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RECENT SEDIMENTATION PATTERNS WITHIN THE CENTRAL ATCHAFALAYA BASIN, LOUISIANA

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Abstract: Sediment deposition and storage are important functions of forested bottomlands, yet documentation and interpretation of sedimentation processes in these systems remain incomplete. Our study was located in the central Atchafalaya Basin, Louisiana, a distributary of the Mississippi River and contains the largest contiguously forested riparian wetland in North America, which suffers from high sedimentation in some areas and hypoxia in others. We established 20 floodplain transects reflecting the distribution of depositional environments within the central Basin and monitored general and local sediment deposition patterns over a three-year period (2000–2003). Deposition rate, sediment texture, bulk density, and loss on ignition (LOI, percent organic material) were determined near or just above artificial markers (clay pads) located at each station per transect. Transect mean sedimentation rates ranged from about 2 to 42 mm/yr, mean percent organic material ranged from about 7% to 28%, mean percent sand ($> 63\ \mu$) ranged from about 5% to 44%, and bulk density varied from about 0.4 to 1.3. The sites were categorized into five statistically different clusters based on sedimentation rate; most of these could be characterized by a suite of parameters that included hydroperiod, source(s) of sediment-laden water, hydraulic connectivity, flow stagnation, and local geomorphic setting along transect (levee versus backswamp), which lead to distinct spatial sedimentation patterns. Sites with low elevation (long hydroperiod), high hydraulic connectivity to multiple sources of sediment-laden water, and hydraulic damming (flow stagnation) featured the highest amounts of sediment trapping; the converse in any of these factors typically diminished sediment trapping. Based on aerial extent of clusters, the study area potentially traps 6,720,000 Mg of sediment annually, of which, 820,000 Mg represent organic materials. Thus, the Atchafalaya Basin plays a substantial role in lowland sediment (and associated contaminant) storage, including the sequestration of carbon. Findings on local sedimentation patterns may aid in management of flow to control sediment deposition and reduce hypoxia.

Key Words: floodplain connectivity, forested wetlands, hydroperiod, sediment trapping

INTRODUCTION

The Atchafalaya River Basin (a distributary of the Mississippi River) contains the largest relatively intact, functioning riparian area in the lower Mississippi Valley and the largest contiguously forested bottomland in North America. The Basin lies entirely within the Coastal Plain physiographic province (Hunt 1967) and covers an area of about 5,670 square kilometers. Alluvial systems within the region typically are flooded annually for prolonged periods. Sediment accretion rates on these floodplains may be among the highest of any physiographic province in the U.S. (Hupp 2000). Over the past several decades the Atchafalaya Basin has experienced rapid and substantial amounts of sediment deposition. Many open water areas in the Basin have now filled (Roberts et al. 1980, Tye and Coleman 1989, McManus 2002); regionally, the Basin provides a sharp contrast to most of the remaining Louisiana coastal area, which is sediment starved and experiences subsidence and coastal erosion. Channel processes and sedimentation dynamics in these low-gradient systems result in the extensive development of broad flood plains (natural levees and backswamps), anastomozing channels, point bars, scroll topography, avulsion, and associated back channels or sloughs and oxbows (Saucier 1994). The Atchafalaya Basin (Figure 1) is a

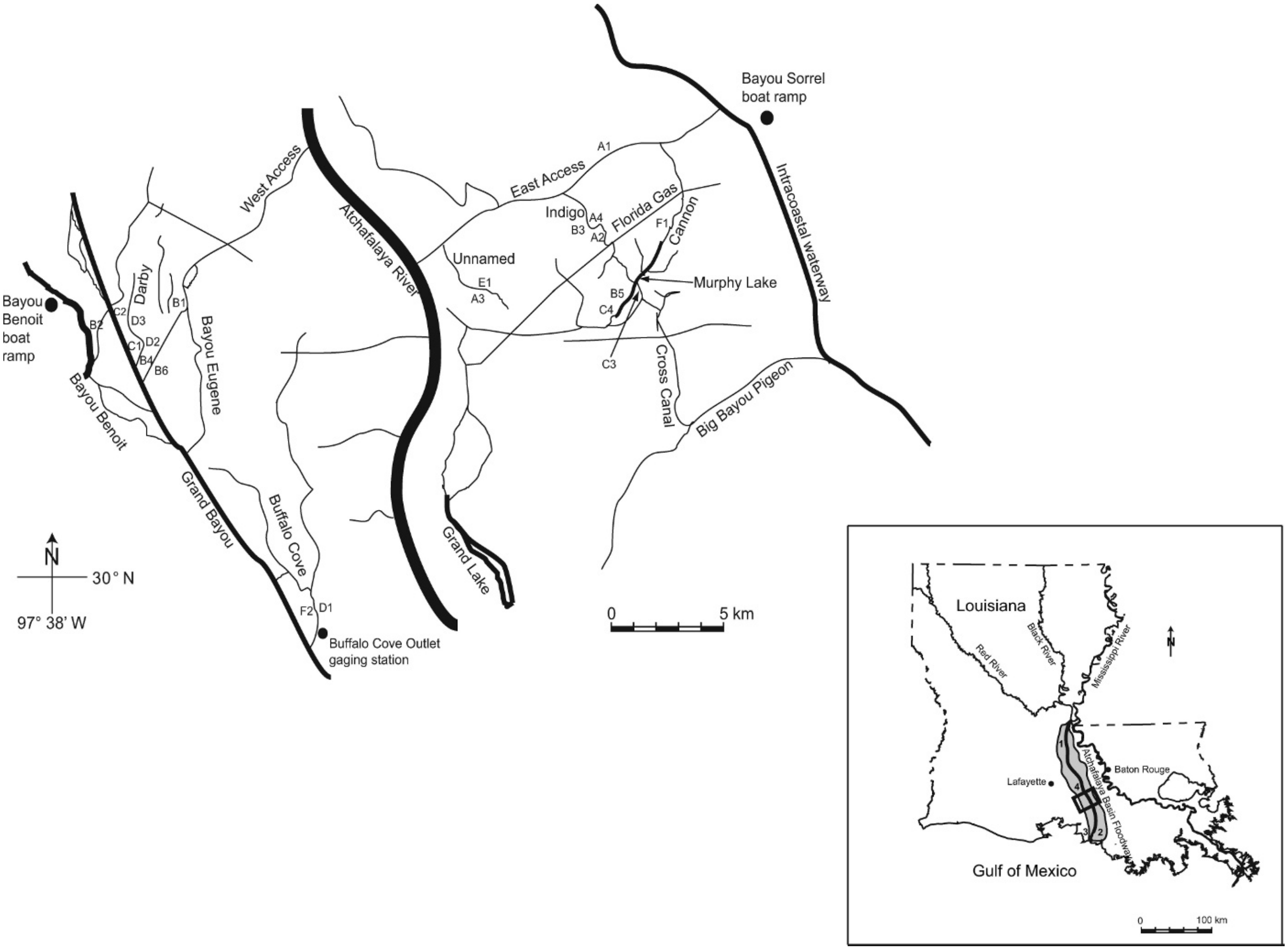

Figure 1. Map and detail of study area; Atchafalaya River divides the study area into east and west sides. Transect (site) locations are shown and correspond to abbreviations provided in Table 1. Flow on the Atchafalaya River is from north to south; the Butte La Rose stage gage is located about 25 river km upstream of the study area. Inset: State of Louisiana, study area is enclosed in box. Gaging stations are numbered: 1) Simmesport, 2) Morgan City, 3) Wax Lake Outlet, and 4) Butte La Rose.

complex of many meandering bayous and lakes that have been altered dramatically by natural processes and human impacts resulting from channel construction for oil and gas exploration and transmission, timber extraction, flood control, and navigation. The pervasive natural geomorphic process affecting the Basin is and has for the past few centuries been that of a prograding delta (Mississippi delta complex, Fisk 1952), which had filled much of the Basin by 1970 (Tye and Coleman 1989). The Grand Lake area, in the south, continues to fill as shown by rapid sedimentation in what was recently open lake.

Vertical accretion, the ''slow'' accumulation of overbank sediment without appreciable later channel migration, is the primary process by which most lowland floodplains develop within the Coastal Plain (Nanson and Croke 1992, Middelkoop and Van der Perk 1998, Walling and He 1998). Discharges that occur about 10% of the time or less frequently may be responsible for 50% to 90% of suspended sediment transport in alluvial river systems (Meade 1982). These floodplains may be inundated multiple times a year, often for extended periods, particularly during the winter and spring. With minimal erosion caused by lateral migration and little remobilization and export of floodplain sediments, particulate storage in the Coastal Plain can be long (decades or longer) (Meade 1982, Walling et al. 1996, Raymond and Bauer 2001). Coastal Plain riverbanks are relatively low and inundation characteristically extends across the entire floodplain, significantly limiting flow competence. Natural levees, typically composed of sand, frequently form adjacent to the channel where relatively coarse suspended load sediments are deposited (Pizzuto 1987, Hupp 2000). Elevations typically vary only a few meters or less within the floodplain, and thus small differences in flood stage or ground-water elevation, can substantially affect inundation frequency and hydroperiod across large areas.

Like many Coastal Plain riparian areas, the Basin is the last place for significant storage of riverine sediments before reaching saltwater (Hupp 2000). Approximately 25% of the Mississippi River (drainage area about 3,200,000 km^2) on an annual basis, and all of the Red River (drainage area about 233,000 km^2) flows through the Basin. The entire suspended- and bed-sediment load of the Red River and as much as 35% of the suspended and a projected 60% of the bed sediment load of the Mississippi River (Mossa and Roberts 1990) are now diverted through the Atchafalaya Basin. As a result, the Basin experiences simultaneous exceptionally high sedimentation rates at sites with high connectivity to the main river and from hypoxia in stagnant areas with little connection to the main river (Hupp et al. 2002). Both of these results may be detrimental to socially and economically important fisheries. There is currently a major effort by the state and federal governments to devise a management plan to maximize freshwater inflows into stagnant areas while simultaneously minimizing sedimentation.

Only a few comprehensive studies of sediment deposition have been made in the area between the two protection levees (Wells and Demas 1977, Arcement 1988) that define the east and west boundaries of the Atchafalaya Basin Floodway System (Figure 1). These studies have examined changes in the overall elevation of the in-channel floodway and the effect on flood stages or floodplain deltaic sedimentation processes (Tye and Colman 1989). The purpose of our paper is to describe and interpret sediment deposition patterns, rates, trends, and the mineral and organic composition of deposited sediment across the central part of the Atchafalaya Basin. Specific purposes include the interpretation of sediment deposition rates as related to elevation or hydroperiod, patterns of flow during the hydroperiod, and degree of connectivity between a sampling point and sediment-laden streamflow. We report also on selected cores taken in a separate study from lakes in the area that were analyzed for deposition rates using ^{137}Cs and ^{210}Pb techniques. Our investigations should provide considerable information that may facilitate management options within the Basin.

Site Description

The Atchafalaya Basin wetland (5,670 km^2) is about 70% forested and the remainder is marshland and open water. Most of the generally north-south trending Basin is bounded by flood-protection levees on the east and west separated by 20 to 30 km. The Basin extends for about 160 km between the Louisiana cities of Baton Rouge and Lafayette (Figure 1). The mouth of the Basin empties into Atchafalaya Bay, part of the Gulf of Mexico, and one of the few aggrading areas on the otherwise eroding Louisiana coastline. The Atchafalaya River flowing through the Basin has an average discharge of about 6,410 m^3/s, among the top five in the U.S. (Demas et al. 2001).

The general study area lies near the center of the Atchafalaya Floodway, between the Bayou Sorrel boat ramp and the Bayou Benoit boat ramp (Figure 1). This area is typical of most of the central part of the Basin with a network of numerous meandering natural bayous, constructed channels, and occasional relatively small lakes. Much of this area, particularly on the west side was open water, prior to about 1917, and now is part of the largely sediment filled Grand Lake (Roberts et al. 1980, Tye and Coleman 1989, McManus 2002). Sedimentation of the Basin here and downstream has been substantial and continues today.

The forested wetlands are generally of three major types: 1) typical bottomland hardwoods (Sharitz and Mitsch 1993) on levees and higher flood plains, 2) cypress-tupelo (*Taxodium distichum* (L.) Richard - *Nyssa aquatica* L.) swamps on low backwater flood plains, and 3) young stands of predominantly black willow (*Salix nigra* Marshall) that have developed on recently aggraded point and longitudinal channel bars (silt and sand). Most of the relatively young forests (70 years or less) have grown since lumbering of old growth cypress and bottomland hardwoods completed by the early 1930s (King et al. 2005). Additionally, the filling of open water areas since the middle of the last century (Tye and Coleman 1989) has created numerous and extensive surfaces for forest establishment.

All flow within the Basin is regulated by structures upstream operated by the U.S. Army Corps of Engineers. Much of the flow in all of the waterways has been altered through various activities (opening cuts, blocking channels) to divert water through the system for various management options (typically for access, pipeline construction, or channel maintenance). Flow in many of the bayous and canals may carry high sediment loads resulting from the ambient alluvial nature of both the Mississippi and

Red rivers and, in some cases, due to substantial resuspension of channel sediment. Discharge and suspended sediment delivered to the basin has been measured at the Atchafalaya River at Simmesport, Louisiana (Figure 1) gaging station since 1963 with an average water discharge of 6,115 cms (218,400 cfs). The gaging stations for the Lower Atchafalaya River at Morgan City (1995 to present) and Wax Lake Outlet at Calumet (1986 to present) record discharge and suspended sediment leaving the basin (Figure 1); average water discharge for these respective stations are 3,510 cms (125,370 cfs) and 2,325 cms (83,030 cfs). Additionally, two other gages (Butte La Rose and Buffalo Cove, Figure 1) operate in or near the study area. The gage at Simmeport records a daily passage of more than 124,000 Mg of sediment on average. Millions of megagrams of sediment are trapped annually (Hupp et al. 2002) within the study area. This sediment trapping function of the Atchafalaya Basin is environmentally important as the sediment while in storage may undergo critical biogeochemical transformations (Noe and Hupp 2005) that may reduce contaminant, nutrient, and carbon inputs into the Gulf of Mexico.

METHODS

Site/Transect Selection and Establishment

We selected 20 sediment monitoring transects (sites) aligned perpendicular to the canal or bayou that began on the channel edge (usually a levee) and continued into the low backswamp area. Each transect typically had four to six sampling points where periodic measurements were made of deposition rate (clay pad), texture, and composition; these sampling points were numbered consecutively starting with the lowest number nearest the channel (Figure 2). Transects ranged from 100–300 m in length; all levee stations along a transect are within 65 m of the adjacent channel. Selection of transects was based partly on known management interests, potential impacts from sedimentation, and property ownership. We also used aerial photography in combination with existing GIS information to select a stratified range of transects (in terms of probable deposition rates) so that our results would be representative of the general area and increase potential exploratory interpretation. The basic sampling strata included relatively high in elevation levee areas, intermediate transition areas, and low elevation backswamp areas; these strata are based on forest cover types, clearly visible in aerial photography that have been verified on the ground to reflect the named surfaces. A GIS map developed from the photography indicates that approximately 22%, 34%, and 24% of the study area is in levee, transitional, and backswamp areas, respectively; the remaining area is largely open water or developed natural gas fields. The portions of the total combined length of transect cover approximately 30% levee, 40% transition, and 30% backswamp, thus providing appropriately divided sampling strata. This breakdown of land types approximates that of the entire Basin; although more area is of the levee type north of our study area, while more backswamp areas are located to the south. We believe this sampling design, while non-random, allowed for a reasonably unbiased estimate of sedimentation rates in the Basin. Each transect was differentially leveled in detail using a laser level. Bank heights were measured near the beginning of each transect from the top of the bank (usually levee) to the low water elevation; all bank height and elevation measurements were corrected for water stage using the stage-only gage at Butte La Rose as a reference for the given date of measurement. Datum for the Butte La Rose gage is sea level (NGVD of 1929). All leveled sites were corrected to the Butte La Rose gage, such that a bank (levee) height of 3 m, for example, is assumed to be 3 m above sea level. This allows for site cross sectional information to be directly related to the gage and its documented stage-percent exceedance relation (hydroperiod). Several site elevations were checked against the Butte La Rose gage at the time of measurement; there is an apparent water-surface drop in elevation between 0.076 and 0.15 m from the gage to any of the study sites. All sites were established between the winter and fall of 2000 and measured for deposition annually (in some cases more frequently); the most recent measurements were taken during the fall of 2003. Thus, all sites were monitored for about three years. Average annual discharge through the Basin as measured at Simmesport was 5,460 cms, 6,580 cms, and 5,940 cms during 2001, 2002, and 2003, respectively. The average annual discharge for the period 1964 to 2003 was 6,280 cms. Thus, our study sites experienced annual flows below, above, and near normal in 2001, 2002, and 2003, respectively.

Sediment Deposition and Sampling

Artificial marker layers (clay pads) were placed at each sampling point, typically spaced along transect by about 50 m. These markers are made by placing powdered white feldspar clay approximately 20 mm in thickness over an area of about 0.5 m^2 on the soil

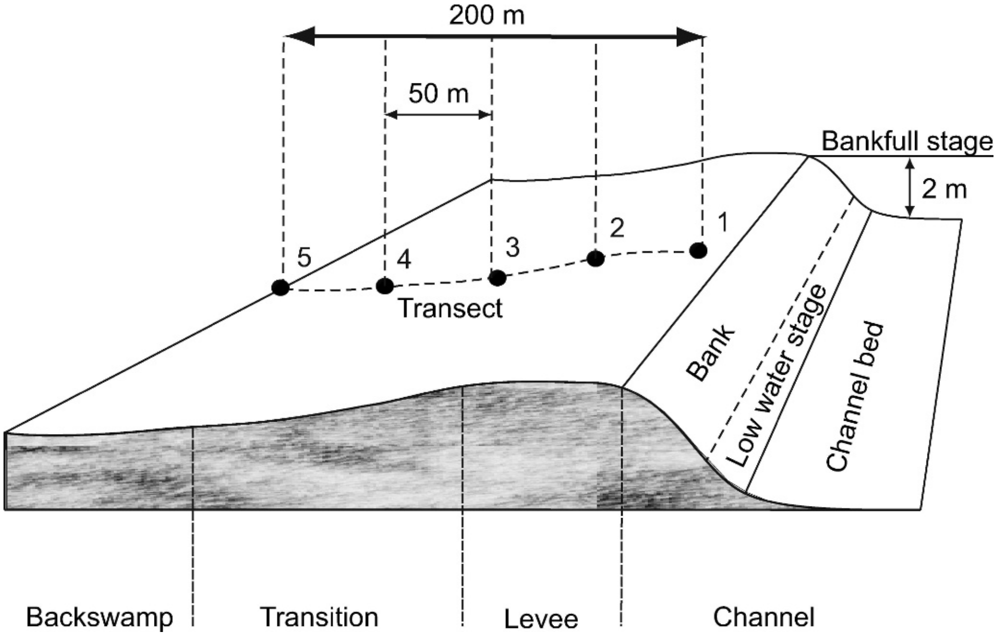

Figure 2. Diagram of typical transect layout at a site showing major fluvial geomorphic features. Bank height and transect dimensions are generalized. Sampling stations are numbered in ascending order from the bank edge on levee into the backswamp.

surface that has been cleared of coarse organic detritus. This clay becomes a fixed marker after absorption of soil moisture that permits accurate measurement of short-term net vertical accretion (Baumann et al. 1984, Hupp and Bazemore 1993, Kleiss 1996, Ross et al. 2004). The clay pads were examined annually and measured for depth of burial during the course of study. Deposition rate data were examined using hierarchical cluster analysis, which places similar entities into a cluster or clusters (Ludwig and Reynolds 1988). A subsequent ANOVA of the means of the clusters was performed using the Tukey HSD method to determine significant differences. Linear regressions were performed on deposition rates against loss on ignition (LOI) values and percent exceedance information to determine possible predictive relations. Deposition rates were compared to rates determined in a separate study using ^{137}Cs analyses of lake bed cores (S. Bentley, Louisiana State University, unpublished data). All transects appeared to be depositional prior to instrumentation.

Sediment samples were taken near all clay pads at both the beginning and end of the study. The last sample was taken from the soil surface to a depth matching that above the clay pad so that only current (past three years) processes are reflected in the sediment analyses. Sediment sample analyses included: 1) bulk density, by taking a known sample volume, which was then dried and weighed, 2) size clast composition by dry sieving with various screen sizes in a vibratory sieve shaker, and hydrometer analyses for size classes less than 0.063 μ (Guy 1969), and 3) organic fraction of the sample by standard LOI procedures (Nelson and Sommers 1996).

RESULTS

Inter-Site Deposition Patterns

Sediment deposition rates measured within the central Atchafalaya Basin generally exceed the 2–5 mm/yr range typical of other floodplains in the Lower Mississippi region (Hupp 2000) except for large, flood-generated deposits (Kesel et al. 1974). Within the present study area, mean annual sediment deposition rates for an entire site/transect ranged from 2 mm/yr on high levees to 42 mm/yr at low elevation sites with substantial hydraulic connection to sediment-laden water (Table 1). All rates are based on net cumulative deposition during the three-year period (2000–2003). Rates for individual clay pads ranged from trace amounts in stagnant areas with no hydraulic connection to 65 mm/yr in rapidly filling locations that formerly were open water areas. Bulk density did not vary significantly among sites (Table 1). However, LOI percentages ranged from 2.4% to 28.2% and generally varied inversely with deposition rate (Table 1). Exceptions occurred at our highest sediment deposition sites, which also had relatively high LOI. Percent of

Table 1. Transect abbreviation, location, deposition rate, bulk density, percent organic material (LOI), percent sand (> 63 μ), and bank height (in relation to sea level) for 20 sites.

Site	Deposition Mm/yr	Bulk Density	LOI, percent	Percent > 63 microns	Bank Height, meters
A1 – Bayou Sorrel	1.8	0.95	28.2	15.4	4.21
A2 – Florida Gas canal off Indigo	2.2	1.08	24.1	13.3	*
A3 – Unnamed Bayou, West	2.2	1.12	14.9	16.5	3.90
A4 – Indigo Bayou, Old (A4)	2.4	1.10	21.4	16.0	*
B1 – West Access near Bayou Eugene	6.4	0.80	13.8	6.9	4.23
B2 – Bayou Benoit	7.3	0.38	*	4.7	1.30
B3 – Indigo Bayou, West	7.4	0.97	18.6	16.2	3.58
B4 – West Access Dog Beat, North	7.9	1.00	14.2	16.6	3.28
B5 – Murphy Lake, Daniel Hoover	9.9	0.59	13.8	14.1	1.67
B6 – West Access Dog Beat, South	10.1	1.12	8.8	10.1	3.09
C1 – Bayou Darby, 1 West	13.6	0.99	7.1	10.2	2.90
C2 – Bayou Darby, 2 West	14.1	1.11	1.8	40.7	2.29
C3 – Murphy Lake, Cross Canal	14.5	0.84	7.9	10.6	2.16
C4 – Murphy Lake, Point Bar	14.9	0.92	10.0	32.0	0.91
D1 – Buffalo Cove, South	19.2	0.88	9.1	7.5	2.41
D2 – Bayou Darby, 1 East	19.3	1.02	7.2	17.8	3.05
D3 – Bayou Darby, 2 East	20.7	1.00	5.7	9.2	2.21
E1 – Unnamed Bayou, East	26.3	1.31	2.4	43.6	3.68
F1 – Florida Gas at old Bayou Canon	36.5	1.02	15.8	12.3	4.74
F2 – Buffalo Cove, North	42.0	1.11	7.0	4.9	2.08

*Missing values at A2 and A4 resulted from incomplete surveys, B2 was inaccessible during sampling period; none of these sites were used in detailed analyses, as explained in text.

mineral sediment exceeding 63 μ was relatively consistent at many sites (between about 10% and 17%); notably high (32% to 44%) exceptions were found in areas with both a high degree of hydraulic connectivity to river flow and high velocities during periods of inundation (Table 1). No clear relation was found between sediment size and sedimentation rate, as evidenced at our three highest sites for deposition rate where sediment greater than 63 μ ranged from 4.9% to 43.6%.

When arrayed in ascending order (Figure 3) deposition rates for each site appear to be separated into relatively distinct clusters. The hierarchical cluster analysis independently sorted the mean site deposition rates into six univariate clusters (Figure 4). Five of these clusters contained two or more sites. The clusters are named A through F (Table 1, Figure 4) in ascending order of deposition rate (Figure 3). Cluster A contains four sites; the remaining clusters B, C, D, E, and F contain, in ascending deposition rate, six, four, three, one, and two sites, respectively (Figure 4). Thus, site name abbreviations (Table 1) reflect the cluster and the deposition rate within each cluster. The E cluster (1 site) is heavily affected by an upstream levee crevasse that will be discussed separately. The ANOVA revealed that all clusters significantly differ ($P \leq 0.002$). These clusters can be described and distinguished largely by their degree of hydraulic connectivity to sediment laden flow and the patterns of suspended sediment sources; most sites have been affected by human-altered flow through the basin.

Local and Temporal Sediment Deposition Patterns

Cumulative deposition along transects (sampling stations from channel edge to backswamp) varied over the three-year period from 0 to 295 mm. Three of the sites became partly inaccessible over the three-year period (B1, B2, and C2) or had too few sampling stations (A4) to interpret spatial and temporal patterns in detail. Deposition rates varied along transect revealing three distinct spatial patterns: 1) uniform or no clear trend from levee to backswamp, 2) deposition mostly on levees decreasing toward the backswamp, and 3) little deposition on levee and increasing toward the backswamp (C3, D1, and F1, respectively as examples, Figure 5). There were no strong temporal patterns over the study period except that sampling dates in 2001 (calendar year) include part of a previous drought (Figure 5); samplings in 2002 and 2003, during near normal years, tend to show higher deposition at most sampling stations than 2001. Transects lacking trends in spatial deposition may occur where there is little deposition (A

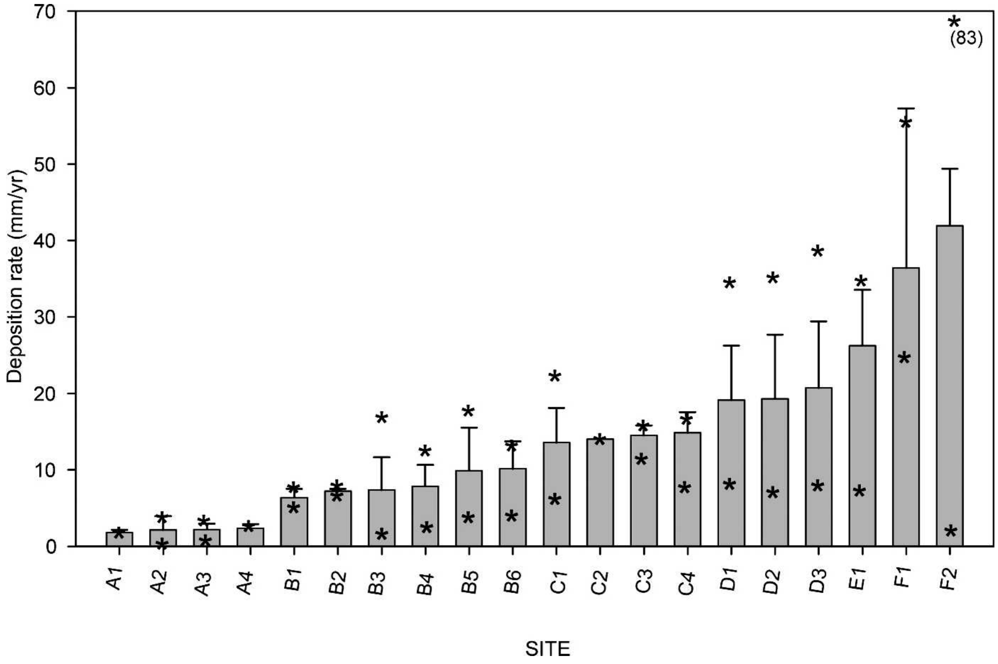

Figure 3. Mean (ascending order) and standard error (whisker) of sediment deposition rates along 20 transects (sites) in the central Atchafalaya Basin (asterisks indicate the data range). Six distinct groups occur indicated by letter portion of the site name (A through F). The E "group" is composed of a single transect.

cluster, Figures 3 and 4) or where there is high deposition along low relief transects such as C3 (Figure 5), E1, and F2. The relatively distinct pattern of decreasing deposition from the levee toward the backswamp occurred in the relatively high deposition rate D cluster (D1 Figure 5) and in the B cluster (not shown). This suggests that the sediment source was from the adjacent channel. The highest deposition amounts occurred at sites E1 (single member of E cluster, Figure 4) and at F1 and F2 (F cluster). E1 and F1 received substantial sediment from sources other than the adjacent channel, where the deposition source was from backswamps (F1, Figure 5).

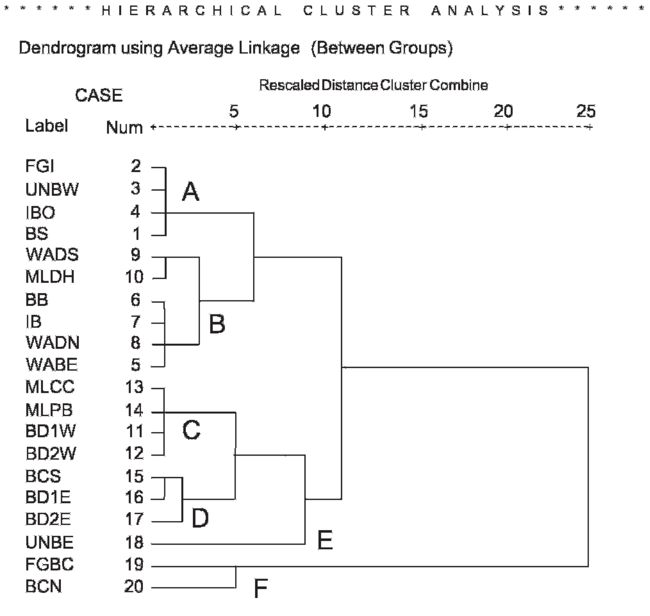

Figure 4. Dendrogram from hierarchical cluster analysis of deposition rate data (univariate) at sampling sites. Six groups or "clusters" are lettered, A through F, in ascending deposition rate. The clusters are statiscally different from each other ($P < 0.002$, Tukey HSD).

Percent Organic Material and Sand—Whole Sites, Levees, and Backswamps

Distinct trends existed among sites in percent organic material (LOI) and percent sand (fraction $> 63\ \mu$) relative to deposition rates (mm/yr) and amounts ($kg/m^2/yr$). These trends, similar to the deposition patterns previously described, were apparent and potentially more interpretable when separated by deposition on levee versus backswamp sampling locations rather than whole sites (Figure 6A); deposition may be even on both levee and backswamp areas, which is the case in low deposition-rate areas, but may also occur in some medium to high deposition rate areas (Figure 6A). The other two patterns were where clearly most of the sediment trapping occurred predominantly on levees (e.g., D1, Figure 5) or, conversely, predominantly in backswamps (e.g., F1, Figure 5); both patterns may occur anywhere along the deposition-

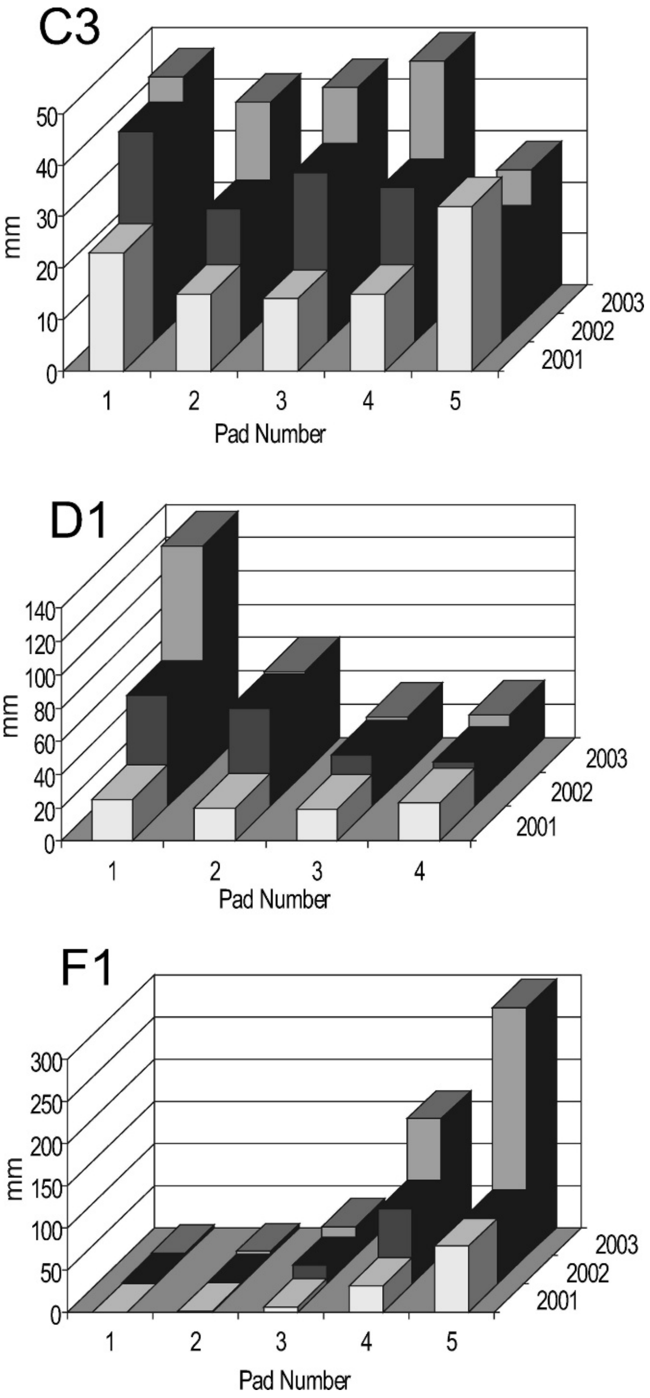

Figure 5. Temporal and spatial sediment deposition patterns for selected sites that represent three distinct trends along transect; transect C3 with even or no spatial pattern, transect D1 with deposition decreasing from the levee to the backswamp, and transect F1 with deposition increasing from the levee to the backswamp. Cumulative net deposition (over three years) above each clay pad in a transect is shown.

rate gradient except the lowest rates (A cluster, Figures 3 and 4).

Trends in percent sand (> 63 μ) and organic material (LOI) were also apparent along whole site, levee only, and backswamp only ascending deposition-rate gradients. Conversion of sediment deposition rate into amount of sediment deposited (using discrete bulk densities) shows that percent sand is positively associated with deposition when looking at whole site data (Figure 6B). However, where there were medium to high deposition rates on levees (Figure 6C) there was greater mass per volume of sediment. Conversely, although less distinct, at most deposition rates in the backswamp (Figure 6D) there was less mass per volume of sediment. Percent of sand along the whole site gradient (Figure 6A) normally ranged between 5% and 15%, except at three sites where the percentage of sand was unusually high (C2, C4, and E1). These sites are dominated by point-bar deposition or an upstream crevasse in the levee. No apparent trends in percent sand occurred when deposition is separated into levee or backswamp only gradients (Figure 6C and D) except at the crevasse splay site (E1). Percent organic material (LOI) tended to be greatest where deposition rates were low regardless of whether the sites were considered in whole or separated into levee or backswamp sections (Figure 6). Organic material (LOI) generally decreased with increasing deposition rate regardless of location or rate at the sites (Figure 6).

Site Elevations and Hydroperiods

Percent exceedance is the percent of time, annually, that an elevation is equaled or exceeded by the flow stage. Elevations and percent exceedance ranged from about 4.6 to 1.3 m and 13% to 85%, respectively (Figure 7). Some sites with high relief ranged about 3.5 m, while relatively flat sites ranged only about 0.5 m (D1 and B2, respectively, Figure 7). Sites with low relief typically do not have substantial levee development. High deposition tended to occur on sites with low elevation and low relief (e.g., C3, D3, and F2; Figure 7), although notable exceptions occurred and will be discussed separately.

Area Sediment Trapping

Assuming that our sampling design reflects the spatial distribution (in area) of sedimentary environments in the study area, and using the site mean amount of sediment trapped (13.4 kg/m^2/yr), mean bulk density (0.97), and mean LOI, 12%), the study area annually traps a net 6,720,000 Mg of sediment,

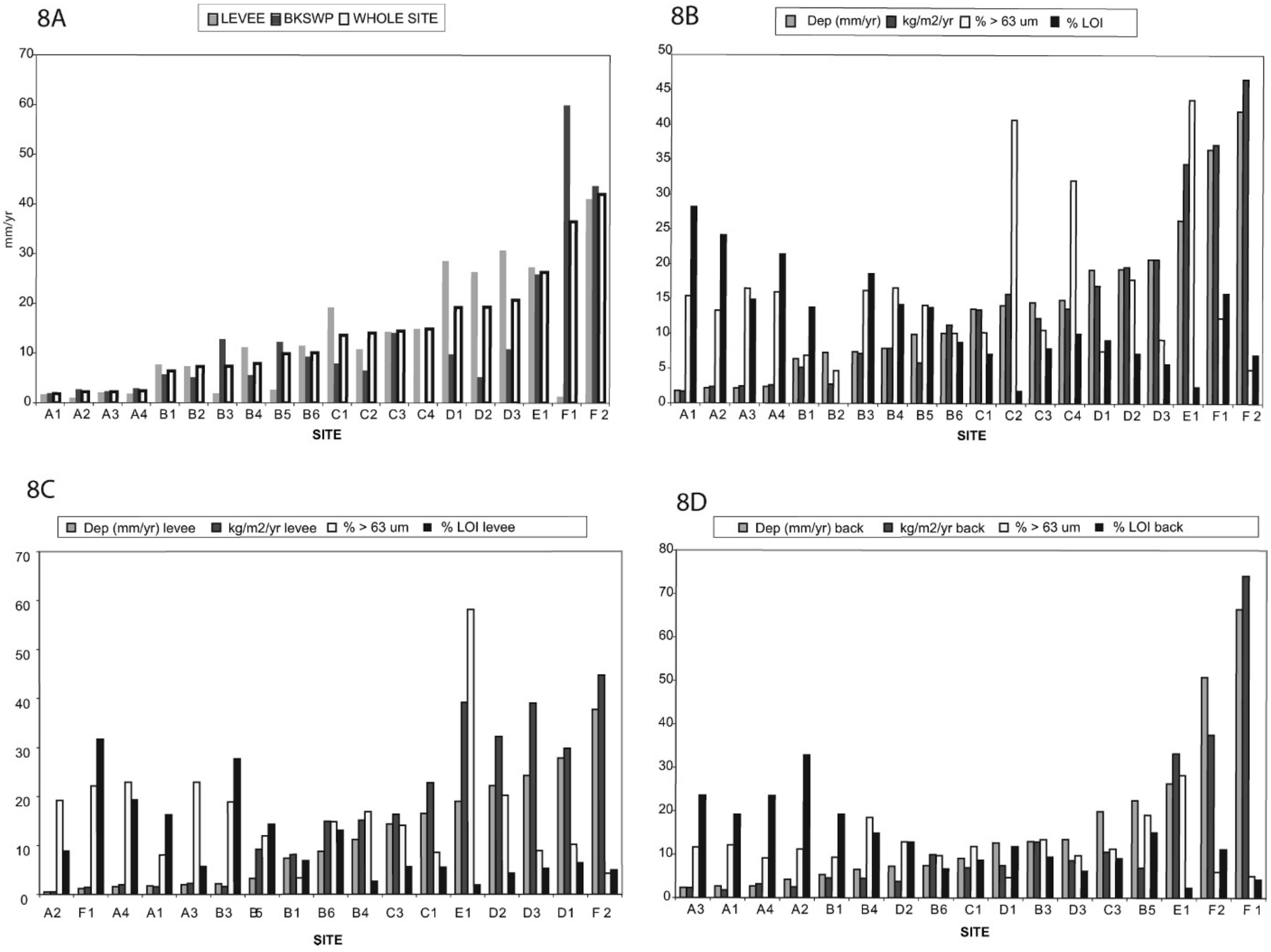

Figure 6. A) Mean deposition rate (Dep) (mm/yr) for whole site (solid gray bar, ascending), backswamp (BKSWP) stations only (solid black bar), and levee stations only (enclosed white bar). Where bar heights are similar neither levee nor backswamp deposition dominated the site. Where either backswamp or levee rates exceed site mean, the site is dominated by deposition on the indicated landform. Deposition rate, amount of sediment trapped (kg/m^2/yr), % sand (> 63 μ), and % organic material (LOI) for each site are plotted in ascending order of sedimentation rates for B) whole site, C) levee, and D) backswamp (back).

of which 820,000 Mg are organic material. These numbers may be high relative to the whole basin. However, basin-wide they may be balanced as sediment deposition rates are likely low in the upper basin where much of the floodplain has already filled (short hydroperiod) and a relatively high elevation bottomland exists. Whereas, much of the lower basin began filling more recently (McManus 2002), particularly the Grand Lake area (Figure 1), which is relatively low in elevation and presumably continues filling today.

DISCUSSION

Variation in sources of sediment-laden flood water and the length of time a floodplain is flooded (hydroperiod) may largely explain sediment deposition patterns in the central Atchafalaya Basin. In alluvial systems, the amount of suspended sediment in flood water at a given location on the floodplain may be a function of “connectivity” (Hupp 2000, Noe and Hupp 2005) of the location to sediment-laden river water. Locations along floodplain flow paths or those that are low and not blocked (typically by levees) and near the river tend to have higher sediment deposition rates than those that are less connected or distant from the over flowing banks (Ross et al. 2004). Crevasses in levees and sloughs on the floodplain are typically areas that have increased flow and form flow paths that may inject sediment relatively far into the floodplain (Patterson et al. 1985, Hupp 2000). The longer an

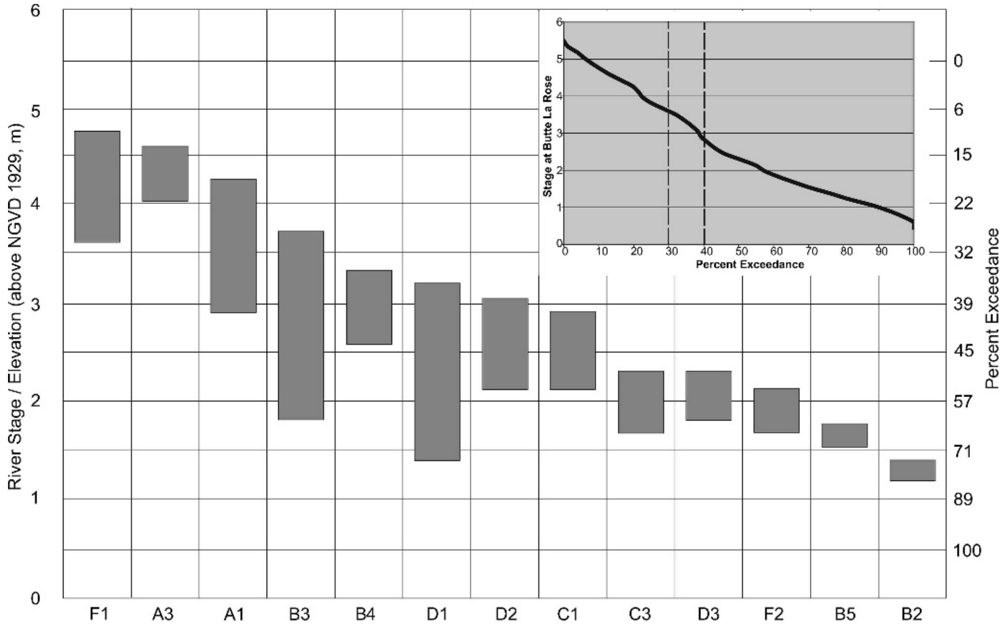

Figure 7. Bar graph of elevation and percent exceedance relations for selected transects. River stage equals elevation; datum for gage is sea level (NGVD 1929). For each transect, the top of bar is the highest leveled point (levee) and the bottom of bar is the lowest leveled point (backswamp). Inset shows the stage/percent exceedance relation (flow duration curve) for the gage at Butte La Rose. Backswamps are typically inundated at a stage of 2.8 m and levees overtopped at a stage of 3.7 m, about the 40% and 30% flow duration, respectively (dashed lines).

area on the floodplain is inundated by sediment-laden water, the greater amount of sediment deposition; hydroperiod is generally inversely related to elevation (Hupp and Bazemore 1993, Hupp et al. 1993, Mitsch and Gosselink 2000, Ross et al. 2004). Thus, sites with relatively high elevation above typical bank heights (now past active levee building when deposition rates on the levee may be high) tend to experience less sediment deposition (Figure 8A) than low sites with long hydroperiods as long as the sites have a good degree of connectivity to river water. On average, most of our sites experienced flooding in the backswamps when the stage gage at Butte La Rose was about 2.8 m and the banks were overtopped about the 3.7 m stage, representing the 40% and 30% flow durations (percent exceedance), respectively (Figure 7). Flow velocity is another important factor that can influence sediment deposition rates. Studies that report detailed flood-flow velocity measurements across a floodplain are rare in the literature. However, relative velocities can be inferred from grain sizes of the deposited sediment; coarse (sand sizes in our study) sediment transport and deposition is associated with higher flow velocities than fines, which can be deposited at lower velocities. Some flows may have velocities high enough to erode and re-suspend sediment, which occurs in crevasses and subsequently deposited as crevasse splays (E1, Table 1).

Recent studies have shown that coastal lowlands may be an important sink for carbon (Ludwig 2001, Raymond and Bauer 2001) and associated nutrients (Hupp et al. 2005, Noe and Hupp 2005), which may be stored in these systems as organic rich sediment. Initial results (Hupp et al. 2002) suggest that the central Atchafalaya Basin may conservatively trap five million Mg of sediment annually, of which more than 500 thousand Mg are organic material. This organic material presumably is from both autochthonous and allochthonous sources; unfortunately, there is little published information on aboveground productivity within the Basin. Thus, studies of lowland fluvial systems such as the Atchafalaya Basin may be critical towards our understanding of global carbon cycling, which, in turn, has direct implications for nutrient processing, marine "dead zones", and global climate change.

Site Sedimentary Environment

Cluster A, which contains the lowest sediment deposition-rate sites A1, A2, and A3 (Figure 3) have high banks and the entire transects are located on relatively high ground (e.g., A1, A3, Figure 7). Although these sites had moderate amounts of sand, they also had some of the highest LOI (Figure 6A). This suggests that autochthonous organic material may be an important element in the total amount of

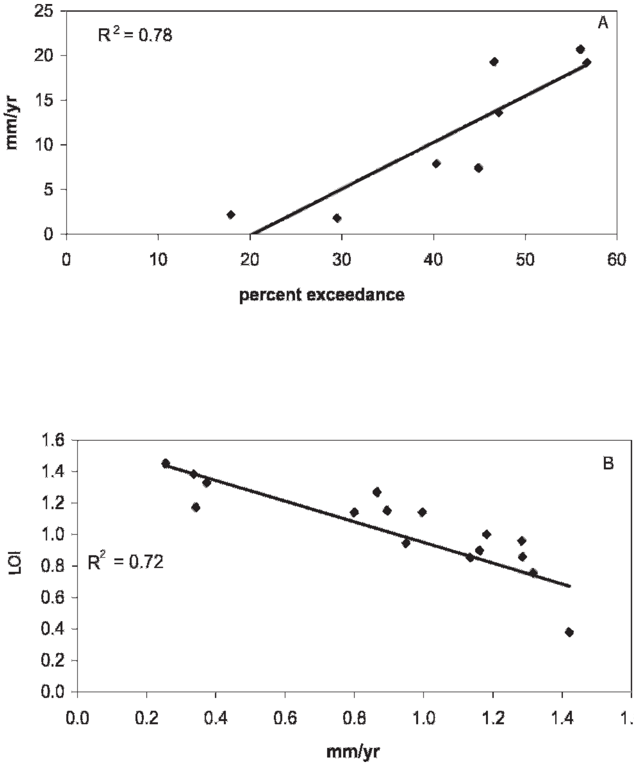

Figure 8. A) Regression results comparing percent exceedance at bank height and deposition rate data after log transformation. B) Regression results comparing LOI data and deposition rate data after log transformation and removal of the two sites (F cluster) with the highest rates and significant hydraulic damming.

sediment at sites in the A cluster. There is little spatial pattern in cumulative deposition at any of these sites (Figure 6), which supports the premise that mineral deposition may be unimportant here. Where mineral deposition may be substantial (all other clusters), a spatial gradient typically develops reflecting the source of the sediment. It is likely that these sites once had higher deposition rates than present, but the depositional environment has changed with the passing of prograding deltaic processes (Tye and Coleman 1989). As aggradation occurs, a negative feedback loop in depositional processes develops where an area will gain in relative elevation over time, decreasing hydroperiod and, thus, decreasing sediment deposition rate.

The first cluster with substantial evidence of mineral deposition is cluster B where a distinct pattern of deposition from the adjacent channel occurs principally on levees (e.g., D1 pads 1 and 2, Figure 5); there is typically less deposition in the backswamps (clay pad 3 and further into the backswamp, D1, Figure 5). Along fairly flat floodplains, deposition rates commonly decrease with distance from the active channel (Pizzuto 1987, Walling et al. 1996, Ross et al. 2004) so long as sloughs downstream of a levee crevasse do not inject sediment along microtopographic flow paths. Cluster B sites have moderate deposition rates and appear stable, having no obvious bar growth or evidence of trees stressed by sediment burial. We infer that these sites are in relative equilibrium with sediment supply such that present sediment deposition rates will not qualitatively change the geomorphic surfaces or forest communities. Sites in this cluster, like cluster A, still have relatively high LOI (Figure 6A), again suggesting that autochthonous sources of organic material are somewhat important.

Cluster C includes sites that differ in sedimentary environment but have statistically similar deposition rates (Figure 4). All of these sites have heightened sedimentation rates that are related to a variety of relatively distinct processes including periods of flow stagnation (C1 and C2), multiple sediment sources (C3), and point bar development (C4). Sites with more than one source of sediment may show a uniform deposition pattern (C3, Figure 5) when one source principally affects the backswamp rather than the levee and vice versa. This cluster contains two of the three sites with unusually high percentages of sand (C2 and C4, Figure 6B); both sites experience high energy flows that lead to sand dominated deposits and rapid levee development.

The pattern of high levee sediment deposition diminishing into the backswamp is continued in the high deposition-rate cluster D (D1, Figure 5). The dominance of levee deposition in this cluster is clearly shown in Figure 6, which is indicative of an adjacent channel sediment source. All sites in the D cluster are adjacent to natural bayous with low floodplains that have been affected by increases in sediment due to dredging in channels near their mouths (Bayou Darby, Buffalo Cove Outlet, Figure 1), which substantially increased sediment-laden flow and flow reversal at these sites. When the adjacent channel is the dominant source of sediment, it is expected that elevation would be an important factor as it would affect hydroperiod, which is borne out in the relatively strong inverse relation between deposition rate and elevation (percent exceedance, Figure 8A). Flows in the Buffalo Cove Outlet (near sites D1 and F2) and Bayou Darby (near sites D2 and D3) channels become slow and ultimately stagnate due to water sources that become active during high stages and impede normal flow (observation and stage/velocity data at the Buffalo Cove gage, Figure 1). This hydraulic dam (Figure 9), in addition to high-suspended sediment concentration, may allow for significant sediment deposition.

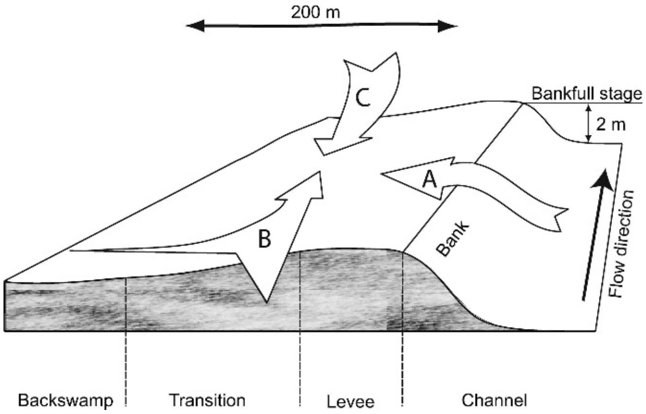

Figure 9. Generalized potential sediment-laden flow sources for floodplain deposition from: A) the adjacent channel, B) the upstream slough, and C) the downstream slough. Flows on B and C, usually, can be from different channels or bayous. When flows on B and C (and sometimes A) occurred simultaneously, flow stagnation via hydraulic dams could develop.

Deposition rate averages about 20 mm/yr at these sites, nearly three times the published highest annual rates (Hupp 2000); when mineral deposition is this high, percent organic material is usually relatively low (all sites < 10% LOI). A feature associated with this sedimentary environment is the development of elongated bars that form on the channel edge (e.g., C4, Table 1). The bars grow as the channel fills in the downstream direction of the sediment source and appear to be associated with a sedimentary wave related to active prograding deltaic processes (Tye and Colman 1989). These bars represent new terrestrial surfaces and are rapidly colonized by black willow and other shrub species. Bars such as this may be seen throughout the study area (often expansive) along channels where suspended loads are high. Backswamps may also experience analogous filling as described in Tye and Coleman (1989) over longer time frames associated with prograding deltas.

Highest sediment deposition rates and amounts occurred in clusters E and F (Figure 3). Site E1 is statiscally different from all other sites and is the sole member of cluster E (Figure 4). The unique nature of the site is confirmed in its high percent sand and low percent organics (LOI) in both levee (Figure 6C) and backswamp (Figure 6D) deposition. Although this site has relatively high banks (3.7 m, Table 1), a crevasse in the levee (normal to the transect) upstream of the site injects substantial amounts of relatively coarse material on all clay pads except pad 1 on the levee, which presumably was high enough in elevation to not be affected by the crevasse splay deposits. This site is also located close to the main Atchafalaya River channel, assuring an ample supply of sediment-laden flood water. Breaks in levees and associated sloughs allow for sediment delivery to the floodplain in the absence of overbank flows (Patterson et al. 1985, Dunne et al. 1998, Hupp 2000). The effect of sloughs and levee breaches in floodplain sediment deposition is possibly the least documented sediment transport mechanism (Ross et al. 2004); extreme examples of this process have been reported along the Missouri River (Schalk and Jacobson 1997) and the Mississippi River (Jacobson and Oberg 1997).

Sites F1 and F2 form the final cluster (Figure 4) and appear to be functionally different (Figure 6) but share two important factors conducive to high sediment deposition rates and amounts: a high degree of connectivity to sediment-laden water near a prograding sedimentary wave (see discussion on cluster D, above) and being supplied from at least two sources from different directions creating a hydraulic dam (Figure 9). F1 receives sediment from backswamp sources (B and C, Figure 9, and F2 receives sediment from all three possible sources (Figure 9). These two sites largely differ in their site histories. F1 has, at least since the channel was excavated, been above (elevation) the 2.75 m stage at the Butte La Rose gage (Figure 7), meaning that most or all of the transect is dry during part of the year. Whereas, F2 prior to about 18 years ago (based on tree-ring data) was open water and part of the lake associated with Buffalo Cove that is now nearly filled. Both of these sites are associated with prograding deltaic processes and lake filling; F1 is receiving water from Murphy Lake. Site F1 has high banks (Table 1) and levee areas such that nearly all deposition is in the backswamp (Figure 5), where the greatest amount of sediment over a single pad occurred in our study (nearly 300 mm in three years, pad 5, F1). Site F2 has the typical uniform pattern of deposition on low areas (C3, Figure 5) with multiple flow sources (see discussion on C3). Sites F1 and F2 have all of the conditions our study has found to facilitate sediment deposition: 1) high connectivity to sediment-laden water, 2) long hydroperiod (low banks), 3) multiple sources of flow, and perhaps most importantly, 4) hydraulic damming (Figure 9). Regression of LOI against site deposition rate yields an r^2 of 0.31; however, if the two highest deposition rate sites (F1 and F2) are removed from the analysis, the r^2 increases to 0.72 (Figure 8B). Increased LOI at these two sites may suggest that where severe hydraulic damming occurs, the potential for trapping allochthonous organic material increases (i.e., potential carbon sequestration).

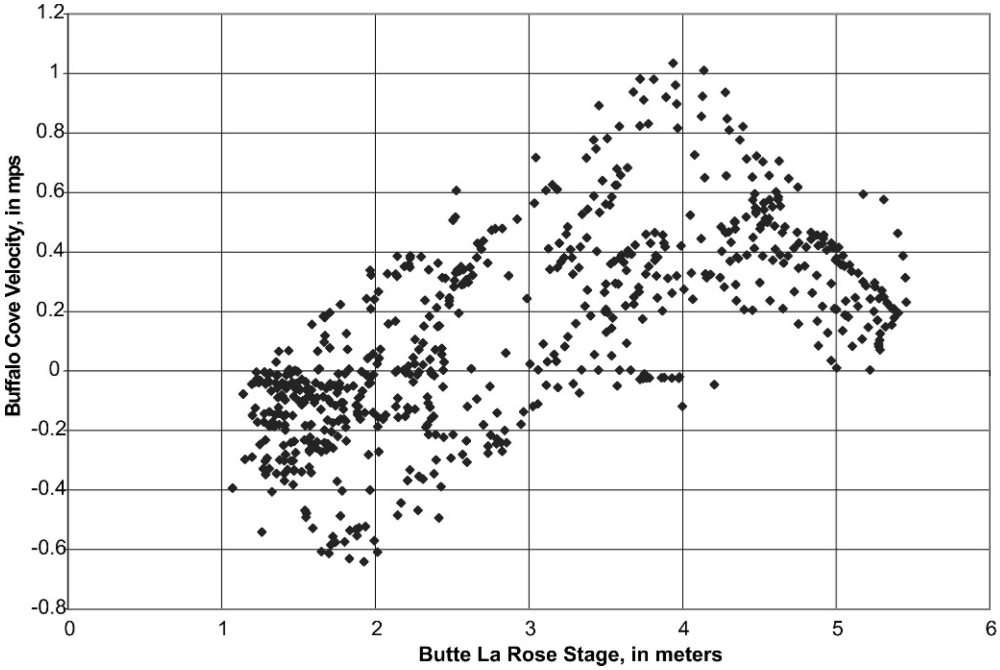

Figure 10. Scatter plot of stage at Butte La Rose gage and velocity and flow direction (positive numbers = flow into Buffalo Cove, the reverse of normal draining flow) from the Buffalo Cove Outlet gage. Note, velocities are near 0 at both low and high stages.

Velocity data (Figure 10) from the stage gage located on the Buffalo Cove Outlet (Figure 1) shows that zero velocity occurs at low flows and again at peak flows where a hydraulic dam may be formed at F2; this channel conveys much of the sediment now filling Buffalo Cove. Positive velocity values (Figure 10) indicate that water is flowing up (northward) this channel, the reverse of the normal flow out of (draining) Buffalo Cove. Evidence of the hydraulic dam is clear both in the flow reversal that occurs at low to moderate stages (data from Butte La Rose stage gage) and in stagnation of flow at the highest stages (Figure 10), where the normal drainage may almost ''catch up'' with the aberrant flow and create near zero velocities facilitating high rates of sediment deposition. Note that the velocity trend reversal occurs at about the 4.0 m stage (Figure 10), which is just past the point (3.7 m) where the levees are typically overtopped in the study area (Figure 7). This scenario is analogous to the conditions along Bayou Darby also on the west side of the study area (Figure 1) and the Murphy Lake area on the east side (and presumably at many other locations within the Basin), where atypical flows with high sediment loads compete with normal draining flows.

Lake Bed Coring

Vibracores, in a separate study by S. Bentley (LSU Coastal Studies Institute), were taken in 2003 from open water areas of Buffalo Cove and Murphy Lake (Figure 1) to estimate the amount and rate of lake-bed sediment accumulation. Three to four cores were taken in each lake; core length ranged from 1.3 to 2.2 meters. These efforts were near the D1 and F2 sites on the west side and B5 and C3 sites on the east side of the study area (Figure 1). The cores were analyzed using standard ^{137}Cs and ^{210}Pb techniques, sampled at 20 mm intervals. All cores of interest (within the present study area) were deep enough to capture the 1963 peak concentration of atmospheric ^{137}Cs (atomic bomb testing), which provides an estimate of sedimentation for the last 40 years.

Lake cores are normally subjected to continuous sediment fluxes by having a 100% (or nearly so) flow duration. Estimated recent fill (since 1963) is 2,070 mm and 1,680 mm for Buffalo Cove and Murphy Lake, respectively. The mean rate of deposition from Buffalo Cove cores was 30 mm/yr, based on ^{137}Cs, and is similar to our rate of backswamp filling of 42 and 19 mm/yr along transects at F2 and D1, respectively. However, a single pad on the F2 transect (historically a lakebed, determined from air photos) had a mean deposition rate of 61 mm/yr, suggesting that greatest deposition rates have occurred in the most recent several years rather than a relatively constant rate since 1963. The mean rate from Murphy Lake cores was 28 mm/yr, based on ^{137}Cs, which may be high compared to our rate of backswamp filling of 15 and 10 mm/yr at C3 and B5, respectively. This may indicate that the bulk of Murphy Lake filling occurred before the placement of our clay pads in 2000. However, unlike F2, both B5 and C3 were historically floodplains with distinctly shorter hydroperiods than F2 over the past decade. The ^{210}Pb core data for Murphy Lake indicated a rate of 43 mm/yr, nearly twice that indicated by ^{137}Cs, which suggests that, like Buffalo Cove, most deposition was relatively recent rather than at a constant rate since 1963 (the natural, atmospheric deposition of ^{210}Pb is constant unlike the episodic spike of ^{137}Cs).

Levees versus Backswamps, Discharge, and Suspended Sediment

Literature regarding natural levee formation is sparse. However, the qualitative differences between levee versus backswamp sedimentary processes and geomorphic form are widely acknowledged (Hupp 2000). Differences between levees and backswamps in distance to the channel and length of hydroperiod (percent exceedance, Figure 7) clearly affected our results, particularly in sediment deposition patterns (Figure 5). Except where levee deposition rates were $<$ 5 mm/yr, levee deposits trap more material than backswamps (B and C, Figure 6). There are three possible explanations for these results related to the depositional environment on levees. First, flow velocities on levees are probably higher than in the backswamp and may transport and deposit all size clasts at least for short distances. Thus, the interstitial space in sandy levee deposits may be filled with silt and clay particles, resulting in higher bulk densities than well-sorted backswamp deposits. Second, most levees are high and dry, relative to backswamps, which could increase solidification of sediment by a reduction of water in interstitial space. Third, there is noticeably less organic material in actively forming levees than in backswamps (B and C, Figure 6). The presence of organic material reduces overall density because it has inherently less bulk density than mineral sediment. It is likely that all three of these factors contribute, as an environmental by-product, to greater mass in levees than in nearby backswamps. Anecdotally, levees are notoriously more difficult to core than backswamps because of their hardness, particularly when dry. Kesel et al. (1974) reported an average of 530 mm of levee deposition and 11 mm of backswamp deposition resulting from the 1973 flood along the Mississippi River floodplain on a reach (about 110 km) adjacent to the flow diversion structure at the head of the Atchafalaya Basin. Benedetti (2003) reported mean levee deposition rates of 10.8 mm/year since 1964 in the upper Mississippi River basin of Minnesota and Wisconsin, using ^{137}Cs profiles.

The Atchafalaya Basin is clearly a trap for sediment before it can enter the Gulf of Mexico. During the period of filling, most intense from about 1930 to 1960 (Shlemon 1972, Kesel et al. 1974, Roberts et al. 1980, Tye and Coleman 1989), the basin probably trapped more sediment than it delivered to the Gulf, and was a net sink for sediment. The last 30 years has experienced an increase in deltaic processes in the Atchafalaya Bay (Tye and Coleman 1989, Roberts et al. 1997, McManus 2002). By 1994, growth of the Lower Atchafalaya deltas past the Wax Lake and Morgan City gauging stations (Figure 1) had grown to 84.2 km^2 and 101.5 km^2, respectively (Majersky et al. 1997). Growth of these deltas indicates a substantial supply of sediment leaving the Basin. Mean daily discharge (6,031 cms) of water passing the Simmesport gaging station (1, Figure 1) located near the head of the Basin (inflow) for the period of our study (2000–2003) approximates the sum of discharges leaving the Basin (6,066 cms) past the Wax Lake and Morgan City gaging stations (3 and 4, Figure 1, respectively). This same approximation is demonstrated in daily suspended load for the three gaging stations; 124,352 Mg enters the Basin (1, Figure 1) while 134,986 Mg exits the Basin (3 and 4, Figure 1). Thus, during the study period there was no net storage of sediment in the Basin; indeed, there was a small surplus and the prograding delta now occurs in Atchafalaya Bay. However, within our study area millions of megagrams of sediment are trapped annually, suggesting there is compensating erosion and resupply of sediment from elsewhere in the Basin. Presumably, the sediment load leaving the Basin is derived mostly from in-channel stores and functions much like a reservoir in equilibrium, where sediment trapping is matched by sediment transport out of the Basin.

Suspended sediment may be the most important water-quality concern in the United States today (USEPA 1994). Increases in suspended sediment, directly and indirectly affects aquatic plants and animals. In critical riparian areas, high sediment-deposition rates may damage other living resources such as riparian vegetation. Additionally, fine suspended sediment is the transport medium for hydrophobic forms of nutrients and pesticides, and most trace elements (Horowitz 1991). Geomorphic analyses (Leopold et al. 1964, Jacobson and Coleman 1986, Hupp et al. 1993, Ross et al. 2004) verify that riparian retention of sediment is a common and important fluvial process, yet retention time of sediment may be the most poorly understood, generally unquantified aspect of sediment budgets (Wolman 1977).

CONCLUSIONS

Our results are a three-year snapshot of present sedimentation patterns in the central Atchafalaya Basin. Human altered hydrologic patterns, from small scale opening or closing of single bayous to the diversion structure at the head of the basin on the Mississippi River, have increased severity of local non-equilibrium sedimentation patterns throughout our study area. Although sediment trapping and aggradation are normal near the mouths of large alluvial rivers, hydrologic alterations have created areas with excessive deposition where there was once open water and conversely prevented river water from flowing in other areas that now experience periods of hypoxia. The impact of these alterations has been felt in the Basin for many decades, possibly as far back as the initial levee construction on the Mississippi River.

The Atchafalaya Basin traps substantial amounts of suspended sediment annually; some areas have the highest documented sedimentation rates in forested wetlands of the United States. Levee sites that annually trap the least amount of sediment tend to be relatively high in elevation (short hydroperiod) and/or have a poor hydraulic connectivity to sediment-laden river water, and tend to be hypoxic. Backswamp sites that have the highest rates of sediment deposition tend to be low in elevation and receive sediment-laden water (high connectivity) from two or more sources, which may create slow velocities through hydraulic damming. The greatest percent organic material in the sediment tended to be in sites with low mineral-sediment deposition rates; this organic material is thus presumably autochthonous. However, in a few high-deposition sites LOI percents were also high, which suggests that some areas may be trapping large amounts of allochthonous organic material. Coarse sediments (sand) were most common on levees and along sloughs associated with levee crevasses. Sedimentation rates and size clasts diminished from the levee to the backswamp where the adjacent channel is the dominant source of floodplain inundation. High backswamp deposition rates (with or without adjacent high levee deposition rates) are typically associated with sediment sources other than or in addition to the nearest channel. Although the Atchafalaya Basin may no longer be a net sink for sediment, millions of megagrams of sediment are stored annually, which may allow for important biogeochemical transformations that potentially reduce contaminant, nutrient, and carbon inputs into the Gulf of Mexico.

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