsh drainage network.

Role of Ponds in Wetland Loss in Louisiana - the life cycle of a pond. The pattern of vegetation die-back, followed by a change from biological to physical processes dominating at the marsh surface, appears to be important in the development of marsh ponds in Louisiana. Thus, the first step in pond formation involves the biological collapse of the vegetation in a very localized area of marsh. The mechanism for initial plant die-back seems to be related to increased salinities of tidal waters or increased submergence of the marsh surface caused by relative sea-level rise and inadequate marsh surface sedimentation (Mendelssohn and McKee, 1987), or both. Which of these factors is dominant depends upon the marsh type (saline, brackish, intermediate, or fresh) and the specific species composition of the marsh. When plant die-back occurs and open water areas appear on the marsh surface, physical processes associated with tidal action and small waves then come into play, and pond expansion is a frequent result. Hydrodynamic processes, such as waves and currents, work directly upon marsh plants and sediments and are the causative forces which move sediments and plants. The marsh resistance to these applied forces prevents movement and allows the biological/chemical processes to continue. The restoration and management of the marsh will be based upon controlling this force balance so that the marsh loss is reduced, and restoration is possible. At the beginning of the study, little data and understanding of the spatial and temporal stresses and resistances occurring in the marsh were available, thus the direct mechanisms of marginal erosion and enlargement are not known.

Whether or not the process of pond formation is reversible also is not clear. Turner and Rao (1987) showed that some ponds were 'transient' (334 out of 7,821), that is that they were observed in 1955/56 and not in 1978. If these transient ponds are not a registration artifact of the aerial imagery analysis, this result suggests that some ponds in Louisiana's marshes can become revegetated.

Role of Ponds in Wetland Loss in Louisiana - a balance of physical forces. The physical stresses (forces) to which the marsh is subjected are the result of the combined effects of the primary hydrodynamic processes of water level changes, wave action and currents. Several types of forces occur when waves and currents interact with the marsh. These forces are of two general types; shear stresses (drag force) and normal stresses (pressures). The shear and normal stresses depend upon hydrodynamic variables and the location and geometry of the object receiving the force. Therefore, in order to convert the hydrodynamic process magnitudes and variations into the actual forces experienced by the marsh, the characteristics of these forces need to be considered in detail. The forces considered in this study included frictional stresses on bottom sediments and plants, inertial forces on plants, pressure forces on sediments and plants, and shear and normal stresses within sediments, as shown in Figure 5.1a, b. It is these forces cause the movements of sediments and marsh plants which constitute marsh erosion. The resistance of the marsh to erosion can be primarily characterized by measurements of shear strength, liquid limits, and bulk density.

The forces caused by the hydrodynamic processes generally depend upon the square of the wave height and current, and therefore physical processes reach their maximum capacity for eroding the marsh during infrequent storm events. These storm events can be distinguished by the time and spatial scales of the meteorological event, such as frontal passage, hurricanes and thunderstorms. Storm events occur within the seasonal cycle of changes in the physical and biological processes in the marsh. In order to understand the linkage between physical processes and marsh erosion, simultaneous measurements were made under different climatic conditions including storm events.

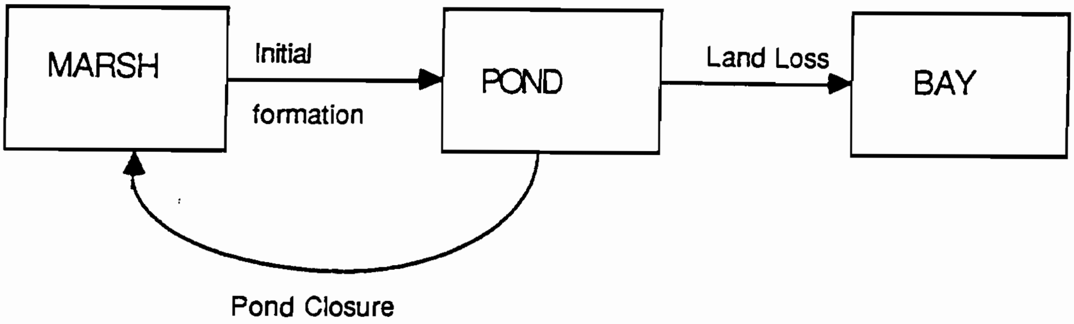


Figure 5.1a Theoretical life cycle of a pond in a Louisiana coastal marsh.

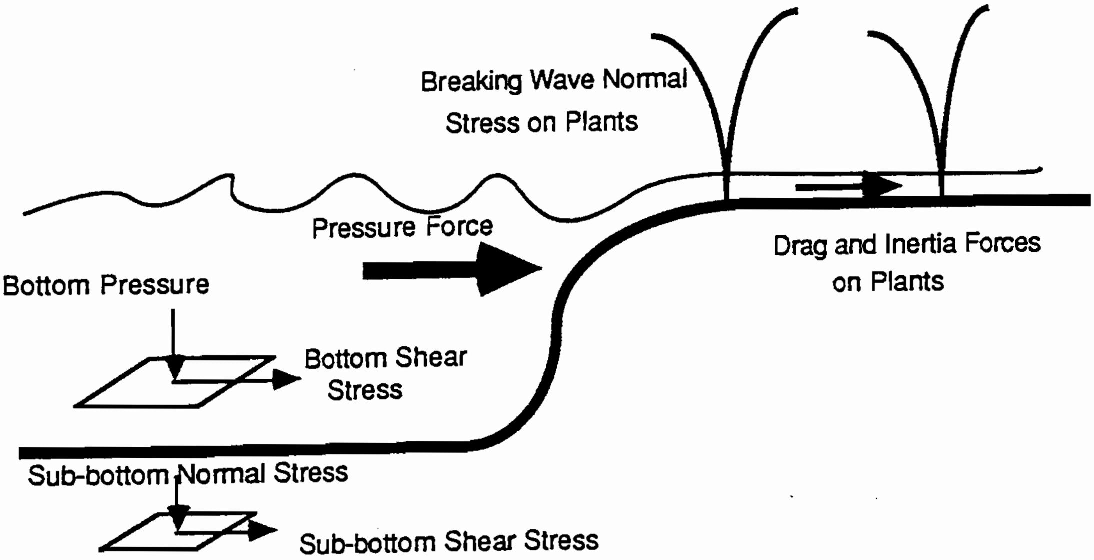


Figure 5.1b Hydrodynamic stress occurring in ponds and marshes.

RESEARCH TASKS

This task focused on the transport of suspended sediments among bayou, pond and marsh and on the physical mechanisms of pond enlargement. The research addressed the following hypotheses concerning the deterioration of coastal marshes, particularly the physical mechanisms of pond enlargement and the influence of ponds on sediment transport processes.

Hypotheses

1. Physical Mechanisms of Marsh Deterioration

Hypothesis 1A. There are two components to pond enlargement. Initially, lateral expansion from marginal erosion is the primary causative factor, but as the pond increases in diameter deepening of the pond through wave-generated phenomena becomes increasingly more important.

> **Finding:** Pond enlargement is primarily a function of marsh death and compaction and slumping of sediments as the root mass is decomposed. By the time wave-generated forces become important, the pond has begun to coalesce into a larger (non-pond) water body.

Hypothesis 1B. The depth of ponds is related to pond width via the fetch/wave generation relationship.

> **Finding:** Under most conditions, waves in ponds are deep water waves and do not exert erosive stresses strong enough to resuspend bottom sediments. During very low water and high winds, such as the set-down phase of a frontal passage, the bottom can be eroded. This loss is normally balanced by sedimentation under normal conditions so that over time depth remains relatively constant. Waves that can regularly erode the bottom propagate into the pond from larger adjacent waterbodies once pond boundaries are breached and coalescence into adjacent waterbodies occurs.

2. Influence of Ponds on Sediment Transport

Hypothesis 2A. Marsh pond sediments act as a direct sediment source for adjacent marshes.

> **Finding:** Ponds are generally a sink for sediments and the larger bayou is the major source of sediments for the marsh surface. Sediments enter the marsh directly from the bayou and not from the pond.

Hypothesis 2B. As ponds enlarge, bed sediments become progressively more important than marginal bank sediments as a sediment source to the adjacent marsh surface.

> **Finding:** Pond sediments are not a major source of sediments to the marsh surface. Rather, pond sediments are much more likely to be exported as the pond grows in size. The pond appears to facilitate export. Bottom sediments are important in larger water bodies, but we do not know the threshold size.

Hypothesis 2C. In sediment poor environments, insufficient sediment is available for the elevation of the pond bed to recover from storm-related scour events.

> **Finding:** Storm-related scour does not seem to cause loss of bed elevation in small ponds, but may be importnat for maintaining depth.

Hypothesis 2D. Major sediment fluxes are event related.

Finding: Major sediment movement and deposition on the marsh surface occurred during frontal passages and tropical storms and hurricanes.

Hypothesis 2E. Net re-suspension of sediment does not generally occur from the surface of the marsh.

Finding: There was no conclusive evidence of significant sediment resuspension from the marsh surface, although this could only be inferred from indirect measurements.

Hypothesis 2F. Distance from pond margin does not influence the amount of sediment deposited on the marsh surface.

Finding: The distance from the pond was not related to the level of marsh deposition, as the pond is not a source.

Tasks

The research focused on the factors leading to sediment flux and pond enlargement. The research was organized around five tasks. These were:

1)Pond size distribution, geometry, baseline information on plants and sediments and changes in pond morphology.

2) Measurements of fluxes of sediments between the ponds and marsh drainage network.

3) Measurement of sediment dynamics in ponds. These included: measurements of wave generation and bed resuspension using an array of pressure transducers, current meters, and transmissometers and quantitative measures of net bed erosion and deposition using sediment tables.

4) Measurement of exchange of sediments between the pond and the marsh surface. The flux of sediments between the marsh and the pond was determined with marsh flumes. The deposition of sediments on the marsh was measured seasonally with marker horizons and during short term events as deposition on filter papers. The change in the surface elevation of the marsh surface was measured with a sedimentation-erosion table.

5) Data Synthesis. A simulation model of sediment dynamics of the pond-marsh system was developed which incorporated theoretical hydrodynamic and sediment relationships and which was calibrated and validated with data collected in the field.

METHODOLOGY

The pond research was carried out in sediment rich and sediment-poor basins. In each basin, ponds were selected in saline and low-salinity/freshwater marshes. The general sampling design for a typical pond is shown in Figure 5.2.

Marsh Pond Survey and Baseline Information

An Everest Geotech Micro VAX-based Image Quantification System was used to capture, register, and define land-water boundaries in a vector format in ten 1985 high-altitude color

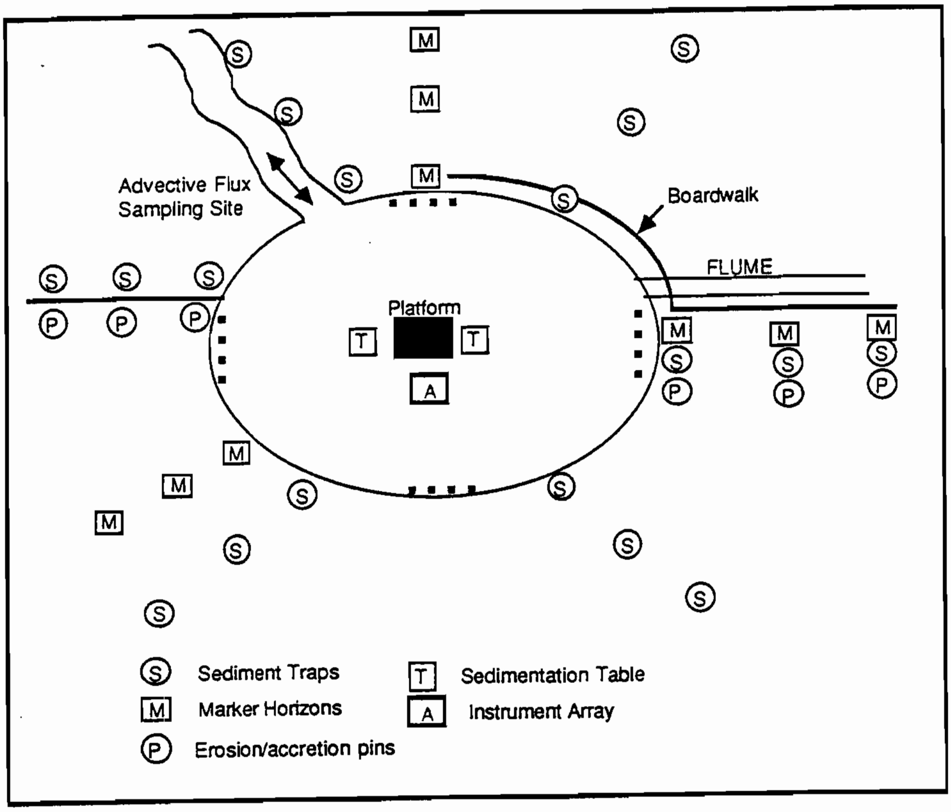


Figure 5.2. Sampling Design for a typical pond.

infrared images obtained by NASA for the Coastal Management Division of the La. Department of Natural Resources to characterize the water bodies and assist in site selection. The images were registered to manually digitized 1978 vector datasets classified by the U.S. Fish and Wildlife Service. Scanned images were examined for water bodies between 0.075 and 10 ha unconnected to any other water body by an opening of more than 15 m. The distribution of marsh waterbodies was mapped on a simple three axis system consisting of area, geometry (aspect ratio), and orientation (major axis). Marsh ponds in size classes of interest were then displayed and summary statistics developed that were compared with similar results from the manually digitized 1978 U.S. Fish and Wildlife Service 7.5' quadrangles.

Changes in Pond Morphology

During each trip to the field, observations on the size, position of the pond/marsh interface, and other characteristics of the pond morphology (slope of the pond/marsh interface, invasion or retreat of vegetation, etc.) were made. From these observations, conclusions concerning changes in the pond were drawn.

Advective Fluxes

The flux of total suspended solids between the pond and connecting waterway was estimated during key periods using data from an OBS instrument and recording current meter placed at the pond entrance on a fixed platform. Water fluxes through the cross-section were calculated using the average velocity and cross-sectional area.

Hydrodynamic Stresses and Pond Bottom Resistance

Although the ponds were about the same depth, marsh surface elevation at the OB site was estimated from water level time-series to be about 10 cm higher than at BC. The OB pond is a stable landscape feature visible in 1940's photography, while the BC pond is of more recent origin and is in an area of rapid marsh break-up and loss.

A schematic showing the equipment layout at the two sites is shown in Figure 5.3. Winds were measured just above the elevation of the marsh grass and wave stress at the pond bed was estimated using pairs of pressure sensors fixed at the bottom that were separated by about 8 m. One sensor ('a') was placed in shallower water at the pond margin, while the other ('b') was placed closer to the center of the pond in water that averaged 20 cm deeper. Wave data were logged in 4.26 minute bursts at a samping interval of 0.25 s. Autosamplers were positioned to collect water samples for suspended sediment analysis from the pond margin 'a' position and from a marsh surface station ('c') located 20 m inland of the edge of vegetation. The autosamplers were synchronized to collect water samples at the start of each wave sampling period. Sediment-erosion table (SET) stations were established at points 'a' and 'c' to monitor changes as small as 0.3 cm in local soil surface elevation as shown in Figure 5.4 (Boumans and Day, 1993). An additional SET station was placed at BC within the pond at location 'b'. Eight cm diameter cores, 40 cm long were collected at from the same locations. Cores were split and tested for fall cone (penetration) and vane shear strengths. They were then sectioned and analyzed for unit weight, bulk density and organic matter content.

Exchanges of suspended sediments between pond and marsh using marsh flumes

Marsh flumes (20 m long) were built at each pond site. A throughflow design was used in the flumes; a modification necessary for use in expansive, microtidal, low energy estuarine marshes. Replicate water samples are drawn simultaneously from both ends of the flume every 30-60 minutes over the sampling period. We determined fluxes of suspended sediments by comparing instantaneous flux into the flume with that out of the flume. Details of the flume design, sample treatments, flux computations, and data interpretation are presented in Childers and Day (1988). Soil bulk density and organic matter content were determined by standard techniques (Blake, 1965; Allen, 1974) for creekside and inland locations at each flume site using shallow marsh cores.

Sediment Deposition and Accretion and Elevation Change

In order to assess the role of short term flooding events in contributing sediment to the marsh surface, surface sediment traps were used (Reed, 1987). Seasonal rates of sediment deposition on marsh surfaces in the vicinity of the ponds (Figure 5.2) were determined by use of feldspar marker horizons using the techniques described by Cahoon and Turner (1987). The feldspar marker plots were cored by the cryogenic technique described by Knaus (1986) approximately four times a year from each marker plot. Changes in the elevation of the marsh and pond sediment surface was determined using sedimentation-erosion tables (Boumans and Day 1993).

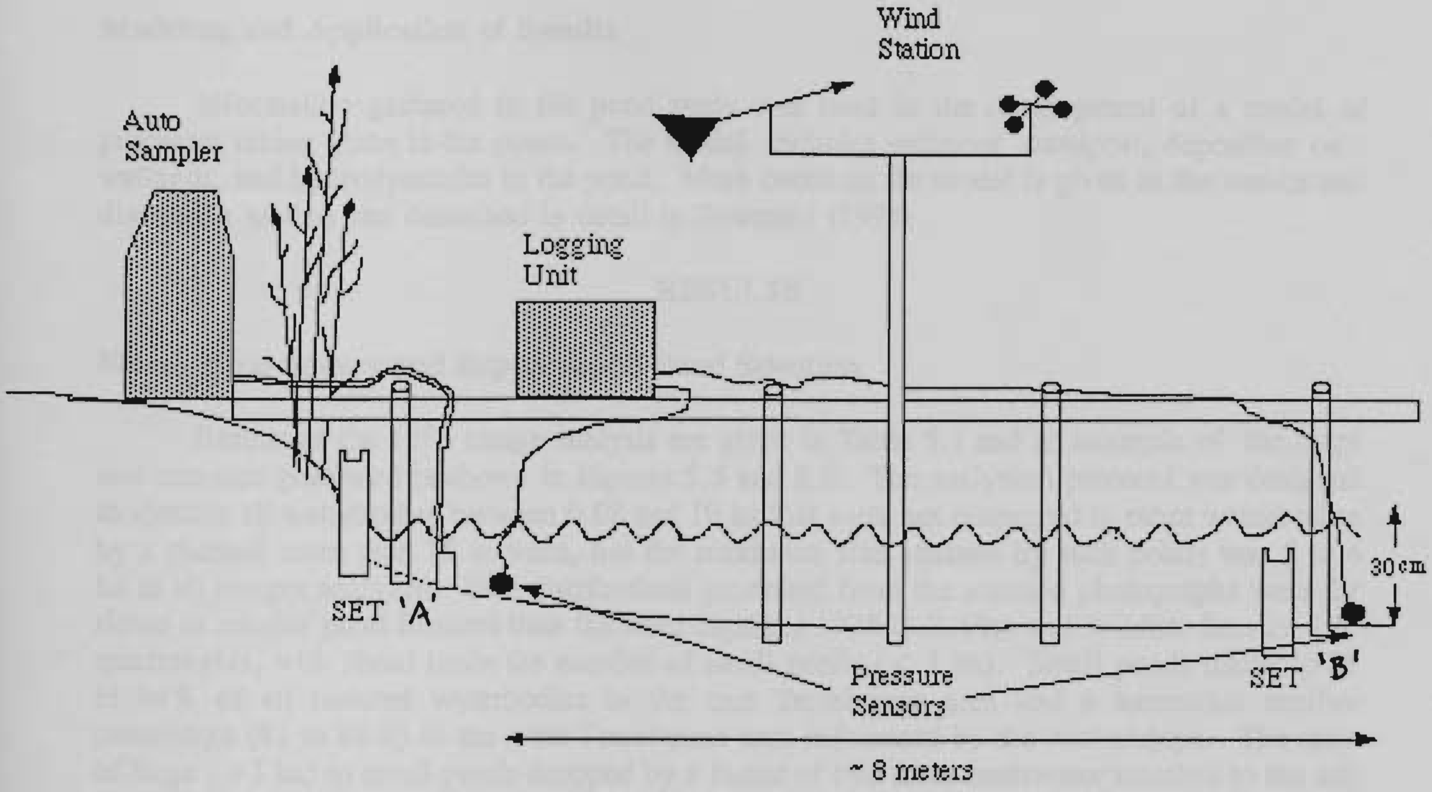


Figure 5.3 Equipment Deployment at Salt Marsh Pond Sites.

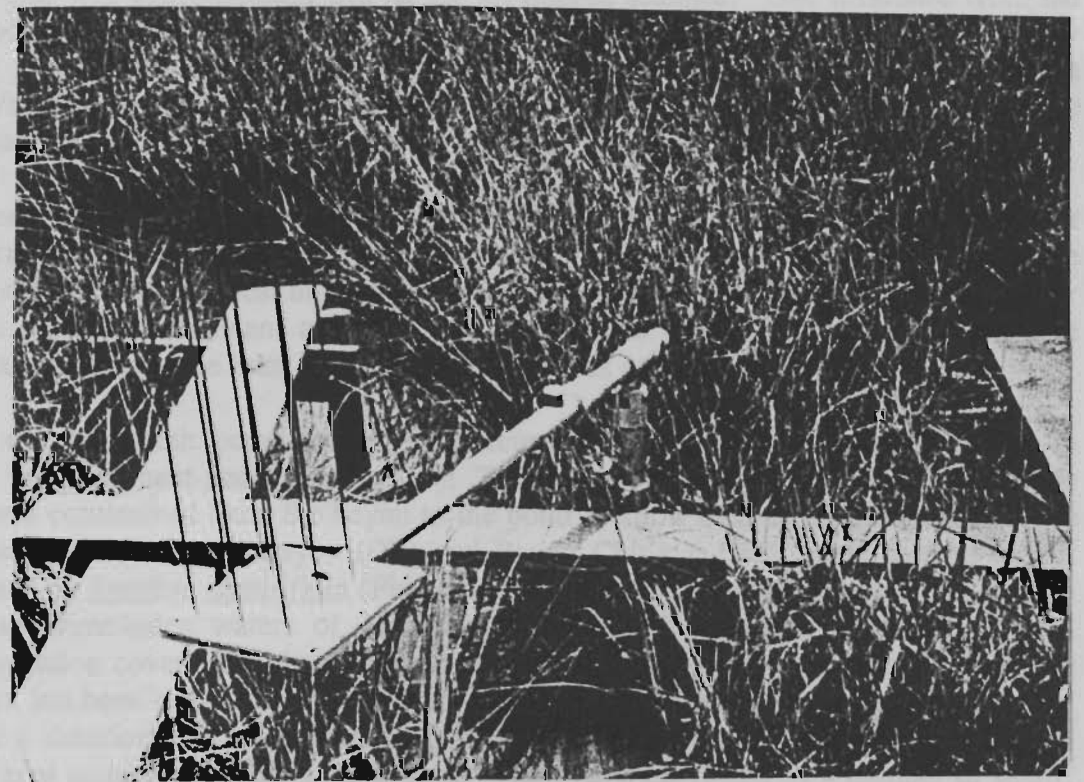


Figure 5.4 Use of Sediment Erosion Table (SET) to precisely monitor soil surface elevation change (+/-0.3 cm).

Modeling and Application of Results

Information gathered in the pond study was used in the development of a model of processes taking place in the ponds. The model includes sediment transport, deposition on wetlands, and hydrodynamics in the pond. More detail on the model is given in the results and discussion section and described in detail in Boumans (1994).

RESULTS

Marsh Pond Survey and Experimental Pond Selection

Results of the 1985 image analysis are given in Table 5.1 and an example of the maps and statistics generated is shown in Figures 5.5 and 5.6. The analytical protocol was designed to identify all waterbodies between 0.08 and 10 ha that were not connected to other waterbodies by a channel more than 15 m wide, but the maximum size attained by such ponds was 5 to 6 ha in all images analyzed. Size distributions generated from the scanned photographs were far richer in smaller pond features than the hand digitized 1978 U.S. Fish and Wildlife Service 7.5' quadrangles, with about twice the number of small ponds (< 1 ha). Small ponds made up 88 to 94% of all isolated waterbodies in the east Terrebonne area and a somewhat smaller percentage (81 to 88%) in the west Terrebonne area influenced by the Atchafalaya. The ratio of large (>1 ha) to small ponds dropped by a factor of two from freshwater marshes to the salt marshes in both study areas, although the total number of ponds in each image were comparable. Median pond size was approximately 0.2 ha for all images scanned. One inference from the distributions observed is that most ponds become significantly integrated into larger waterbody complexes or, alternatively, become revegetated before they ever expand to cover more than a single ha. We actually observed both engulfment and revegetation during the course of the study, but it can be assumed that enlargement leading to engulfment is the dominant process.

The pond populations in the eastern and western Terrebonne study areas do not differ significantly in terms of elongation or orientation of the major chord. One reason is that the small ponds (<1 ha) that are most numerous are essentially circular. The less frequent larger ponds tend to display a dominant axis that is 2 to 3 times the minor axis, but no single orientation characterized more than 10% of the large ponds (>1 ha) in any image.

Based on the marsh pond survey, four representative pond sites were selected in sediment-rich and sediment-poor areas of the Terrebonne basin. At each of the ponds boardwalks were constructed from the bayou to the pond to allow ease of access and minimize marsh disturbance. Old Oyster Bayou (OB) and Bayou Chitigue (BC), were located in salt marsh dominated by Spartina alterniflora (Figure 5.7). Site OB is a firm, healthy marsh located close to the sediment-laden waters of Atchafalaya Bay and Fourleague Bay. There is a continuous vegetation cover with almost no exposed mud surface within the marsh. Wetland loss in this area has been negligible and the pond has been a stable landscape feature since the 1940's. BC is a deteriorating marsh remote from a riverine source of sediment and located adjacent to an area undergoing rapid wetland loss. The area is interlaced by a number of small, shallow channels and the marsh is humocky with considerable exposed mud within the marsh.

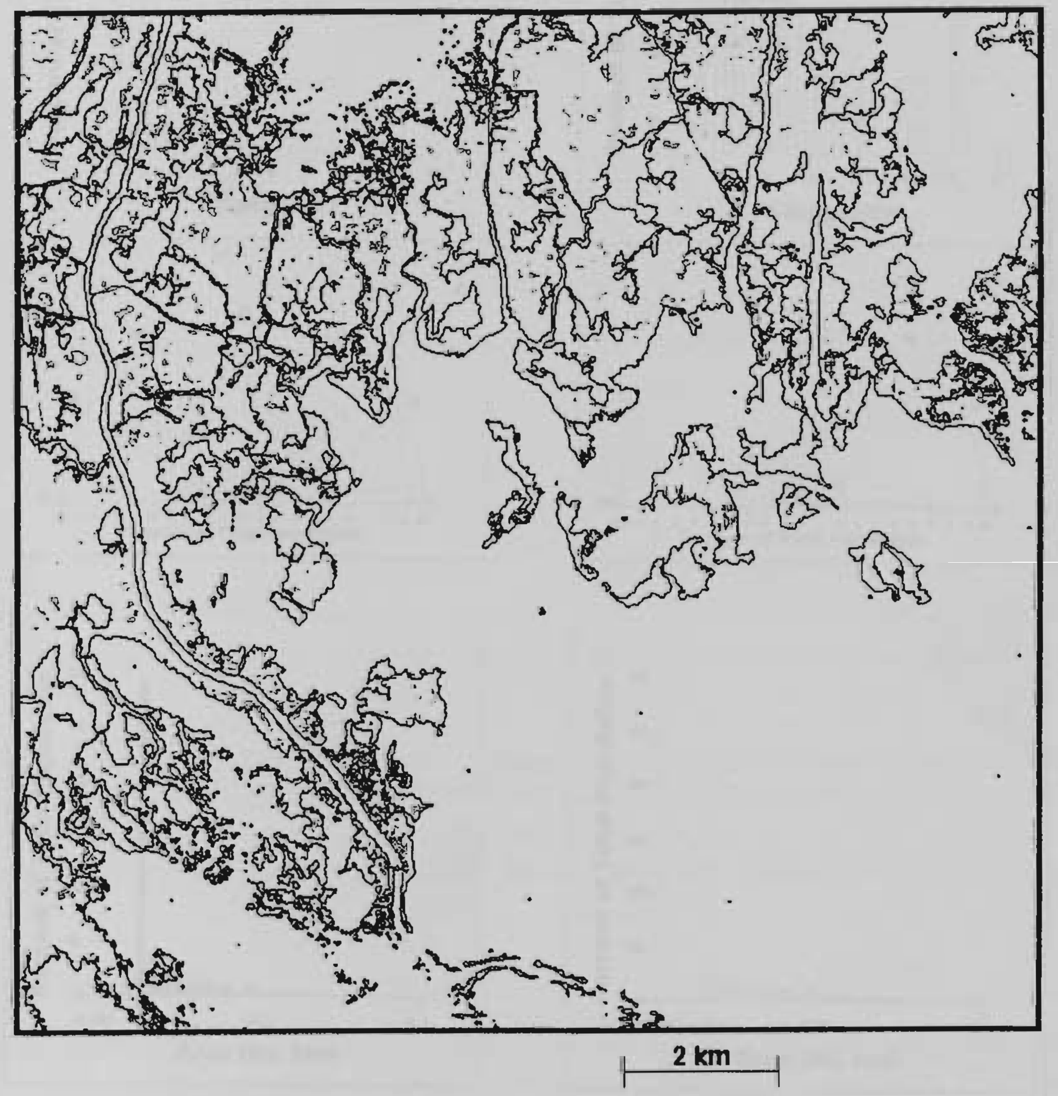
TABLE 5.1 RESULTS OF POND ANALYSIS 1985 SCANNED CIR IMAGES

Quadrangle	Pond Number	% <0.2 ha	Ratio 1 Large:Small	Large Ponds Elong(Orient)2	Small Pond Elong(Orient)
Sediment-Poor					
L. Bully Camp	525	52%	0.12	2.5(175)	1.0(005)
L. Tambour	742	58%	0.09	2.3(160)	1.2(005)
L. Felicity	401	45%	0.06	2.4(085)	1.2(135)
Mean			0.09	2.4(140)	1.1(048)
Std. Dev.			0.02	0.1(039)	0.1(061)
Sediment-Rich					
Plumb Bayou	514	31%	0.19	3.0(005)	1.3(115)
Fourleague Bay	585	40%	0.16	2.0(135)	1.1(115)
E. Bay Junop	581	41%	0.12	1.8(012)	1.2(065)
Mean			0.16	2.3(051)	1.2(098)
Std. Dev.			0.03	0.5(060)	0.1(024)

1 Ratio of number of ponds > 1 ha (large) to those < 1 ha (small).
2 Elongation factor mode for pond population; compass orientation mode in brackets.

The substrate is dominated by mineral sediment but has a relatively low bulk density. At both OB and BC, a permanent channel connecting the pond to the bayou. Carencro Bayou (CB) is a brackish to intermediate marsh dominated by Spartina patens, Scirpus olneyi, and Phragmites australis which forms a nearly continuous cover in the area site. CB is located near Fourleague Bay and has high sediment input and a firm marsh substrate. The area has undergone negligible land loss. Water exchange between the marsh and the bayou is influenced by a natural berm along the bayou and fixed-crest weirs in nearby drainage channels. There are no well defined channels connecting the pond directly to the bayou, but behind the berm (about 20 m from the bayou edge) there are a number of small, shallow sloughs (approx. 1 m wide and 10-20 cm deep) which convey water flowing from the bayou to the interior of the marsh. At the beginning of the study, the boardwalk passed through several small ponds (approx. 3-5 across) before reaching the study pond. Bayou Blue (BB) is a fresh to intermediate marsh site where Paspalum vaginatum is the dominant vegetation type. The substrate is highly organic and fluid. Like the CB site, the pond at BB had an indirect connection with the bayou and the pond was hydrologically connected only during high water periods. This locale has undergone considerable wetland loss. The BB pond was irregular in shape as compared to the other three ponds which were more oval or circular.

LAKE TAMBOUR - CIR 1440



Red = 0 - 0.01 km² **Green = 0.01 - 0.1 km²** **Black = > 0.1 km²**

Figure 5.5 Distribution of ponds by size in the Lake Tambour Quad Sheet (which includes Bayou Chitique).

LAKE TAMBOUR CIR 1440

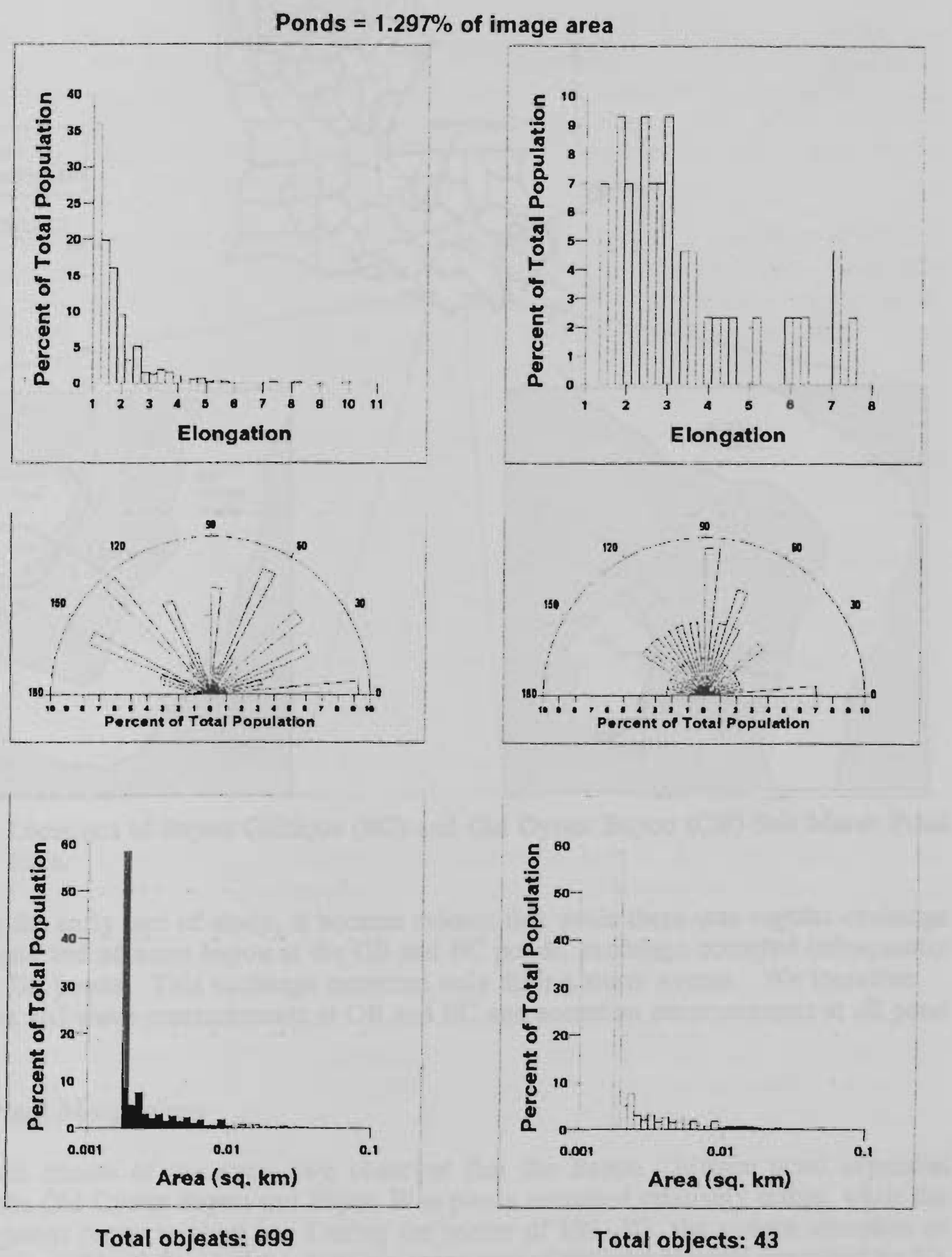


Figure 5.6 Frequency distribution of pond size in the Lake Tambour Quadrangle (bottom 2 panels), Ponds smaller than 0.01 square km (1 ha) are in red and ponds greater than 1 ha are in green.

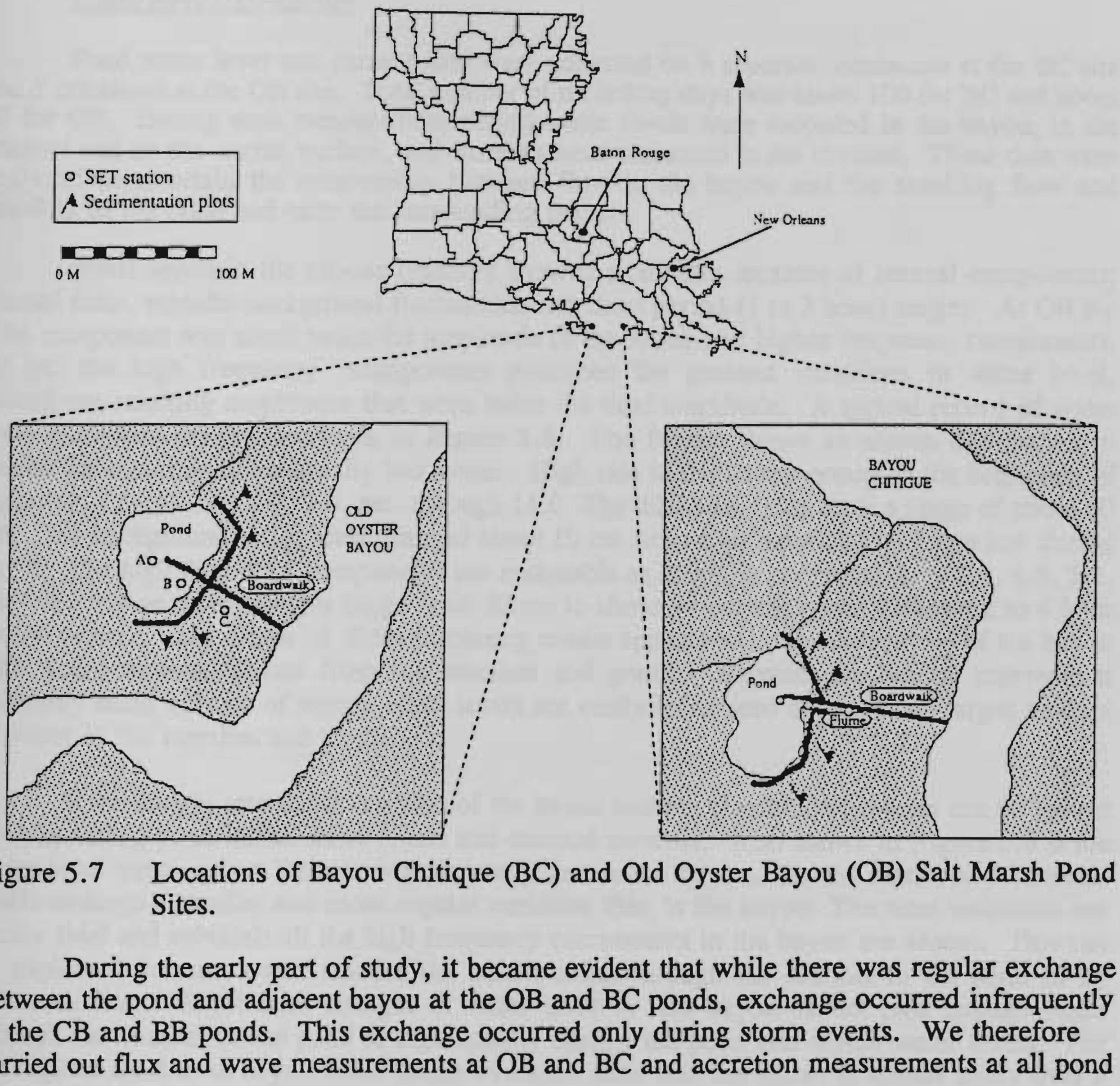


Figure 5.7 Locations of Bayou Chitique (BC) and Old Oyster Bayou (OB) Salt Marsh Pond Sites.

During the early part of study, it became evident that while there was regular exchange between the pond and adjacent bayou at the OB and BC ponds, exchange occurred infrequently at the CB and BB ponds. This exchange occurred only during storm events. We therefore carried out flux and wave measurements at OB and BC and accretion measurements at all pond sites.

Changes in Pond Morphology

Over the course of the study, we observed that the Bayou Chitique pond expanded dramatically, the Old Oyster Bayou and Bayou Blue ponds remained relatively stable, while the Big Carencro ponds began to close in. During the winter of 1991-92, the eastern shoreline of the BC pond retreated by 2-3 m and the northern shore east of the inlet channel expanded by 50-100 m. This shoreline retreat followed death of the marsh in these zones. At the OB and BB sites, there was little discernible change in the depth or shoreline position of the ponds. At CB, the small ponds which were traversed by the boardwalk had become vegetated by the end of the study and were no longer recognizable as ponds. The main CB pond was filling and becoming shallower.

Pond/Bayou Dynamics

Pond water level and current data were collected on 6 separate occasions at the BC site and 5 occasions at the OB site. Total number of recording days was about 100 for BC and about 80 for OB. During each measurement period water levels were recorded in the bayou, in the channel and on the marsh surface, and currents were measured in the channel. These data were analyzed to ascertain the relationship between flow in the bayou and the resulting flow and flooding in the pond and onto the surrounding marsh.

Water levels in the bayous typically showed a complex mixture of several components; diurnal tides, subtidal background fluctuations and short period (1 to 3 hour) surges. At OB the tidal component was about twice the amplitude of the lower and higher frequency components. At BC the high frequency components produced the greatest variations in water level, sometimes reaching amplitudes that were twice the tidal amplitude. A typical record of water level variations for BC is shown in Figure 5.8. The Figure shows an eleven day period in December at a time of seasonally low water. High tide in the bayou occurs at the beginning of each day, i.e., at 1.0, 2.0, 3.0, etc. through 11.0 The tidal variations have a range of about 20 cm. The background water level changed about 10 cm from a high during day 2 to a low during day 5. The high frequency components are noticeable as spikes occurring at days 3.4, 4.5, 5.5, and 7.5. These rapid changes range from 30 cm to about 50 cm and occur within a 2 to 4 hour period of time. The origin of these frequency events appears to be the interaction of the bayou with water moving to and from the marshes and ponds. Because the bayous represent a relatively small volume of water, water levels are easily influenced by the much larger amount of water in the marshes and ponds.

Some insight into the interaction of the bayou and the marsh/pond system can be gained by considering pond/marsh water levels and channel currents. Also shown in Figure 5.8 is the water level measured on the marsh surface adjacent to the bayou. On the marsh surface water levels undergo a smaller and more regular variation than in the bayou. The time variations are purely tidal and subtidal; all the high frequency components in the bayou are absent. This can be explained because water reaches the marsh either through the channel to the pond or by overbank flow. Short term changes in water level in the bayou cannot pass enough water through the channel to the pond to significantly change the pond and marsh water levels. For the highest short term bayou water levels overbank flow into the marsh is spread thinly over a large area and so is attenuated. Thus the marsh/pond system at BC acted as a low pass filter on bayou water level variations. At OB the high frequency components were relative small, so that the bayou water levels and the marsh water levels are more alike. However, high frequency components are observed on the marsh surface.

Water levels in the BC pond show similar time variations to those on the marsh surface. The high frequency components are absent. As water levels in the bayou fall, the pond drains, but at a slower rate than the bayou level falls. As the bayou rises during one of the high frequency events, water flow in the channel reverses and the pond begins to fill at a low rate. After the high frequency event has ceased, the bayou water level continues to fall with continued drainage of the pond. The channel velocity shows two periods of inflow to the pond for each tide cycle. The first occurs during the rise in bayou water level due to the tides and a second time when bayou water levels briefly rise during the falling tide.

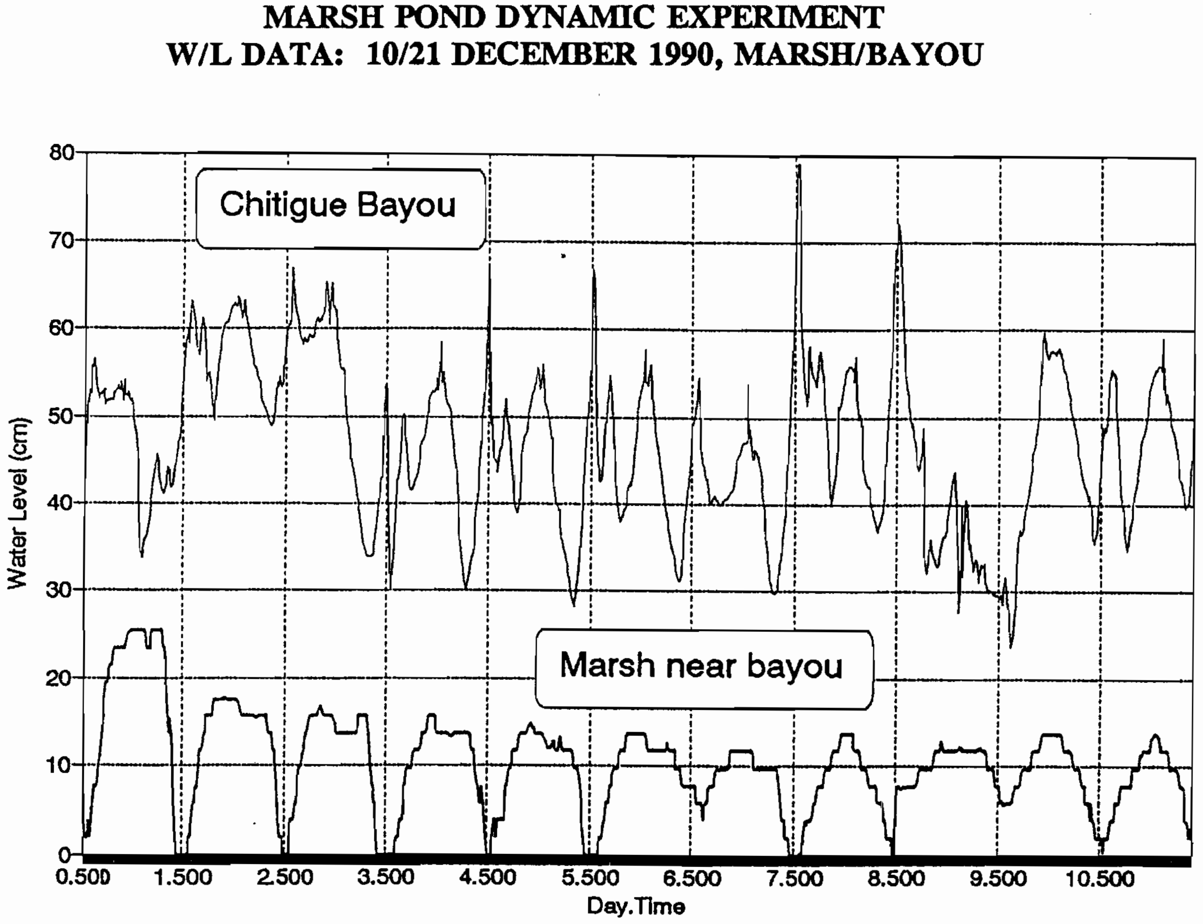


Figure 5.8 Water level records from Bayou Chitigue and the adjacent marsh showing low pass filtering.

The marsh/pond system acts as a trap for sediments because of the low water velocities which occur. Flow into the ponds through the channels was observed to be 10 to 20 cm/s. This is not sufficient to erode or even transport sediment. The flow is decreased as it enters the pond and floods the marsh surface. Flow velocities of a few cm/sec or less occur. For flow on the marsh surface of a depth of 5 cm or less, the Reynolds number approaches the lower limits of turbulent flow. At these low flow conditions, transport of suspended sediment is inhibited by a lack of turbulence and deposition through settling occurs on the marsh surface. If the surface becomes exposed at low water levels, then this sediment can be rapidly consolidated through desiccation. If the surface is continually flooded the deposited soil will remain essentially unconsolidated. Hence shear strengths of surface sediments in BC are less than the shear strengths of surface sediments at OB.

Wave And Suspended Sediment Measurements

Synoptic wind, wave, water level and suspended sediment data were acquired in the BC pond on 13 days and at the OB pond on 15 other days for a total of 191 ensemble datasets. About half of these datasets were used in the analysis reported here and summarized in Table 5.2. The highest wind speed recorded at 1 m was 5 m-s^{-1}, which corresponds to an estimated speed at 10 m of 8 m-s^{-1}. Water depths ranged from 0 to 50 cm at the pond margin pressure sensor ('a') and from 9 to 64 cm at the offshore sensor ('b'). Total wave energy and frequency were extracted from spectra generated from each detrended pressure record to provide an analog of bed shear stress. Wave height was not measured directly, but waves were never observed in the ponds with heights greater than about 5 cm. Virtually all records were affected by aliasing because of the dominance of frequencies greater than the 2 Hz nyquist frequency in the locally generated waves, but very little of the energy in this range actually penetrated to the bed.

TABLE 5.2 RESULTS FROM WAVES STUDIES AT BAYOU CHITIQUE AND OLD OYSTER BAYOU

	Wave Records No.	Wind Speed @ 1 m (std dev) m/s	Wave Freq. Hz	Depth (std dev) cm	Bed Wave Energy (std dev) cm^2/Hz	Suspended Sed. (std dev) mg/l	Organics in TSS (std dev) % dry wt.
Bayou Chitique Marsh	***	***	***	***	***	83(136)	35.4(8.5)
Pond Edge	50	2.28(1.13)	5.0 to 0.7	21.3(14)	0.0101(0.0280)	67(33)	34.1(10.0)
Pond Center	50	2.28(1.13)	5.0 to 0.7	37.3(16)	0.0026(0.0035)	***	***
Oyster Bayou Marsh	***	***	***	***	***	88(131)	31.4(14.1)
Pond Edge	23	1.30(1.03)	5.0 to 2.5	19.1(14)	0.0114(0.0286)	107(75)	28.9(10.5)
Pond Center	23	1.30(1.03)	5.0 to 2.5	29.1(16)	0.0035(0.0054)	***	***

Despite the shallow depths of the ponds, the locally generated waves measured were so limited by the 50 m fetch that they were essentially deep water waves that did not impose significant stresses on the bed. The records were examined to see whether an intrusion of lower frequency and perhaps larger waves from outside the pond system occurred when the marsh surface was flooded. We did not observe such intrusion on high tides. After Hurricane Andrew, however, the BC pond opened up rapidly along the north side, as has been described. Then, waves with frequencies between 1 and 2 Hz were recorded and provided the highest energy conditions monitored as shown in the spectra in Figure 5.9.

Pond depth, in addition to fetch, limits the effect of wave energy on the bed. The attenuating effect of depth on wave energy is clear at both sites (Table 5.2 and Figure 5.9). Wave energy reached the pond bottom only when water level was less than 5 and 20 cm above the pond margin sensor at BC and OB, respectively. As a result, the limited wave energy present affects the shallower pond margin more often than the rest of the pond bottom. The difference between the sites was due to the presence of lower frequency, non-local waves in the BC pond after Hurricane Andrew. Although the pond bottoms are soft and muddy, we did not see evidence when comparing the two pressure records of significant deviation from the rate of energy dissipation that would be predicted by linear wave theory. These were, however, essentially deep-water waves that experienced very little interaction with the bed, so little effect would be expected.

Total suspended sediment (TSS) concentrations in the ponds ranged from 10 to 200 mg-l^{-1} at BC and from 20 to 400 mg-l^{-1} at OB. Mean TSS concentration in the OB pond (107 mg-l^{-1}) was nearly twice that at BC (67 mg-l^{-1}) while values from the marsh surface were similar (83 at BC, 88 at OB). These data are insufficient to support a statistical analysis of seasonal variability, but are consistent with the observations of short-term sedimentation patterns discussed later. TSS concentrations in the BC pond were highest in the winter, while the highest TSS values obtained at OB were acquired during the spring, suggesting the importance of river influence. TSS did not differ significantly between the pond and marsh samples taken 20 m apart at each site.

If wave resuspension of sediments within the pond were the primary forcing for TSS concentrations within the pond, a negative correlation with depth would be expected. In fact, a significant positive correlation explaining 51 percent of the variation is found when water level and TSS data from the pond margin are compared for both the BC and OB sites, indicating that TSS rises as water levels rise. This suggests that sediments enter the ponds from the bayou via the inlet channel. TSS in the OB pond was also significantly negatively correlated with the percentage by weight of organic matter in the suspended sediment (%OM), indicating that most variation of TSS in the OB pond could be explained by the introduction of inorganic sediments, which could only come from the bayou. Such a correlation was not significant in the BC pond.

Two classes of pond TSS samples were noted at both sites that could be distinguished on the basis of %OM (Figure 5.10). Low concentration samples below 50 mg-l^{-1} are highly organic and become more than 80 percent organic by weight at the lowest concentrations measured. High concentration samples (>50 mg-l^{-1}) retain a relatively constant 20 to 30 percent organic matter content as TSS increases. The high and low concentration TSS populations may result from different process histories, perhaps reflecting a difference between water draining from the marsh surface and that entering the pond from the bayou.

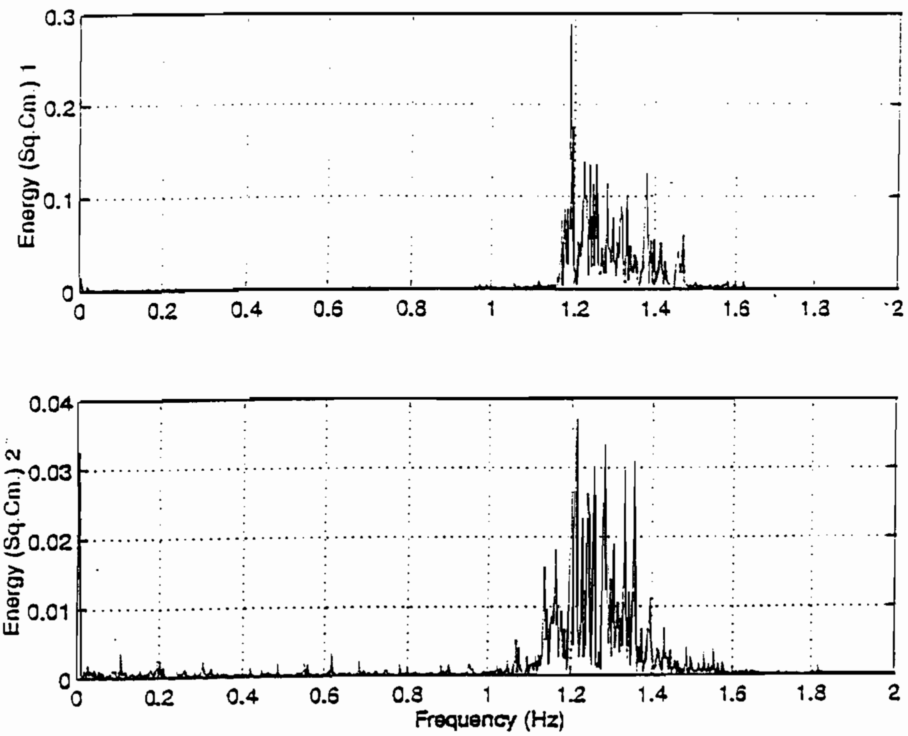


Figure 5.9 Spectra from simultaneous bottom pressure records from the Bayou Chitique pond margin (a) and from 8 meters away toward the pond center (b) on January 13, 1993. Water depths were 15 and 28 cm at 'a' and 'b' respectively. Note difference in scales.

Soil Elevation, Composition And Strength Measurements

Soil elevation changes, composition and strength data are provided in Table 5.3 SET measurements of local surface elevation changes resulting from deposition, erosion and consolidation in the upper 2 m of the sediment column showed a two year loss of 1 cm (+/-0.3) in the elevation of the pond bottom ('b') at the BC site. Elevation at the pond margin ('a') dropped 2.8 cm at both sites. The passage of Hurricane Andrew did not alter the elevation trend of the pond margin or bottom.

Marsh surface elevation showed no significant change at BC (-0.3 cm) but increased at OB by 1 cm over two years. No change, as measured by the SET, actually translates into an absolute reduction in elevation as it means that the surface is sinking at the regional rates of ASLR. It is not possible to precisely establish the regional ASLR for the two years during which we monitored local elevation change at both sites, but it is clear that the BC marsh is not aggrading at a sufficient rate to offset any regional ASLR greater than zero. The OB marsh, in contrast, appears to be building up its surface at least 0.5 cm-yr^{-1} which is at the lower end of ASLR estimates for this area. More detailed results of the SET and marker layer studies are reported later.

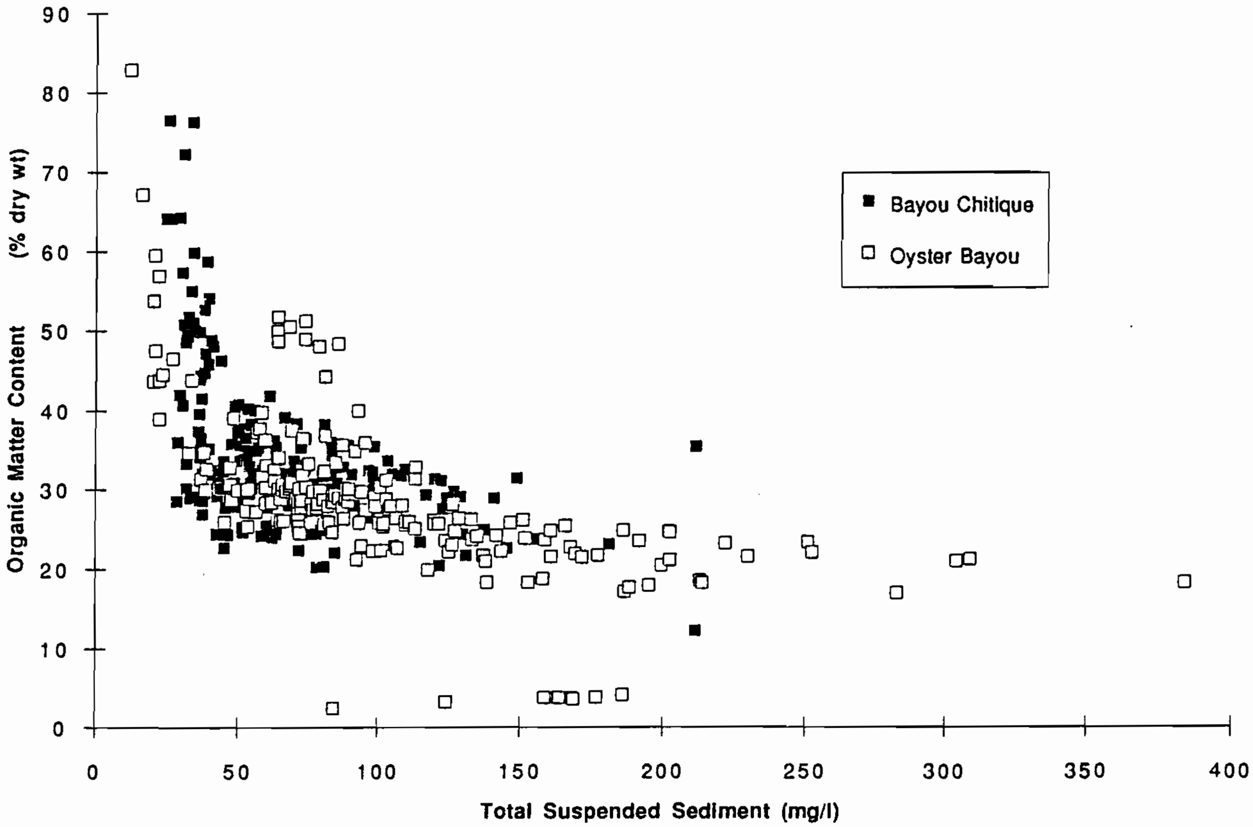


Figure 5.10 Organic matter content of suspended sediment in salt marsh ponds as a function of total suspended sediment (TSS) concentration.

TABLE 5.3 SOIL PROPERTIES AT TWO SALT MARSH/POND SITES

	1991-'93 Surface Elev. Change (Sign=*)	Sat. Wet Unit Wt	'Drained' Unit Wt	Dry Unit Wt	Organic Content	Organic Content	Mineral Content	Water Content	Cohesive Strength (Fall Cone)
Bayou Chitique	cm	kN/m^3	kN/m^3	kN/m^3	%dry wt.	%wet wt.	%wet wt.	%wet wt.	kN/m^2
Marsh (SET: 11/8/91-12/12/93)	-0.29	10.48	2.93	1.71	27.84	4.54	11.78	83.68	0.98 H_2O=24%Sat
Pond Edge (SET: 11/8/91-12/12/93)	-2.72 (*)	10.82	2.43	2.38	23.84	5.25	16.78	77.97	0.98 H_2O=17%Sat
Pond Center (SET: 11/8/91-7/27/93)	-0.90 (*)	10.45	2.81	1.58	26.34	3.99	11.16	84.85	0.49 H_2O=22%Sat
Mean	---	10.58	2.72	1.89	26.01	4.60	13.24	82.17	0.82
Std. Dev.	---	0.21	0.26	0.43	2.02	0.63	3.08	3.68	0.28
Oyster Bayou									
Marsh (SET: 10/18/91-11/29/93)	+0.99 (*)	11.31	2.11	3.24	19.29	5.53	23.14	71.33	103.01 H_2O=14%Sat
Pond Edge (SET: 10/18/91-11/29/93)	-2.76 (*)	12.75	1.94	5.32	8.27	3.45	38.25	58.31	9.81 H_2O=11%Sat
Pond Center	---	11.62	3.64	3.44	11.55	3.42	26.19	70.39	29.43 H_2O=22%Sat
Mean	---	11.89	2.56	4.00	13.04	4.13	29.19	66.68	47.42
Std. Dev.	---	0.76	0.94	1.14	5.66	1.21	7.99	7.26	49.13

Saturated soil unit weights are higher at the OB site than at BC. The organic matter contribution to the wet weight was similar at both sites but samples from OB cores had more than twice the mineral matter content as those from BC cores. 'Dry bulk densities' at OB were also twice those at BC, averaging 4.0 (0.4 g-cm^{-3}) and 1.9 kN-m^{-3} (0.19 g-cm^{-3}), respectively. Fall cone penetration tests provided the most repeatable means of estimating cohesive shear strength as the soils were nearly liquid, particularly at BC. The shear strength of the vegetated marsh at the OB site (103 kN-m^{-2}) is two orders of magnitude higher than that at BC (1 kN-m^{-2}) and is one order of magnitude higher in cores from the pond edge and bottom.

The process of pond enlargement through edge failure and slumping is favored at the BC site over the OB site. Fundamental differences were observed in the strength of the marsh soil surrounding the ponds at the two experimental sites that are more important to explaining the pond expansion phenomenon than any change in the shear forces exerted by waves and currents. Marsh and pond soils at the OB site had cohesive strengths that were greater than at BC by one to two orders of magnitude. These observations led us to think that failure of the marsh scarp due to loss of cohesive strength might play a more important role in pond enlargement than any change in locally generated wave energy.

Slope stability in cohesive sediments is commonly modeled as a function of the cohesive shear strength, soil bulk weight and the slope angle (Sowers, 1979). The formula for the maximum vertical height of a scarp ('H_c') is given by

$$H_c = \frac{C}{mW}$$

where 'C' is the cohesive strength, 'W' is the unit weight (wet) and 'm' is the dimensionless stability number. The stability number depends upon the slope angle and the geometry of the failure surface, and ranges from 0.08 for gentle slopes up to 0.33 for vertical faces. The scarp that defines the pond edge is quite shear with a slope angle of about 70 degrees, indicating an 'm' of about 0.25. Using this value and the mean saturated unit weight and strength estimates from Table 5.3, the maximum supportable scarp height at the BC site would be about 0.3 m. In contrast, the marsh soils at the OB site had a cohesive shear strength more than 50 times greater, and could theoretically stably support a scarp nearly 16 m high. Scarp heights at both sites are about 0.3 m, so the BC marsh edge is essentially at its maximum height and can be expected to fail, while that at OB should be quite stable. The preferential deepening of the pond margin that was noted in SET data from both ponds would enhance any instability. Edge failure would be most likely following rapid drainage of the ponds, when the pond edge is exposed and the full weight of the saturated soil must be resisted by the cohesive strength.

Marsh Sediment Flux

The TSS data from the ponds indicates that as water depth increases to the point where it could begin to supply water (and sediment) to the marsh surface, settling is favored as the bottom becomes increasingly isolated from wave action and turbulence is reduced. It could be argued that these results are not representative of conditions that would occur during a storm because wave data were not acquired at such times, but SET measurements obtained after the passage of Hurricane Andrew show no evidence of scour.

TSS did not differ significantly between the pond and marsh samples taken 20 m apart at each site, and were positively correlated. While the mean TSS at the OB site was nearly twice that at BC, the difference was not significant. Relatively few marsh TSS samples were acquired at the OB marsh station as the marsh flooded so infrequently.

Complete flux records were obtained from four sampling trips, three at BC and one at OB. Because of the high elevation of the marsh and resultant infrequent flooding, most flume measurements at OB did not result in complete inundation of the marsh within the flume. The results of the three flux studies at BC generally show a net uptake of suspended sediments on the flood tide and a net export on the ebb tide, with a very small net gain or loss of sediments to the marsh surface (Table 5.4). The three records at BC were during non-frontal periods with a water level range of about 10, 30 and 40 cm. The lack of net input to the marsh surface during normal tides is consistent with short term deposition patterns reported below where most sedimentation occurred during storm events.

TABLE 5.4 NET UPTAKE AND EXPORT OF TOTAL SUSPENDED SEDIMENTS (TSS) MINERAL (MIN) AND ORGANIC MATTER DURING FOUR FLUME STUDIES.

				flood			Ebb	
Site	start date	end date	TSS (g)	Min (g)	OM (g)	TSS (g)	Min (g)	OM (g)
B. Chit.	3/22/92	3/24/92	513.1	392	121.1	-609.5	-440.5	-169
B. Chit.	3/20/93	3/21/93	-6.5	-4	-2.6	1.4	0.8	0.6
B. Chit.	5/25/93	5/27/93	48.1	74.9	-26.8	-155.3	-147.5	-7.8
Oy. B.	11/24/93	11/25/93	15.1	1.1	14	-165.6	-125	-40.6

The one flux study at OB showed a strong export of suspended sediments on the ebb tide. This is a result of high levels of suspended sediments at the pond end of the flume as the water level approached low water. The use of the flume assumes that pond water fills the flume from the water's edge to the inner marsh on the flood tide and drains from the marsh to the pond on the ebb tide. Therefore, concentrations of water samples taken at the pond end of the flume should represent water flowing out of the flume. The wave studies in the pond showed that waves are most likely to suspend bottom sediments on a falling tide with strong winds. Thus, the high suspended sediment concentrations may be more a reflection of such wave activity rather than representative of the characteristics of water flowing out of the flume.

In addition, the results of another phase of the USGS study (Wang 1994) indicate that over marsh flow is most often dominated by flow from the bayou. Wang (1994) mapped flow patterns at the BC and OB sites for different water level conditions around the BC and OB ponds. Similar general patterns were found at both sites, indicating two conditions of over marsh flow. The first takes place when water elevation in the bayou is insufficient to overtop the natural levee. Bayou water circulates into the pond through the connecting channel. As the pond fills, it supplies water to a narrow pond edge marsh zone. That zone extends approximately 40 m inland from the pond margin at BC and about 10 m into the marsh at OB.

The second condition occurs when water elevation in the bayou rises above the natural levee. Then flow is unidirectional from the marsh into the pond until bayou level drops below the natural levee. The first condition occurs on normal tidal cycles and is far more frequent than direct overland flow to the pond, which may occur for only a brief period as the tidal maximum is reached. At OB, over marsh flow from the bayou takes place only during spring tides.

The geomorphologic evidence suggests that isolated marsh ponds should function more effectively as a sink for sediments than a source. Primarily because of the limited fetch, the bottoms of even the most shallow marsh ponds are virtually unaffected by waves except briefly during weather events that produce the combination of extremely low water levels and high wind speeds. Such events occur frequently each winter and spring in Louisiana's north-south trending estuaries during the stiff northerly winds that follow passage of cold fronts. But the high suspended sediment concentrations that waves may induce briefly during pond drainage will serve to mobilize accumulated bottom sediments and feed them into channels rather than onto the marsh surface. Conversely, the quiescent, sheltered pond environment favors the rapid settling of introduced sediments previously maintained in suspension by the turbulence of channeled flow or high-velocity sheet flow across the marsh surface.

Marsh Surface Dynamics

Short Term Sedimentation Patterns

Influence of Forcing Events on Sediment Deposition. General variations in the amount of sediment deposition between February 1992 and August 1993 can be observed in Figure 5.11 which compares the average rate of sediment deposition for each interval for each location. Error bars represent standard errors for each location based on sampling sites on all transects. All locations show increased rates of sediment deposition during and for a period of several months after passage of Hurricane Andrew on 8/26/92. This is described in more detail in the section on The Impact of Hurricane Andrew below. During February - August 1992 there is considerable variation from one biweekly interval to the next at all locations but rates are generally low. During winter 1993, rates of sediment deposition are again variable on a biweekly basis until April 1993 when all locations show an increase. In some cases (e.g., BC) this increase is to higher rates of sediment deposition than those documented after Hurricane Andrew. Sediment deposition rates at all sites decrease in late July and August 1993.

Marsh surface sediment deposition is controlled by two factors: (1) of the opportunity for sediment deposition(i.e.,flooding of the marsh surface), and (2) the availability of sediment (i.e., the amount of suspended sediment in marsh flood waters). Specific examination of the relative importance of these factors was not possible as the study did not include detailed measurements of suspended sediment concentration of water-level variations at each location. However, data from the National Ocean Service tide gauge at Cocodrie was used as a an indicator of water levels within the vicinity of the study locations. The mean water level at Cocodrie for each of the sampling intervals was calculated. Regression analysis was used to determine any relationship between mean water level and the rate of sediment deposition in each biweekly interval (Figure 5.12). The results showed a significant ($p=0.05$) positive relationship between water level at Cocodrie and the rate of sediment deposition at each study location. Although not providing specific information about processes at each location, this analysis indicates that sediment deposition is greater during periods of higher water level. Variations in mean water level at Cocodrie explain 38% of the variation in sediment deposition at BC, 15% at BB, 35% at OB and 34% at CB. These lowlevels of explanation reflect that the water level measurements were not taken at the particular study locations, and that other factors such as sediment supply must also be considered.

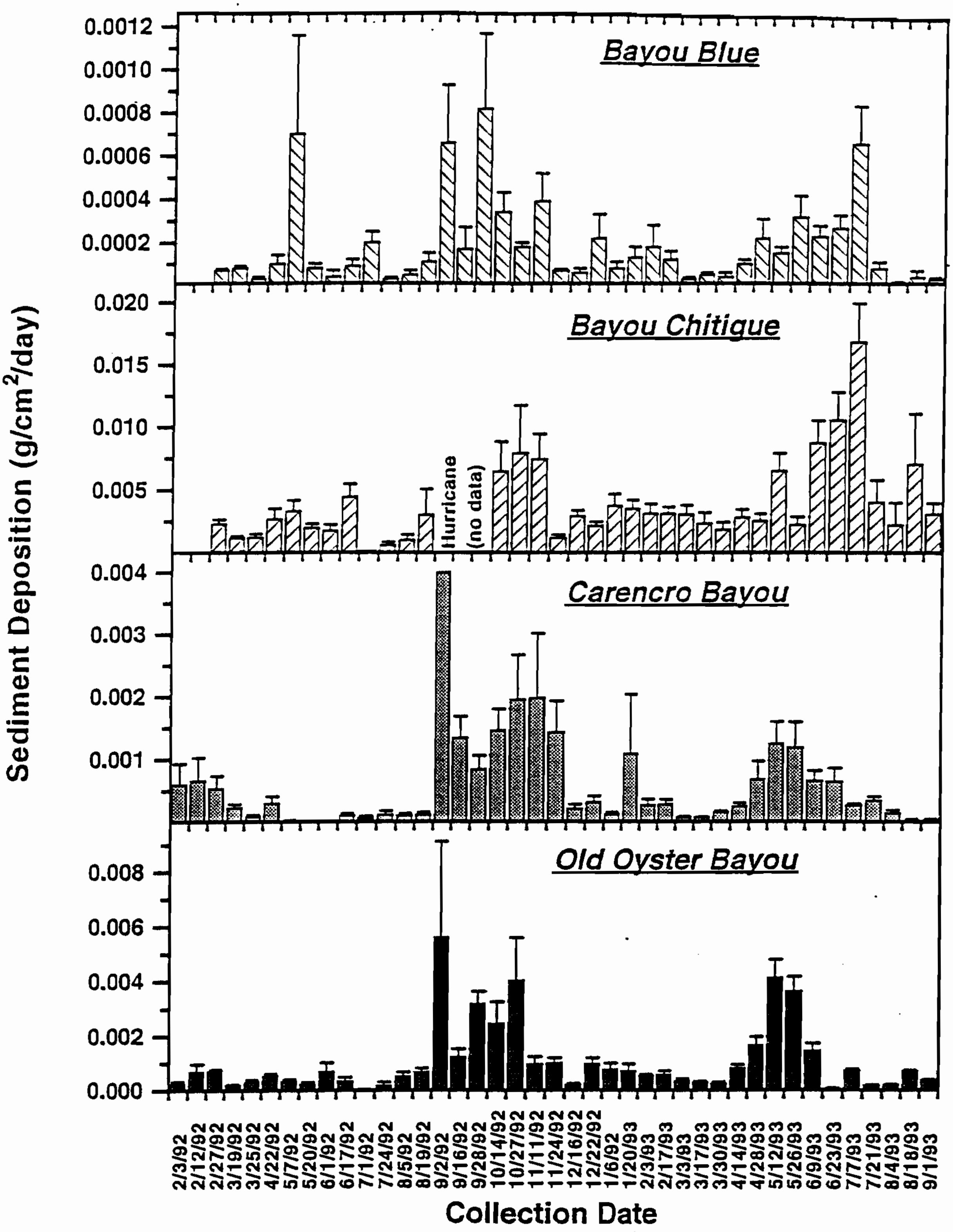


Figure 5.11 Short-term sedimentation pattern at the four pond sites.

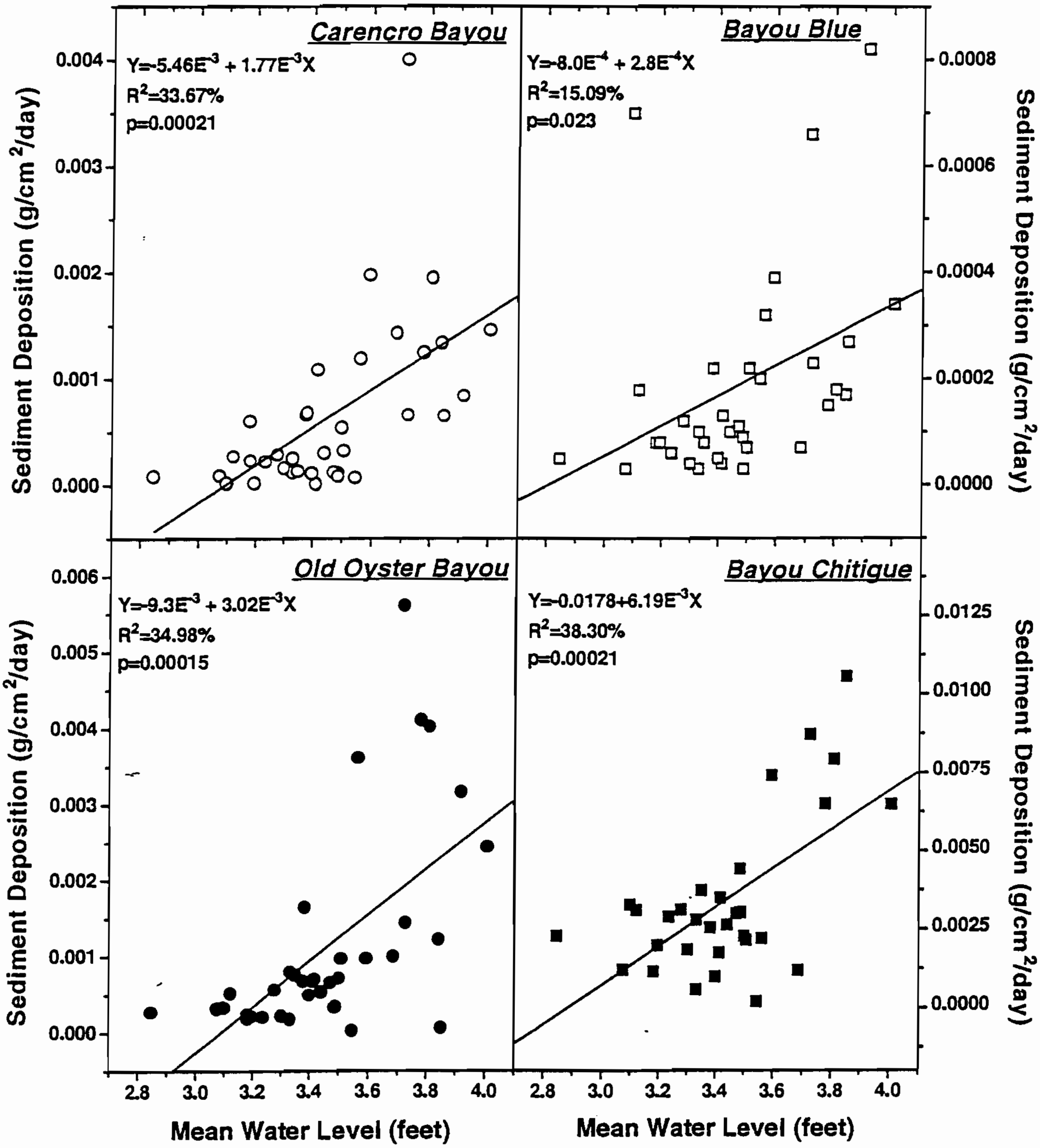


Figure 5.12 Relationship between mean water level and sediment deposition at the four pond sites.

During the period of sampling, several different types of forcing events impacted either water levels or suspended sediment concentrations in the vicinity of the study locations. The impact of Hurricane Andrew is discussed below. OB and CB sites are close to the influence of the Atchafalaya River and the increase in sediment deposition in spring 1993 may be associated with an increase in suspended sediment (and possibly water level) associated with the river's spring flood. The pattern of increase from 4/14/93 to 5/21/93 is similar at these two sites. However, the levels of sediment deposition during spring 1992 are very low and there does not appear to be a similar pattern. Inspection of discharge data from the Mississippi River (30% of the Mississippi River discharge flows through the Atchafalaya River) for 1992 and 1993 indicates very little increase during April-June 1992 compared to 1993. Consequently the variation in sediment deposition between spring 1992 and spring 1993 at OB and CB could be attributed to interannual variations in discharge in the Atchafalaya River.

The increase in sediment deposition at BC and BB which begins in April 1993 continues through early July, for approximately one month longer that at CB and OB. June 1993 is a period of high water levels in coastal Louisiana (as indicated by the Cocodrie NOS gauge and tide gauges deployed in the Barataria Basin Marshes) with a particular increase between June 18 and 22. This is associated with Gulf Tropical Disturbance weather patterns influencing much of coastal Louisiana(Louisiana Monthly Climate Review, June 1993). High monthly rainfall totals are recorded at stations in Thibodaux and New Orleans, and wind records from New Orleans indicate persistent winds from the SE, S and SW quadrants. Rainfall records from Houma and Cocodrie indicate significant rain between 18 and 28 June. The coincidence of high water levels in coastal marshes and heavy local rainfall appear to have provided conditions necessary for enhanced sediment deposition in the coastal marshes. Local runoff can increase suspended sediment concentrations especially at BB which is close to the Gulf Intracoastal Waterway and Bayou Lafourche, while winds from the south can effect sediment mobilization from coastal bays. High water levels in the marsh provide adequate opportunity for sediment to be deposited on the marsh surface. These events do not seem to have influenced sediment deposition at CB and OB. The rainfall records for Morgan City do not show any increase in sediment deposition during June is apparent inferring that deposition may have been limited by the supply of suspended sediment after river discharge levels had declined from their spring peak.

The Impact of Hurricane Andrew. The biweekly measurements show a significant increase of 1-3 orders or magnitude in sediment deposition associated with the passage of Hurricane Andrew. The influence of the storm appears to be sustained beyond the two-week sampling interval in which the storm occurred (Figure 5.11). Rates of sediment deposition at the study locations remain elevated for 4-6 biweekly samples following that which included the storm (10-14 weeks in all) and then sediment deposition falls to levels not significantly different from before storm passage. The sustained period of high sediment deposition rates is attributed to the greater availability of unconsolidated sediments within marsh channels and ponds. These sediments are then redistributed through the marsh system by regular tidal flooding for some 2period after the storm. The abrupt decrease in sediment deposition shown in BC (Figure 5.11) also occurs at the other sites. The first sampling interval with lower sediment deposition (11/10-11/25) at BC includes the first prolonged low water stand of the season associated with the passage of a cold front. Studies of suspended sediment transport close BC (Murray et al., 1993) suggest that strong flows out of the marsh following cold fronts can export large amounts of sediment from the marsh system. Also, extended periods of low water and exposed marsh substrates which typically occur after the passage of major cold fronts (Reed, 1989) would allow the storm deposits to become consolidated. Hence the onset of winter cold fronts may account for the sudden decrease in the availability of sediment introduced by Hurricane Andrew.

At Carencro Bayou and Old Oyster Bayou, Two sites adjacent to Fourleague Bay in the west of the study area and close to the track of the storm, the same pattern of sustained high sediment deposition for a number of biweekly samples following that period which included the storm. However, sediment deposition rates then fall to values significantly lower than the storm interval but significantly higher than the 12 weeks before the storm. The same changes associated with the first major cold front appear to occur but to a lesser degree. The continued availability of sediments to these marshes may be a consequence of their location closer to the storm track and greater initial amounts of readily resuspended sediment. Alternatively, discharge in the Mississippi River began its seasonal increase during November 1992 and this likely increased suspended sediment discharge from the river above its late summer low.

Patterns of Sediment Deposition Adjacent to Marsh Ponds. Differences in sediment deposition between transects were compared for each sampling interval using analysis of variance, ANOVA. This analysis was conducted for all study locations. Significant ($p=0.05$) differences were found for only one (of 44) sampling interval at BB, one (of 41) interval at CB, five (of 44) intervals at BC, and eight (of 41) intervals at OB. No pattern was discerned of one transect consistently showing higher (or lower) sediment deposition compared to other transects at that study location.

At each study location, mean rates of sediment deposition were compared to distance to the pond margin using regression analysis. In no case was a significant ($p=0.05$) relationship found between distance to the pond and the rate of sediment deposition. Thus, distance from pond margin has no influence of the amount of sediment deposited on the marsh surface.

The regression analysis was repeated using the relative elevation of the sampling sites adjacent to each pond as the independent variable. At both CB and OB locations, there was a significant ($p=0.05$) positive relationship between elevation and sediment deposition. Although the relationships were significant, elevation explained only 53% and 40%, respectively, of the variation in sediment deposition at CB and OB. No significant relationships were found at BB and BC. The relative elevation between sampling sites is approximately 6cm at CC and 11cm at OB. This analysis indicates that greater sediment deposition is occurring on the highest parts of the marsh, those which are flooded the least. This is contrary to the pattern which would be expected if depth and duration of flooding (or the opportunity for sediment deposition) were the most important control. Rather, events which contribute sediment to the marsh surface are those which flood even the highest parts of the marsh and other factors, such as vegetation density, may contribute to variations in sediment deposition. This pattern is consistent with previous studies (Baumann et al., 1984; Reed, 1989) which have suggested the importance of storms in controlling sediment deposition in Louisiana coastal marshes.

Because of the data gap after Hurricane Andrew at BC, statistical comparison of data between study location focused on two periods: (1) the post-hurricane period from mid-October 1992 through the end of August 1993, and (2) a period in winter 1993 between January 5 and March 29.

Results of ANOVA, analysis revealed that mean sediment deposition during these periods (calculated from the mean sediment deposition at all sampling sites for each sampling intervals) was significantly greater at BC than at any other location. No differences amongst the other three locations were revealed by ANOVA. Comparisons by T-test of locations within each sub-basin showed that sediment deposition was significantly greater at BC than at BB, but that there was no significant difference between OB and CB. Correlation analysis using Pearson's product-moment correlation coefficients was applied to examine correlation's between the temporal changes in sediment deposition at the locations. For the post-hurricane period BB and BC showed significant correlation in variations in sediment deposition between BC and OB for the post-hurricane period, but the correlation was significant for winter 1993 ($r=0.93$).

These analyses indicate higher rates of sediment deposition at BC but a temporal pattern of variation which is similar to that at BB. The influence of Hurricane Andrew was evident for some time at both locations (see discussion above) and the pattern of increasing and then 8decreasing sediment deposition in late spring early summer 1993 is also common across the sub-basin. This indicates the importance of high water levels across the coastal zone and the impact of local rainfall can have if sediments are mobilized co-incident with high water levels. Similar processes appear to be operating at both CB and OB where the influence of both Hurricane Andrew and the spring rise in the Atchafalaya River are apparent across the sub-basin. This analysis indicates that the hypothesis that proximity to a fluvial sediment source does influence marsh surface sediment deposition should be accepted.

Vertical Accretion and Surface Elevation Change

There were high levels of accretion at all sites (Table 5.5). The highest overall accretion was at CC. This high accretion was due to the proximity to the Atchafalaya River mouth and the high deposition rate during the passage of Hurricane Andrew.

The surface elevation changes at the different sites were consistent with findings from other aspects of the study. One of the most interesting and dramatic changes occurred at the BC site (Figure 5.13). As described earlier in the pond morphology section, there was significant shoreline retreat at the BC pond. The elevation of the marsh and pond bottom were relatively constant until the fall of 1991. At the marsh edge site, there was a loss of nearly 8 cm in elevation over the winter of 1991-92. This coincided with the marsh loss and shoreline retreat that occurred at the same location. In September 1991, the SET pipe for the marsh edge site was located in the marsh about one meter inland from the vegetation edge. By March 1992, due to the retreat of the shoreline, the SET pipe was about two m into the pond. In contrast to the edge site, the elevation of the pond bottom and the interior marsh site changed little from the beginning to the end of the study.

TABLE 5.5 RECENT VERTICAL ACCRETION MEASUREMENTS. VALUES AREMEAN (± SD) IN CM. THE FINAL MEASUREMENTS WERE TAKEN AFTER HURRICANE ANDREW.

SAMPLING INTERVALS

LOCATION	n	Accretion 1st Sampling	n	Accretion 2nd Sampling	n	Accretion 3rd Sampling	n	Accretion 4th Sampling	Accretion Rate (cm/yr)
Bayou Chitique	21	0.48 ± 0.34	12	1.33 ± 0.72	14	3.27 ± 1.98	1	8.68	3.44 ±1.54
Old Oyster Bayou	21	1.43 ± 0.93	23	1.47 ± 1.04	10	2.75 ± 1.10	-	-	2.06 ± 0.83
Carencro Bayou	13	0.56 ± 0.22	11	1.20 ± 0.51	9	6.19 ± 2.37	-	-	5.31 ± 2.03
Bayou Blue	6	1.15 ± 2.4	11	2.25 ± 0.88	14	3.73 ± 3.06	12	3.43 ± 1.47	3.81 ± 0.98

Sampling periods were as follows:

Bayou Chitigue	=	Nov-90	Mar-91	Jul-91	Mar-92	Oct-92	
Old Oyster Bayou	=	Apr-91	Oct-91	Mar-92	Oct-92		
Carencro Bayou	=	Jun-91	Nov-91	May-92	Oct-92		
Bayou Blue	=	Dec-90	May-91	Jul-91	Dec-91	Mar-92	Oct-92

From these data and observations, we offer the following hypothesis on marsh loss at BC. The marsh at BC is flooded for long periods of time leading to waterlogging stress on the plants. Continued subsidence increases this stress until plant death occurs. Following plant death, the formerly living root mass is rapidly decomposed by anaerobic sulfate reducing bacteria. The H_2S produced during sulfate reduction supports the *Beggiatoa* mats we observed. The root mass gives both volume and structure to the soil, and with its loss, there is a rapid loss of soil strength and volume. This leads to the loss of elevation we observed. Export of liquefied soil material can occur through the channel. After the loss of elevation, the process of marsh loss is essentially irreversible at the site without massive new sediment introduction because the elevation of the substrate is too low to support marsh colonization. The resulting soils have almost no shear resistance and are easily eroded.

In comparison to BC, the other sites remained relatively stable or gained elevation during the study (Figure 5.13). At OB, both the interior and edge marsh sites changed less than ± 2 cm. At CC, the pond bottom gained about 5 cm and the marsh edge gained about 3 cm during the period which included the passage of Hurricane Andrew. At BB, the interior marsh site gained about 6 cm over the course of the study while the marsh edge changed very little. The interior marsh site is closer to Bayou Blue. The results of our studies indicate that bayous rather than ponds are the main source of sediments to the marsh surface, and that ponds function primarily as sediment sinks and pathways for export.

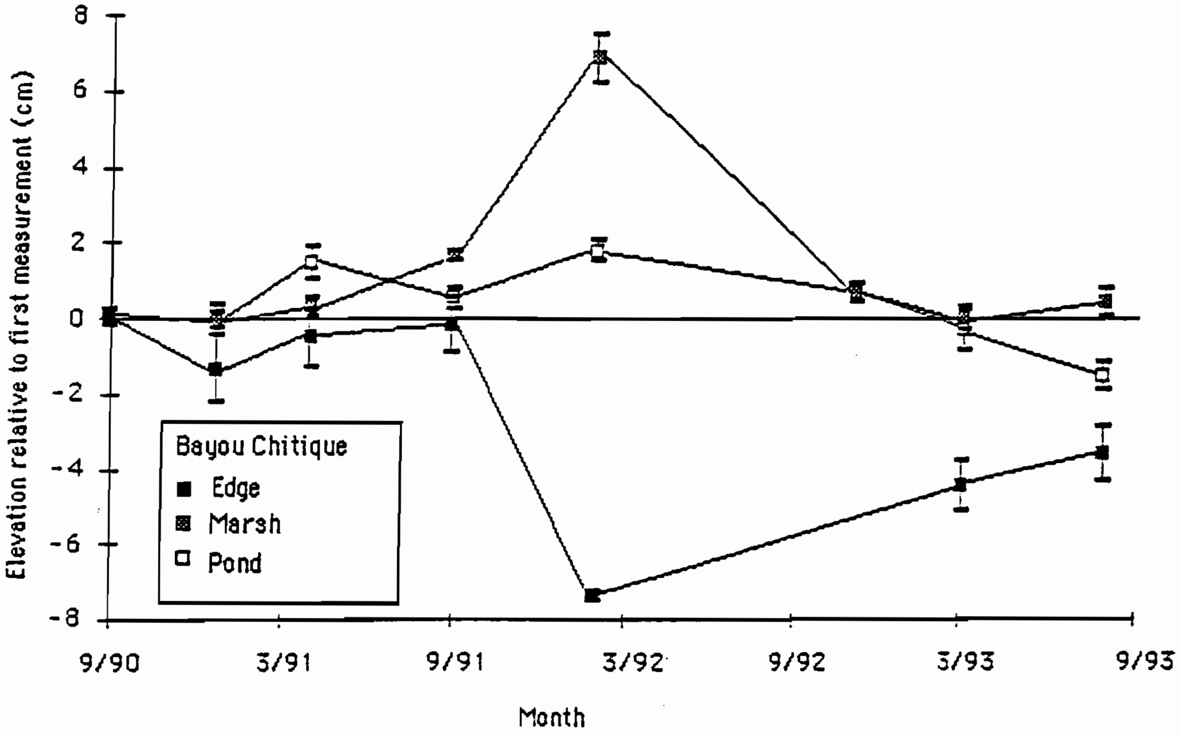


Figure 5.13a Changes in surface elevation at Bayou Chitique measured with the sedimentation erosion table.

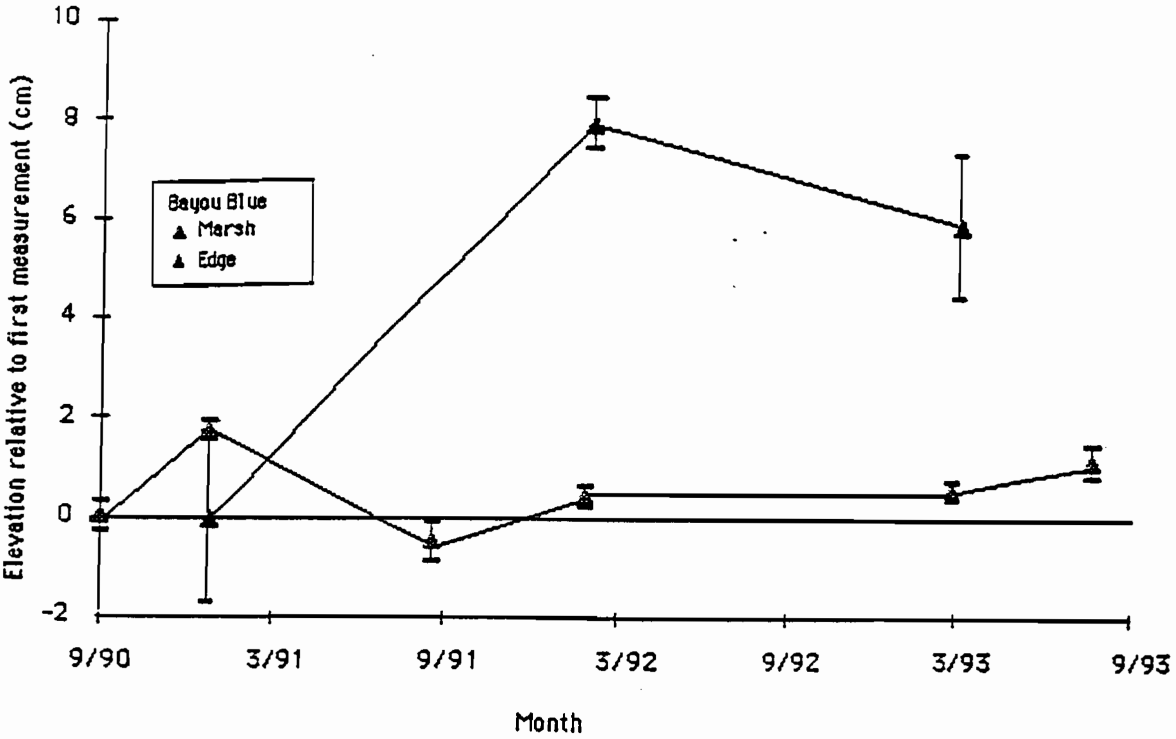


Figure 5.13b Changes in surface elevation at Bayou Blue measured with the sedimentation erosion table.

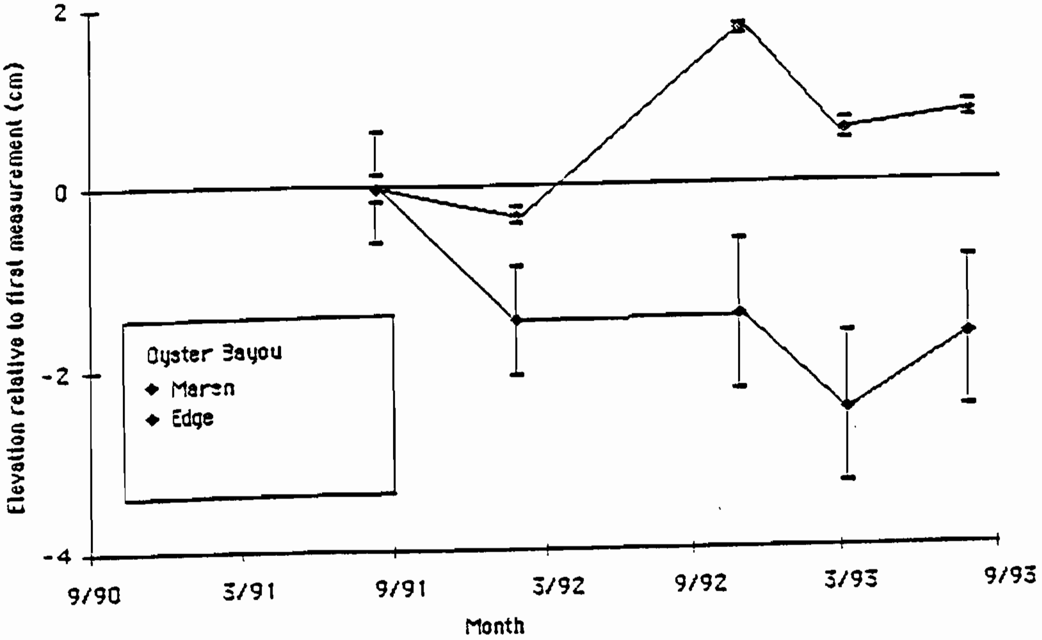


Figure 5.13c Changes in surface elevation at Oyster Bayou measured with the sedimentation erosion table.

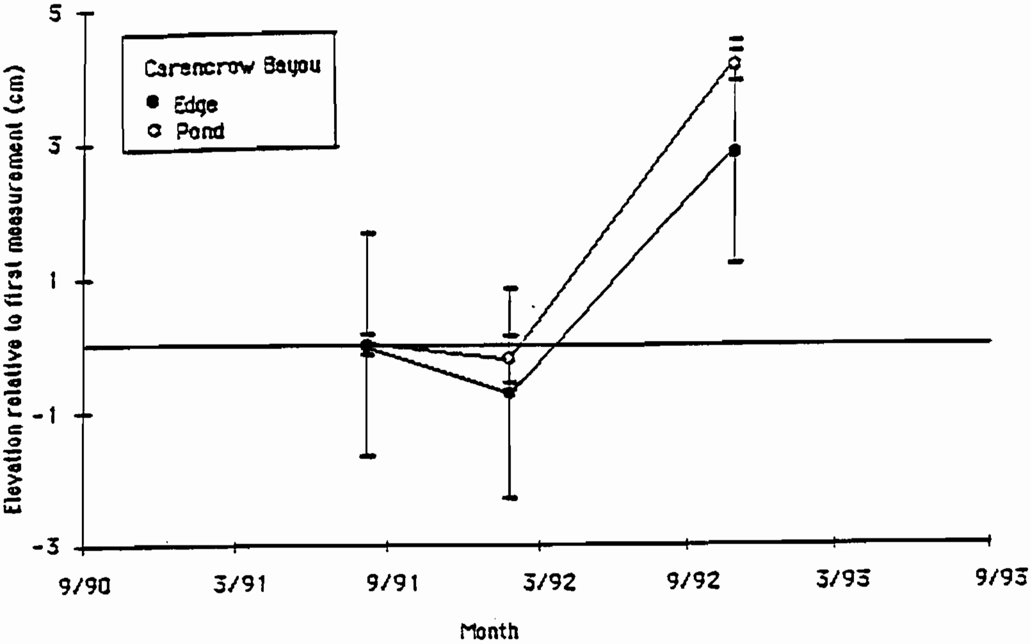


Figure 5.13d Changes in surface elevation at Oyster Bayou measured with the sedimentation erosion table.

Modeling

The spatial simulation model used hydrodynamic process data to predict erosion transport and deposition of sediment in the pond/marsh system. Input data included regionally available meteorological data, spatial geometry of the marsh pond system and baseline plant and sediment data. Local water level, wave and current parameters were calculated and related to erosion and deposition of sediments through the disparity between applied stresses and resistance. Data sets collected during this study were used to calibrate the model. The output can be used to predict sediment erosion and deposition patterns within the pond/marsh system and water and sediment fluxes. Structured in this way the model is designed to be used to make management decisions on manipulating marsh hydrology.

SYNTHESIS AND CONCLUSIONS

The results of the pond study provided insights into the sequence of events leading to wetland loss and gain and the role of ponds in this process. This information is summarized in Figure 5.14 and Table 5.6. The discussion here is limited to marshes growing on firm substrate and cannot be extrapolated to floating marshes.

Wetland loss and gain can be considered within the context of the life cycle of a typical pond (Figure 5.14). Pond formation begins with vegetation death. This can be due to a number of factors such as submergence, impoundment, grazing, burning, burial by wrack or salinity stress that are not generally associated with erosion through normal or tangential shear. The marsh at Bayou Chitique is lower in elevation and was flooded for longer periods of time and waterlogging stress caused the marsh to die. Vegetation death leads to the formation of bare soil areas and as the root mat decomposes, rapid loss of elevation and shear strength. As shear strength drops toward zero, the soil becomes fluid and unable to resist any shear no matter how small. At BC, we measured an elevation drop of about 8 cm accompanied by a loss of substrate material following the death of the marsh grass.

Our measurements of waves in the marsh ponds suggest that the pond depth initially does not appear be a function of wave climate, but is more likely defined by the removal of the living root mat which extends 30-40 cm below the marsh surface. After this stage a channel develops and the pond may continue to expand, stabilize, or fill in.

If the stress which caused vegetation death does not affect the health of vegetation surrounding the pond, then the pond can stabilize because waves in ponds of less than 0.5 ha are too small to initiate physical erosion of healthy marsh. Because the waves developed in these small ponds are deepwater waves that do not affect the bed, material introduced either via the channel or from the marsh has a tendency to settle on the pond bottom which serves as a temporary sink or storage. These waves are effective during extremely low tides in resuspending unconsolidated pond bottom sediments which may then be exported via the channel. Because of this the pond develops an equilibrium form. This appears to be the case for ponds at OB and BB.

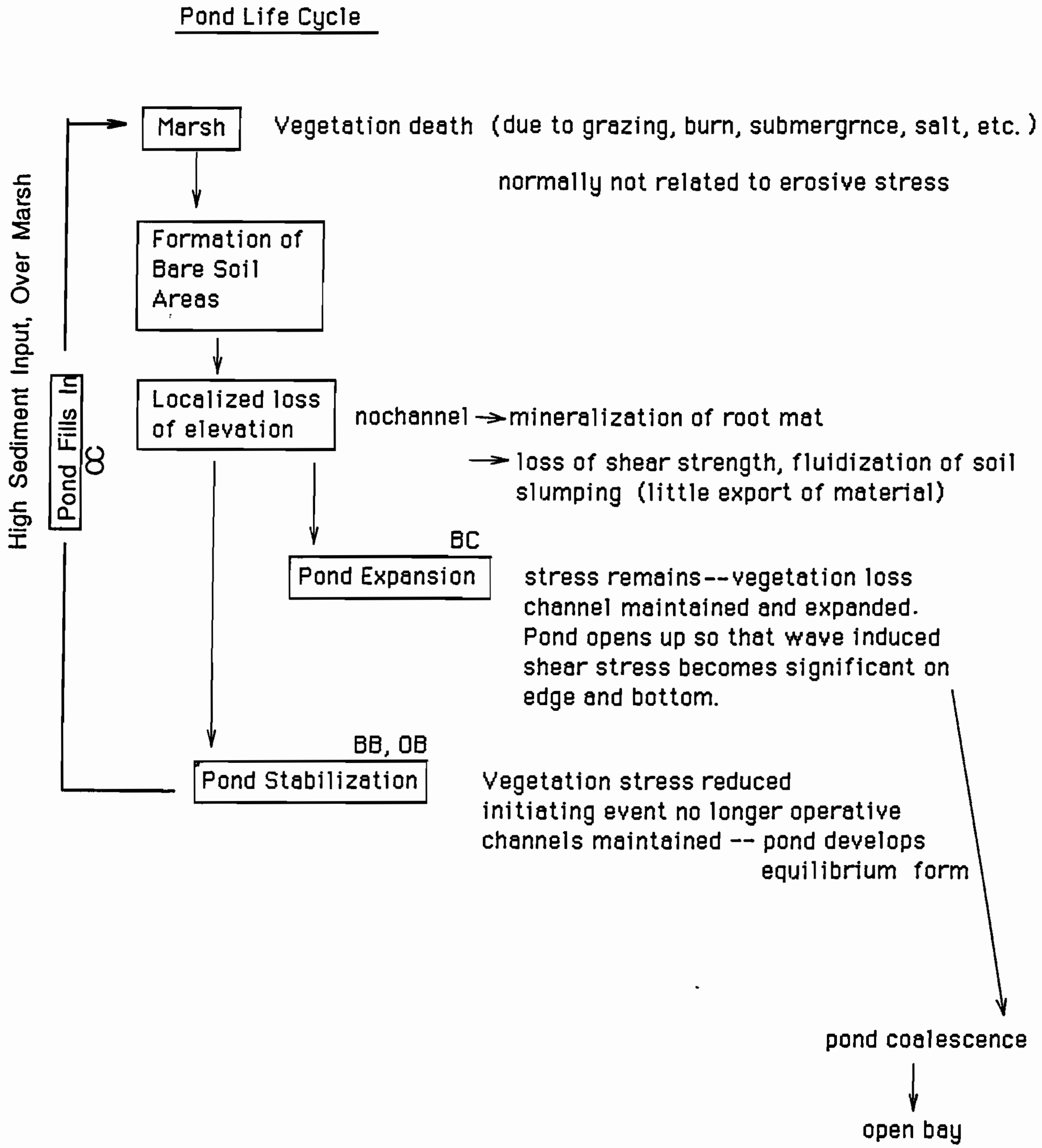


Figure 5.14. Diagram illustrating the different pathways in the life cycle of a pond.

TABLE 5.6 DYNAMICS OF SEDIMENTS IN DIFFERENT PARTS OF THE PONE-MARSH SYSTEM DURING DIFFERENT CLIMATIC EVENTS. P=PONE, M=MARSH.

Event	Pond-Channel	Pond	Pond-Marsh	Marsh
Tidal	Import	Setting	Minimum Exchange	Minimum Sediment Deposition
Fronts				
Set-Up		Settlement	P → M	Sediment Deposition from Bayou
Set-Down	Export	Resuspension	P ← M	
Low Water		Consolidation	Drainage Slumping	Consolidation
River Discharge	Import	Settling	Some Exchange	Increased Sediment Deposition
Tropical Cyclones	Over Marsh Processes Dominate	Accumulation	Overwhelmed By Regional Processes	High Sediment Deposition

If the stress which caused vegetation death affects the health of vegetation surrounding the pond, there is continued loss of vegetation. This can occur at the margin of the pond or over large areas of the marsh. Erosive forces are still not important in this expansion. Both of these conditions occurred at BC, where the eastern shore retreated 2-3 m and the northern shore disappeared and the pond began to merge with an adjacent pond. As the pond enlarges, it reaches a point where waves can impose shear stresses capable of eroding pond bottoms and margins. At this point, the isolated pond may well no longer exist as coalescence into larger waterbodies takes place. Our analysis of pond size distribution indicates the virtual absence of isolated ponds greater than one ha in size (90% of ponds are smaller than this). At this point, the process is irreversible in the absence of massive sediment introduction.

If there is a semi-continuous, high level of sediment input, ponds can fill in and become marsh again. This happened at CC, where several small ponds filled in completely and became vegetated and the main experimental pond became shallower. There was no direct channel connection between the CC pond and the bayou. This may indicate that channel closure is an important factor leading to pond closure where there is high overmarsh sediment input. Channel closure would prevent low water erosion of the pond bed.

The results indicate that different hydrodynamic forcing events affect bayou/pond/marsh interactions in different ways (Table 5.6). During normal tides, suspended material is imported from the channel to the pond where most of it settles. There is minimum exchange between the pond and marsh and little sediment deposition on the marsh surface. Frontal passage results in a greater set-up and import of higher levels of suspended material to both the pond and marsh surface. Short term deposition was consistently higher during frontal passage. The low water levels and high winds during set-down lead to erosion of the pond bottom and export of material. The strong drainage also leads to consolidation of both pond and marsh sediments. River discharge generates higher TSS concentrations and in conjunction with frontal passage can lead to high deposition on the marsh surface. During tropical cyclones, channel flow is less important and over marsh flow dominates. The highest deposition rates at our sites were measured during Hurricane Andrew.

We conclude that the factors that predisposed the BC, and not the OB, pond to expand were unrelated to any difference in the wave or current regime affecting the two systems. Specifically, they are (1) the starting elevation of the surrounding marsh surface, (2) the rate of local marsh surface elevation change (as measured by the SET) relative to ASLR and (3) the inherent strength of the marsh soils. All are related. Because the marsh at BC is lower, it is flooded for longer periods such that infrequent opportunities exist for drainage and consolidation. As waterlogging continues, the plants are increasingly stressed, leading to lowered productivity and finally death. The formerly living root mass decomposes rapidly, reducing surface elevation through loss of soil volume. Perhaps more importantly, however, plant death further reduces soil strength. Marsh scarps that were previously stable become unstable and fail. The relationship between water depth and wave action in the pond ensures that any sediment that enters the pond from the bayou is deposited in the pond rather than the marsh and is later exported via the channel. After the marsh surface collapses, the process of marsh loss is essentially irreversible without massive new sediment introduction. Other specific conclusions arising from this study are as follow:

CONCLUSIONS

1. Rates of marsh surface sediment deposition are positively related to variations in water level.

2. Differences in sediment deposition between study locations within one hydrologic basin are influenced by local sediment-supply factors such as local rainfall runoff and proximity to fluvial sediment source.

3. A strong direct increase in sediment deposition was associated with the passage of Hurricane Andrew. Sediment deposition rates remained high until the onset of the winter storm season when low water levels enhanced sediment consolidation and exported mobile sediments from coastal marshes.

4. There is no relationship between distance from marsh ponds and sediment deposition.

5. There is a significant relationship between marsh surface elevation and sediment deposition at some locations but this does not appear to be directly related to increased tidal flooding of lower elevations.

6. Highest rates of sediment deposition were measured at a study location close to an extensive coastal bay system, not closest to the Atchafalaya River.

7. Within hydrologic sub-basins the processes contributing to marsh surface sediment deposition occur at the same time scale but there are differences in the magnitude of the deposition.

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