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Sediment and nutrient trapping as a result of a temporary Mississippi River floodplain restoration: The Morganza Spillway during the 2011 Mississippi River Flood

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ABSTRACT

The 2011 Mississippi River Flood resulted in the opening of the Morganza Spillway for the second time since its construction in 1954 releasing 7.6 km^3 of water through agricultural and forested lands in the Morganza Floodway and into the Atchafalaya River Basin. This volume, released over 54 days, represented 5.5% of the Mississippi River (M.R.) discharge and 14% of the total discharge through the Atchafalaya River Basin (A.R.B.) during the Spillway operation and 1.1% of the M.R. and 3.3% of the A.R.B. 2011 water year discharge. During the release, 1.03 teragrams (Tg) of sediment was deposited on the Morganza Forebay and Floodway and 0.26 Tg was eroded from behind the Spillway structure. The majority of deposition (86 %) occurred in the Forebay (upstream of the structure) and within 4 km downstream of the Spillway structure with minor deposition on the rest of the Floodway. There was a net deposition of 26×10^{-4} Tg of N and 5.36×10^{-4} Tg of P, during the diversion, that was equivalent to 0.17% N and 0.33% P of the 2011 annual M.R. load. Median deposited sediment particle size at the start of the Forebay was 13 μm and decreased to 2 μm 15 km downstream of the Spillway structure. Minimal accretion was found greater than 4 km downstream of the structure suggesting the potential for greater sediment and nutrient trapping in the Floodway. However, because of the large areas involved, substantial sediment mass was deposited even at distances greater than 30 km. Sediment and nutrient deposition on the Morganza Floodway was limited because suspended sediment was quickly deposited along the flowpath and not refreshed by incremental water exchanges between the Atchafalaya River (A.R.) and the Floodway. Sediment and nutrient trapping could have been greater and more evenly distributed if additional locations of hydraulic input from and outputs to the A.R. (connectivity) were added.

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1. Introduction

Levee construction along the Mississippi River (the Mississippi) has restricted sediment and nutrient deposition to the area predominantly within its levees, a small fraction of its historic floodplain. The artificial disconnection of the river from its floodplain outside of the levees has exacerbated eutrophication problems in the Gulf of Mexico by limiting the trapping of nitrogen (N) and phosphorus (P) in the river system (Mitsch et al., 2001). In addition, levees have prevented the distribution of sediment across the vast marshes and low swamps of the lower reaches of the Mississippi River Delta contributing to wetland loss (Snedden et al., 2007; Blum and Roberts, 2009; Schaffer et al., 2009).

The Mississippi and Missouri River Floods of 1993 resulted in several levee breaches, spawning numerous propositions for large scale floodplain restoration by levee removal or changing the placement of levees. Models of the effects on nutrient reduction to the Gulf of Mexico were created (Galat et al., 1998; Lane et al., 2003; Mitsch et al., 2009; Opperman et al., 2009). Gergel et al. (2005) modeled different hydrologic scenarios including lakes and leveed rivers as well as natural floodplains. They found that short, frequent floods processed more NO_3 than long infrequent floods. Zhang and Mitsch (2007) found that breaching levees along the Olentangy River, OH resulted in increased deposition of sediment and the associated nutrients. Kroes and Hupp (2010) found that if flood frequency and duration were not affected, frequent levee breaches along the channelized Pocomoke River, MD resulted in

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similar sediment deposition between natural and breached levee reaches. Florsheim and Mount (2002) monitored substantial deposition as sand splays from levee breaches along the Cosumnes River, CA. Kronvang et al. (2009) measured sediment and phosphorous retention along restored portions of the Odense River, Denmark. Wolf et al. (2013) showed that connectivity with streams enhanced nitrogen removal in created wetlands.

The study of the effects of floodplain restoration along smaller streams is fairly common. However, restoration studies along large rivers are not common because the restoration of large floodplain areas is fairly rare as a result of the logistics, cost, and uncertainty of benefits. Mitsch et al. (2001, 2005) have suggested that to reduce nutrient loading to the Gulf of Mexico by 40%, there would need to be approximately 21,000–52,000 km^2 of floodplain restoration.

Along larger rivers the volume of transported sediment is considerably higher, and when flow is restored, much greater masses of sediment and their associated nutrients are transported to the floodplain and potentially deposited. However, because the floodplains of large rivers are often vast, there can be order of magnitude spatial heterogeneity in sediment and nutrient trapping, ranging from meters to less than a millimeter of deposition or erosion.

One common theory of floodplain restoration is that if the hydrology is restored most restoration goals will be met (Junk et al., 1989; Lammens and Marteijn, 1992). Hydrologic restoration can be challenging to assess because the duration of flooding is only one variable that may influence material trapping and does not infer connectivity. For the purposes of this study, connectivity refers to the similarity of physical and chemical properties (suspended sediment and nutrients) of water at a point on the floodplain in relation to the adjacent river water. Perfect connectivity would infer no difference between the properties of the water at the point on the floodplain and the river and is achieved by there being no flow resistance or time lag between the two. As flow resistance increases and physical and chemical processes accumulate over time and space between the points, the water properties become increasingly dissimilar until a particular constituent could be considered disconnected from the source. Flow rates, depth, sediment load, vegetation, distance from the river (via flow path) and numerous other factors interact to affect the volume of water

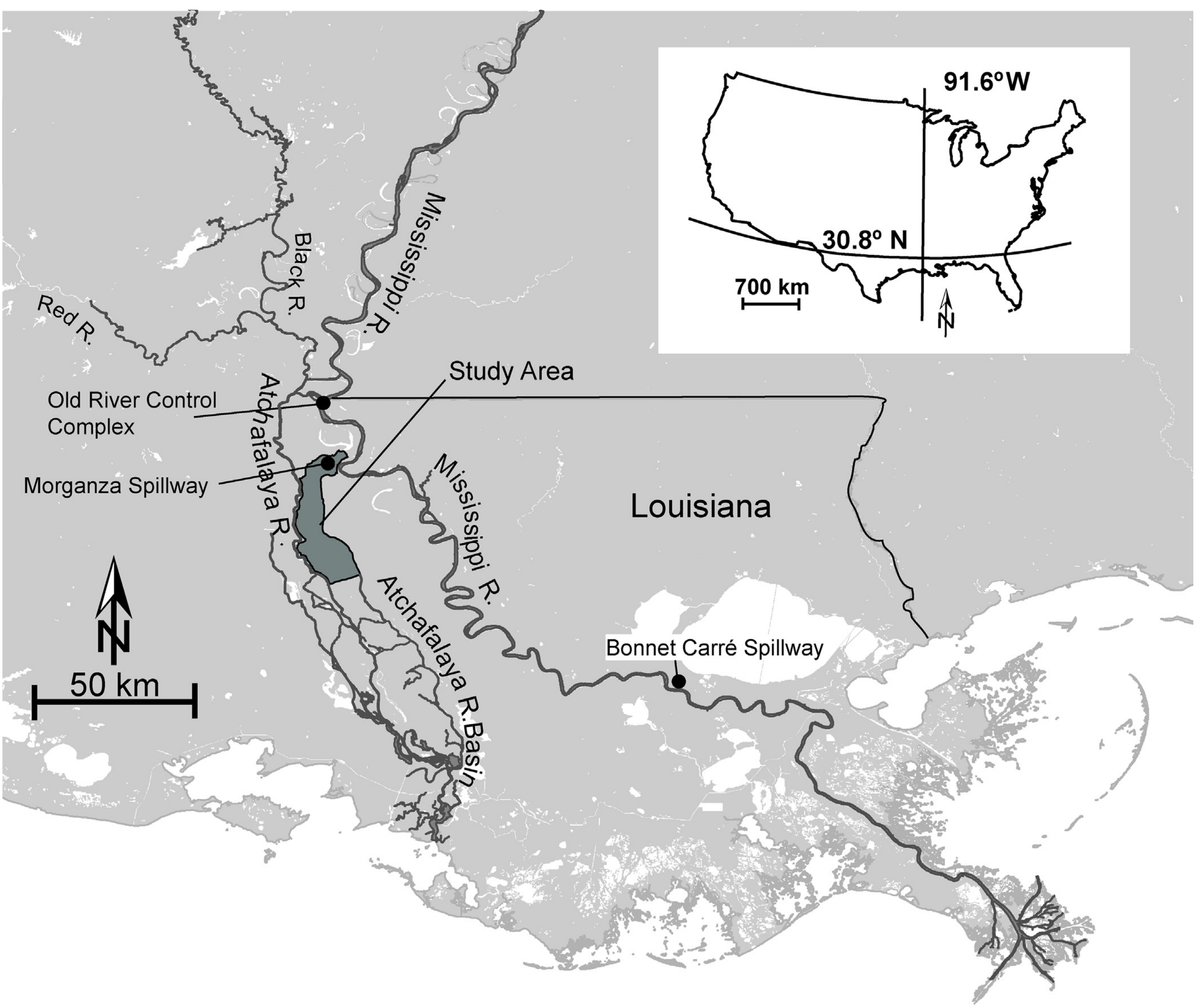

Fig. 1. The study area and locations of constructed diversions. The Old River Control Complex that controls flow from the Mississippi River into the Atchafalaya River is composed of three structures. The Morganza Spillway is an overbank type floodgate located at approximately N 30.8° W 91.6°.

and sediment flowing across the floodplain (Schenk et al., 2012). Studying these systems can be very labor intensive because of the logistics required to measure large scale floodplain and hydrologic processes and the reality that parameters are highly variable over a flood cycle. Sediment and nutrient deposition can be an excellent indicator of hydrologic restoration success because they integrate many of the variables over time and space.

Permanent reconnection of large floodplains to their rivers can have large effects but is difficult and expensive as a result of the sheer scale of altering the levees, ditching, and channel ablation common to farmed land after levee construction. The uncertainty of the magnitude of water quality benefits relative to the expense of restoration limits the implementation of large floodplain restorations. This study investigates mass, particle size, nitrogen (N), phosphorous (P), and carbon (C) content of deposited material as a function of flow distance from the Mississippi and velocity through the Morganza Spillway, a large temporary floodplain reconnection. The patterns of deposition may inform land managers in site selection and levee gap spacing for large river floodplain restoration projects or diversions by clarifying the distance from a water and sediment source where a floodplain becomes disconnected from watershed sourced sediment, diminishing functional returns.

2. Study area

The Atchafalaya River receives all of the flow from the Red River, the Black River, and roughly 25 percent of the Mississippi flow to equal 30 percent of the latitudinal discharge (the total of all Mississippi River Valley rivers at the point of the Old River Control Structure; A. Horowitz, USGS, written communication 2010) as mandated by the U.S. Congress. This ratio is variable during floods that would result in the Mississippi exceeding the design channel capacity (42,000 m^3/s) at Baton Rouge and overtopping its levees (USACE, 1958). The Morganza Spillway is capable of diverting 17,000 m^3/s and is used during floods in conjunction with the Old River Control Complex that controls flow from the Mississippi into the Atchafalaya (Fig. 1). Since its construction in 1954 the Morganza Spillway has only been opened partially in 1973 and 2011; full opening of the structure has not occurred during a flood.

The Morganza Spillway is part of the Atchafalaya River Basin which is located in south central Louisiana and includes the Atchafalaya River and a hydraulically complex system of back

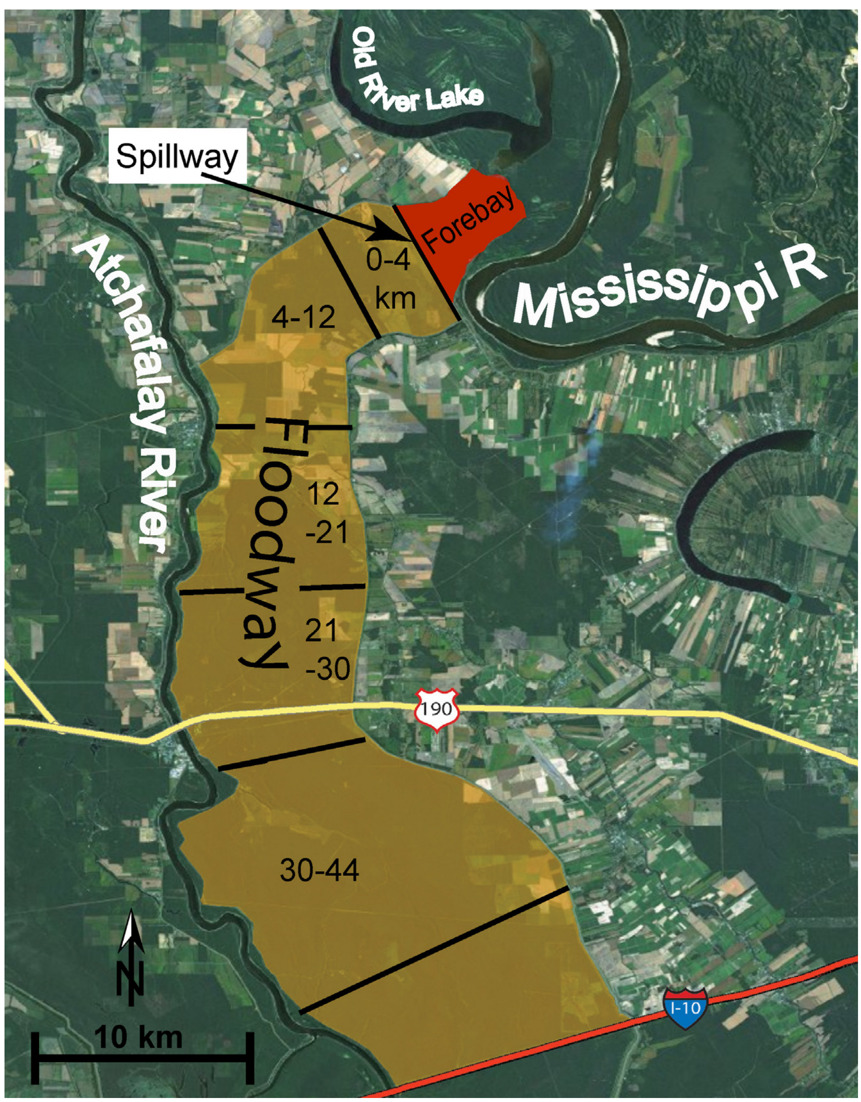

Fig. 2. The location of the study area; the Forebay, Spillway, and the Floodway, distance groups are noted by thick black lines (base map modified from Google Inc., 2013).

swamps, channels, and open water within the Mississippi River Delta. Roughly half (2900 km^2) of the Basin wetlands are located inside a flood control levee system hydraulically dominated by the Atchafalaya (Kroes and Kraemer, 2013). The Basin has a mean annual air temperature of 19.6 °C and a mean annual precipitation of 1.49 m (NCDC, 2013). Rainfall exceeds evapotranspiration estimates by 0.1–0.5 m/yr (Fontenot 2004). Within the levees, the Basin has mean accretion rates of 13.9 mm/yr or 4.3 Tg/yr (1 teragram = 10^{12} grams or 10^6 metric tonnes) (Hupp et al., 2008).

Despite a high mean accretion rate and floodwaters that can be 3 m above the floodplain, large areas of the Basin (>150 km^2) inside the levees are disconnected from the majority of incoming sediment. The range of watershed sourced sediment transported from the few divergent channels to the swamp is limited as a result of high flow resistance and slow water movement in the swamp. Because of the vastness of this swamp almost all of the sediment (>90%) in the water that leaves navigational channels is deposited within the swamp (normally representing about 6% of total Basin discharge; Kroes and Allen personal communication 2011, unpublished data).

The 2011 Mississippi River Flood occurred in late spring following heavy rainfall across the Ohio, White, and Mississippi River Basins (Vining et al., 2013). River stages in the lower Mississippi reached their highest recorded levels, exceeding levels set during the flood of record in 1927. The 1927 discharge was estimated to be 65,000 m^3/s (Clark, 1982). The same discharge was measured during the 2011 flood at Vicksburg, Mississippi (USGS, 2012a). The Bird's Point (Missouri), Bonnet Carré (Louisiana), and the Morganza Floodways were partially opened to prevent the Mississippi from overtopping the levees, which would have resulted in substantial loss of life and property.

Suspended sediment load during the 2011 water year (October 1, 2010–September 30, 2011) was 165 Tg (Mississippi River at Tarbert Landing; USGS, 2014). The 2011 N and P loads were 1.5 Tg (14% particulate) and 0.162 Tg (64% particulate) respectively (Welch and Barnes, 2013). The 2011 N and P load falls within the normal range of nutrients exported to the Gulf of Mexico. During Spillway operation the Mississippi transported 0.265 Tg of N (11% particulate) and 0.028 Tg of P (55% particulate; USGS, 2012c).

The Forebay of the Morganza Spillway is located between the Spillway structure and the Mississippi on the downstream side of a river bend. The structure is approximately 12 km from the river by flow path through an oxbow lake (Fig. 2). The Forebay is hydraulically connected to the Mississippi by overbank flooding. During this flood, the Forebay gained a surficial hydraulic connection to the Mississippi on May 4–5, 2011 and lost the connection on June 14–15, 2011. Water continued to pass through the structure for weeks after the hydraulic connection was lost as water drained from the Forebay.

The width of the Forebay ranges from 3.2 km near the river to 6 km at the Spillway structure. The total length of the Forebay is 6 km and had a maximum water depth of 8.3 m during the 2011 flood. After passing through the Spillway structure, water flowed through the Floodway, 500 km^2 of agricultural fields, bottomland hardwoods, and swamps that comprise the Floodway before combining with water from the Atchafalaya River. The Morganza Spillway hereafter refers to the combined Forebay, Spillway structure (Spillway), and Floodway. The Floodway is bounded on the east by the "East Atchafalaya Basin Protective Levee" and on the west by the "East Atchafalaya River Levee."

The northern two-thirds of the Floodway downstream of the Spillway has only received rainfall, runoff and occasional minor leakage through the Spillway since 1973, whereas the lower one-third of the area receives occasional backwater flooding from the Atchafalaya (USACE gage 03120). Backwater flooding typically does not transport substantial sediment loads. Since 1973 the primary deposited material has been autochthonous leaf litter.

3. Methods

3.1. Discharge and suspended sediment in the Mississippi River and Morganza Spillway

The U.S. Geological Survey's (USGS) National Stream Quality Accounting Network (NASQAN) program collected discharge measurements and water quality samples five times in the Mississippi during the time when the Mississippi and the Forebay were hydraulically connected. Discharge measurements were made using acoustic Doppler velocity profiler (ADCP) hardware and software (Simpson, 2001). During the discharge measurements depth-integrated water samples were collected using the multiple-vertical method (Guy and Norman, 1970). Samples were analyzed for suspended sediment (SS), particulate organic carbon, total N, particulate N, total P, and particulate P (USGS, 2012c).

Daily discharge measurements and depth-integrated samples were taken by the USGS in the Floodway from the US Highway 190 bridge, 28 km downstream of the Spillway. Discharge measurements were made from the bridge using a Price AA meter. Depth-integrated water samples were collected at equal-width increments (USGS, 2006) and analyzed for SS. On May 21, 2011, near maximum Spillway discharge, ADCP measurements were made across a section of field that crossed the Floodway, 8.5 km downstream of the Spillway.

3.2. Water velocity in the Morganza Floodway

Prior to the flood, water level recorders recording at 10-min intervals were placed throughout the Floodway. After the flood, the elevations of the recorders were determined using elevation grade GPS equipment (±20 mm) and optical levels (±1 mm/25 m). The analyzed recorders were located at 0.7, 6.7, 9.9, 20, and 41 km downstream of the Spillway. Manning's equation was used to determine maximum water velocity for each reach, excluding the gate velocity.

$$V = \frac{k}{n}(R)^{2/3}(S)^{1/2}$$

where V = velocity (m/s), k = 1 $m^{(1/3)}/s$, n = Manning's roughness, R = hydraulic radius [area (m^2)/wetted perimeter (m)], and S = slope (m/km). The mean depth was determined from the recorders. Slope was determined by using the peak water elevation and time for each recorder location compared to the same time water level at the next downstream recorder. Manning's roughness ('n') was back calculated to be 0.20 to match the highest water velocity of the USGS flow measurements at Hwy 190 and applied to similarly forested areas after comparison with Arcement and Schneider (1984). Open fields were assumed to have an 'n' of 0.03 (Li and Zhang, 2001). The mixed reach (12–20 km) 'n' was calculated to be 0.13 from the percentage of field to forest.

3.3. Deposition measurement

In a typical, regularly inundated, brown-water river floodplain, every flood pulse (ascending limb of the hydrograph) of water brings a layer of organic material deposition and in many cases is followed by mineral sediment deposition. This layering has been observed to occur up to five times per year in the Basin. Many floodplain studies measure sedimentation on floodplains by placement of marker horizons that are used to periodically measure accretion (Hupp et al., 2008; Kroes and Hupp, 2010). For this study, the marker horizon method was unavailable because of the short forecast time prior to the Spillway opening (14 days). However, a 38-yr leaf pack with very little mineral sediment deposition existed in most areas and was used as a marker horizon to sample new sediment deposited during the 2011 flood (Fig. 3). A total of 51 sites were sampled, stratified by geomorphic setting and access. All sampling sites were located at elevations that exceeded normal flood levels from the Atchafalaya.

Accretion was measured in the field by cutting a plug of sediment with a sharp knife and measuring accretion over the leaf pack. Forested areas where the leaf pack was absent were considered to be erosional. A blanket erosion of −0.5 mm was applied to erosional sites because herbaceous roots were present at the surfaces and indicators of greater erosional amounts, such as eroded tree roots, were absent.

The Forebay was almost entirely an agricultural field and lacked a leaf pack marker horizon. In this situation, areas around trees, fence posts, abandoned machinery, and wetland potholes were cored and measured to the level at which the grass root layer and other dead vegetation was found. All locations were sampled in October and November of 2011, prior to leaf fall. At the time of sampling, the Forebay had not been plowed since before the flood.

3.4. Depositional mass

Sediment cores were collected at a subset of sampling sites for nutrient, bulk density, and sediment particle size analyses simultaneous to accretion and scour holes measurements (four samples Forebay, six Floodway, eight scour-hole). Cores were collected using a 7.5-cm pipe with a sharpened lip. The pipe was sectioned vertically into halves, and the contact between new flood sediment and antecedent leaf pack and sediment was identified. Antecedent sediment had differing chroma, organic content, texture, and oxidized rhizospheres (Fig. 3). New sediment was measured for thickness, dried at 60 °C, and weighed to estimate mass and bulk density of deposited material.

The mass of deposited sediment was calculated for distance groups based on land use and geomorphic setting: the Forebay, 0–4, 4–12, 12–21, 21–30, and 30–44 km downstream of the Spillway (Fig. 2). The Forebay extends 6 km upstream of the Spillway and was primarily agricultural field with few trees. Distance group 0–4 km was primarily forested, 4–12 km was primarily agricultural fields, 12–21 km included the transition from 50% field to 100% forest, 21–30 km was entirely forested, 30–44 km was entirely forested and had an abrupt increase from 6.7 km to 15.4 km in width at approximately 32 km from the Spillway. For each of the six distance groups, the mean bulk density of all samples was applied to the group mean accretion and floodplain area to calculate the mass of sediment deposited during the flood.

The 4–12 km group had some sites that showed minor erosion and a blanket 0.5 mm of erosion was applied for reasons previously discussed. The eroded material was assumed to have a similar bulk density as the deposited material because the observed herbaceous root exposure would have been consistent with the leaf pack and a small mineral component. Erosional sites were compiled with all sites in that group to compute the mean deposition.

3.5. Measurement of scour holes

Scour (plunge) holes developed downstream of every open gate along the Spillway. These holes were surveyed on May 22, 2012. The perimeters of the holes were mapped by walking the edges with a GPS (±3 m). Dimensions of the holes were measured using a laser range finder (±1%). Exposed shelves were surveyed using a rotating laser level (±1 mm/25 m). Water level below ground surface was surveyed. The depths of wadeable holes were directly measured. Holes that were too deep to be waded were measured using a GPS enabled chart plotter SONAR (±60 mm). Depth and edge data were analyzed using GIS software for the scour-hole volumes. The volume of the pre-existing stilling pond downstream of the Spillway was determined from the original stilling pond construction plans (1974) and was subtracted from the total hole volume.

Bulk density samples for the scour hole material were collected by removing the outer 0.3 m of the face of the exposed edges prior to collecting samples of undisturbed material at −0.1 m, −1.2 m, and −4 m below land surface. Mean bulk densities were applied to the volume of scoured material.

3.6. Nutrient analyses

Coarse organic matter was ground with a Wiley mill (Thomas Scientific, Swedesboro, New Jersey, USA); the rest of the sample was ground with a mortar and pestle and passed through a 1-mm sieve. Both fractions of ground sediment were combined and analyzed for total carbon (TC) and total nitrogen (TN) (CHN analyzer; Thermo Electron, Milan, Italy), followed by microwave-assisted acid digestion and measurement of total phosphorus (TP) (ICP-OES; PerkinElmer, Waltham, Massachusetts USA). The mineral content of sediment was measured from loss-on-ignition by combustion at 400 °C for 16 h (Nelson and Sommers, 1996). Freshly deposited tree leaves in hydraulically isolated floodplain swamps were collected from the Basin in February 2013 and analyzed for TC and TN. Suspended sediment and water quality samples were collected by the USGS NASQAN program from the Mississippi at Vicksburg, MS and St. Francisville, LA during the time the River and Forebay were hydraulically connected (USGS, 2012b,c). The C:N of river suspended sediment is reported here (measured as

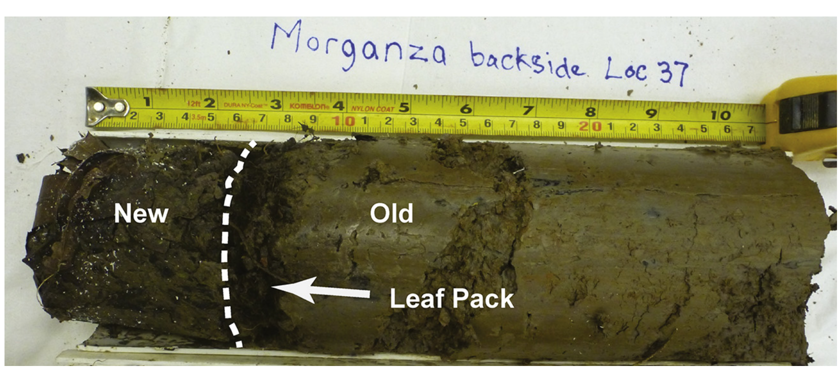

Fig. 3. A picture of a core showing the pre-flood material, the leaf pack, and the deposited material from the 2011 flood. New material is to the left of the dashed line.

particulate organic C and total particulate N) for comparison with deposited sediment and fresh floodplain litter from the Floodway. The mean nutrient content of all samples was determined and applied to the depositional mass of each distance group to determine nutrient deposition.

3.7. Sediment particle size analyses

Sediment particle size was measured using a LISST-100X type A (1.25–250 μm) laser particle size analyzer (Sequoia Scientific, Inc., Bellevue, Washington, USA). A mixture of well-mixed sediment was combusted at 550 °C for 4 h to remove organics and sieved to ≤250 μm. A 0.02 g sample of sieve-passed sediment was added to a solution of 0.5 g NaHMP and 100 mL deionized water, placed in an ultrasonic bath for 5 min, agitated on a shaker table at 100 rpm for 16 h to disaggregate the sediment, and analyzed on the LISST-100X fitted with a stirring chamber. Background noise correction (zscat) was conducted using bubble-less deionized (DI) water, with prior tests indicating no difference in laser scatter between DI and NaHMP solution. There was no volume-to-mass correction. Median particle size (d50) was interpolated from the cumulative size distribution of LISST output. The percentage of clay was identified using the 1.44, 1.68, and 1.97 μm bins, silt using 19 bins from 2.31 through 44.4 μm, and fine sand using the 10 bins from 52.4 through 231 μm bins (Gee and Bauder, 1986; U.S. Department of Agriculture definition), and corrected for the mass of sediment >250-μm (medium sand or larger). The resulting particle size distribution was volume and not mass based.

4. Results

During the 2011 flood operation of the spillway a substantial volume of water was diverted through the Morganza Spillway. A peak discharge of 5500 m^3/s flowed through the Forebay with a mean velocity of 0.21 m/s at the closest point to the river, decreasing to 0.11 m/s in front of the Spillway gates. Water passed through the Spillway for 52 days, with a total volume of 7.6 km^3 and a mean discharge of 205 million m^3/day. There was a surficial hydraulic connection of the Mississippi to the Forebay for 9 days prior to the opening and for 31 days after the opening. The opening represented approximately 14% of the total discharge through the Basin (at Simmesport) and 5.5% of the Mississippi during the Spillway's period of function. Flow through the Morganza equaled 3.3% of the discharge through the Basin and 1.1% of the total Mississippi discharge (at Vicksburg, MS) during the 2011 water year (USGS, 2012a).

The diverted water was measured and sediment samples were collected by the USGS at U.S. Hwy 190. The cross-sectional area of the Floodway at US Hwy. 190 was 24,700 m^2 and had a mean velocity of 0.23 m/s with a maximum velocity of 0.32 m/s at maximum discharge. Daily suspended sediment was 20 mg/L on the first day (May 18, 2011) that flood water reached the point of measurement and decreased to 4 mg/L on June 10, 2011. The mean daily suspended sediment concentration (SSC) in the Floodway at US Highway 190 was 13 mg/L (Fig. 4). The total calculated suspended sediment load passing this sampling point from May 18 to June 10 was 0.106 Tg. During this time period the mean SSC in the Mississippi at St. Francisville was 64 mg/L and ranged from 46 to 72 mg/L. The mean C:N mass ratio of suspended sediment in the Mississippi was 8.7 (range 5.5–12.3; USGS, 2012c).

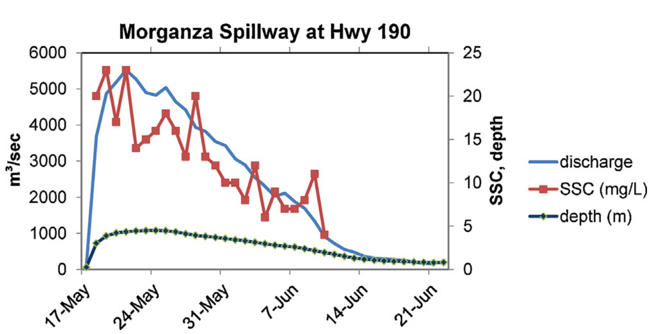

Fig. 4. Discharge, suspended sediment concentration (SSC), and depth of flooding over the Floodway at U.S. Highway 190 during the Flood of 2011. Discharge below 100 m^3/s was not measureable in this cross-section.

4.1. Water slope and velocity in the Spillway

Mean velocity in the Forebay was 0.21 m/s with a depth of 8.3 m. Maximum discharge through the Floodway was 5500 m^3/s. The crest of the flood took 5 days to travel the 41 km between the first and last pressure transducer, indicating that the speed of the flood wave was 0.09 m/s. The calculated maximum velocity of the water varied from 0.64 m/s in the open field (4–12 km) to 0.32 m/s in the dense forest of the 12–21 km reach. The greatest slope during the water peak was 0.25 m/km in the 0–4 km reach, and the lowest slope was 0.015 m/km in the 4–12 km reach (Table 1). ADCP measurements in the 4–12 km reach showed flow preference to the eastern side with a mean velocity of 0.31 m/s (maximum 0.64 m/s). ADCP measurements on the western half of the 4–12 km reach showed a mean flow velocity of 0.17 m/s, reducing to the west, with a mean velocity of 0.07 m/s for the western-most 1 km of the transect.

4.2. Sediment and nutrient deposition and erosion

The greatest mass of total sediment, N, and P deposition was in the Forebay with mean total accretion of 37.8 mm. Sediment accretion decreased toward the Spillway. There was high variability of accretion in the Forebay (Figs. 5 and 6; Table 1).

As water passed through the Spillway it gained velocity and experienced an elevation drop resulting in the creation of 17 scour holes of varying size. The largest scour hole was 490 m × 170 m with a maximum depth of 10 m below land surface. Beyond the scour holes there was no deposition apparent in the fields occupying the first 400 m past the Spillway. Sedimentation began near the edge of the forest at approximately 400 m. The deposition within the first 1 km of the Floodway was composed primarily of small balls (<3 mm) of aggregated clay.

Considerably less sediment accretion occurred on the rest of the Floodway. The 4–12 km reach showed very little accretion with several sites being slightly erosional. Mean accretion in the 12–21 km reach was 1.4 mm (Table 1). The highest accretion in the 12–21 km reach occurred at continuous edge of forest downstream of a field. The only erosional site measured in the 12–21 km reach was located in a narrow strip of forest between two fields where a field extended another 4 km in the downstream direction. In the 21–30 km reach mean accretion was 0.4 mm (Table 1). There were no erosional measurement sites in this reach, but half of the locations showed no accretion. Mean accretion in the 30–44 km reach was 0.6 mm (Table 1). There were no erosional sites and 75% of sites showed accretion. The range of accretion values also had lower variation than in the other groups (Fig. 6).

Four outliers were removed from deposition calculations. Outliers were associated with downvalley channel edges. Measurements were made laterally from the channel edges and typically showed a range of less than 30 m of higher deposition, but these outliers are notable. In the 4–12 km group the outlier was in a small dry channel and had 62 mm of accretion. In the 12–21 km group, the outlier (25 mm) was along a large channel. In the

Table 1
Deposition mass by reach for the Morganza Spillway, eroded mass from behind the Spillway, net deposition, and kg/m^2.

Spillway reach (km)	Flow max. (m/s)	Slope (m/km)	*n*	Area (km^2)	Accr. (mm)	Depo. (Tg)	N depo. (10^{-4} Tg)	P depo. (10^{-4} Tg)	C depo. (10^{-4} Tg)
Forebay	0.21[a]	--	--	19	37.8	0.489	14.2	3.57	155
0-4	0.48[c]	0.25	0.2	22	23.4	0.371	10.8	2.71	118
04-12	0.64[c]	0.015	0.03	58	0.1	0.00329	0.1	0.02	1.05
12-21	0.32[c]	0.07	0.13	78	1.4	0.0753	2.18	0.55	24
21-30	0.34[b]	0.17	0.2	79	0.4	0.0231	0.67	0.17	7.35
30-44	0.32[c]	0.22	0.2	161	0.6	0.0668	1.93	0.49	21.2
Total				417	3.5	1.03	30	7.5	327
Scour				0.07	NA	−0.259	−4.03	−2.14	−30.4
Net depo.						0.77	26	5.36	297
Total depo (g/m^2)						2470	7.19	1.8	78.4
Net depo. (g/m^2)						1850	6.23	1.28	71.2

Accr, accretion; Depo, deposition, *n*, Manning's *n*; --, not measured; NA, not applicable.
[a] Calculated from cross-section and discharge through Floodway.
[b] Measured flow rate.
[c] Calculated using Manning's equation.

21–30 km group the outlier site (14 mm) was located along a road that went down the Floodway from a where a channel that ran 20° off of parallel to the valley changed angle to 60° off of parallel to the Floodway flow. In the 30–44 km group, the two outliers (7 and 6 mm) occurred on the south side of a large channel that had an orientation 35° off of parallel to the Floodway flow.

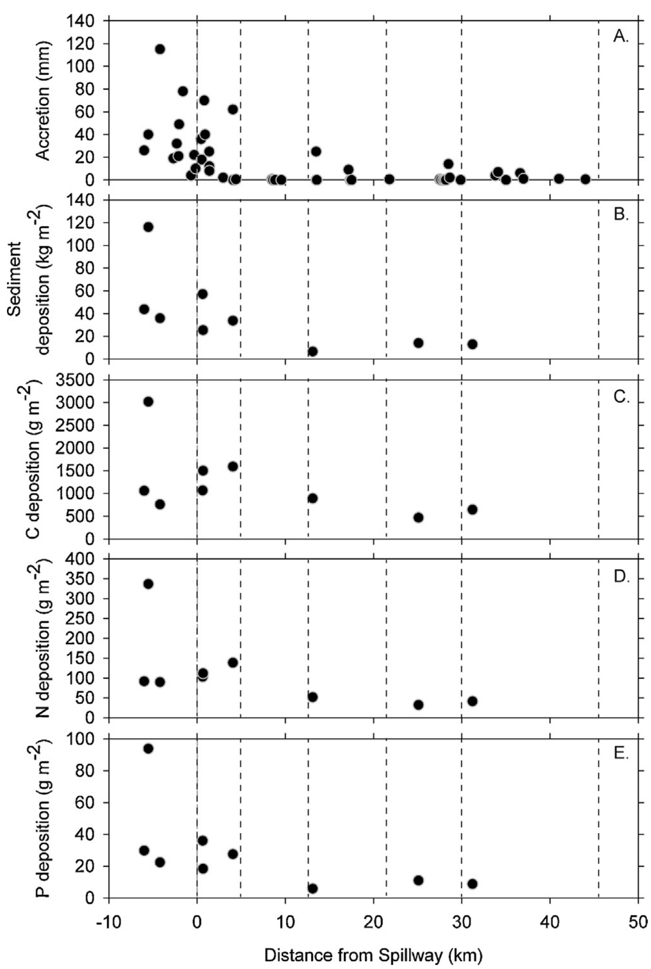

Fig. 5. Graphs of mm of accretion (A), mass of sediment deposition per m^2 (B), carbon (C), nitrogen (D), and phosphorous (E), as a function of distance from the Spillway; the start of the Forebay (−6 km) to the last sampling location. Distance groups are noted by dashed lines.

4.3. Total deposition and erosion

The floodplain of the Morganza Spillway trapped 1.03 Tg of sediment during the 2011 operation of the Spillway and 0.259 Tg was eroded from scour holes. Because the scour holes became a source of sediment the mass of erosion should be subtracted from the total deposition resulting in net deposition of 0.77 Tg. Deposited material included 30×10^{-4} Tg of N, 7.5×10^{-4} Tg of P, and 327×10^{-4} Tg of C. Nutrients eroded from the hole included 0.403×10^{-4} Tg of N, 0.214×10^{-4} Tg of P, and 30.4×10^{-4} Tg of C (Table 1). If this deposition were evenly distributed over the Morganza Spillway it would have resulted in a mean sediment accretion of 3.4 mm.

4.4. Sediment particle size

The d50 of deposited sediment decreased in an exponential pattern with distance relative to the Spillway ($y = 6.4$ exp. -0.11 distance, $R^2 = 0.62$, where y is in μm and distance is in km; Fig. 7). Median diameters ranged from 13 μm at the start of the Forebay to 1.5 μm at 14 km down the Floodway. LISST analyses of the deposition samples showed composition of 16% fine sand (50–250 μm), 57% silt (2–50 μm), and 27% clay (<2 μm). LISST analyses of the scour-hole samples showed composition of 9% fine sand, 55% silt, and 36% clay and a d50 of 2.7 μm.

Samples were collected adjacent to the outlier samples described above at 28 and 35 km. The d50s of these samples were 14 μm (near Bayou Latanache) and 5.2 μm (near Bayou Alabama; Fig. 6). The larger d50 of these samples indicate that at least some channel scour occurred, although we make no estimate of how much scour beyond the raw outlier measurements.

4.5. Nutrient deposition

The C and N concentration in deposited sediment increased with distance relative to the Spillway, whereas P concentration did not. Total C and N were lower in the Forebay and proximal to the Spillway and increased down the Floodway. The mean C and N content of the scour holes downstream of the Spillway were two to three times lower in concentration than the deposited sediment. Sediment chemistry from the scour hole was more similar to the sediment deposited in reaches closer to the Spillway than farther down the Floodway.

The C:N ratio of deposited sediment increased linearly with distance from the Mississippi ($y = 0.75 \times$ distance $+ 8.0$, $R^2 = 0.60$, $p = 0.008$, where y is the C:N ratio and distance is in km; Fig. 8). In the Forebay and immediately downstream of the Spillway

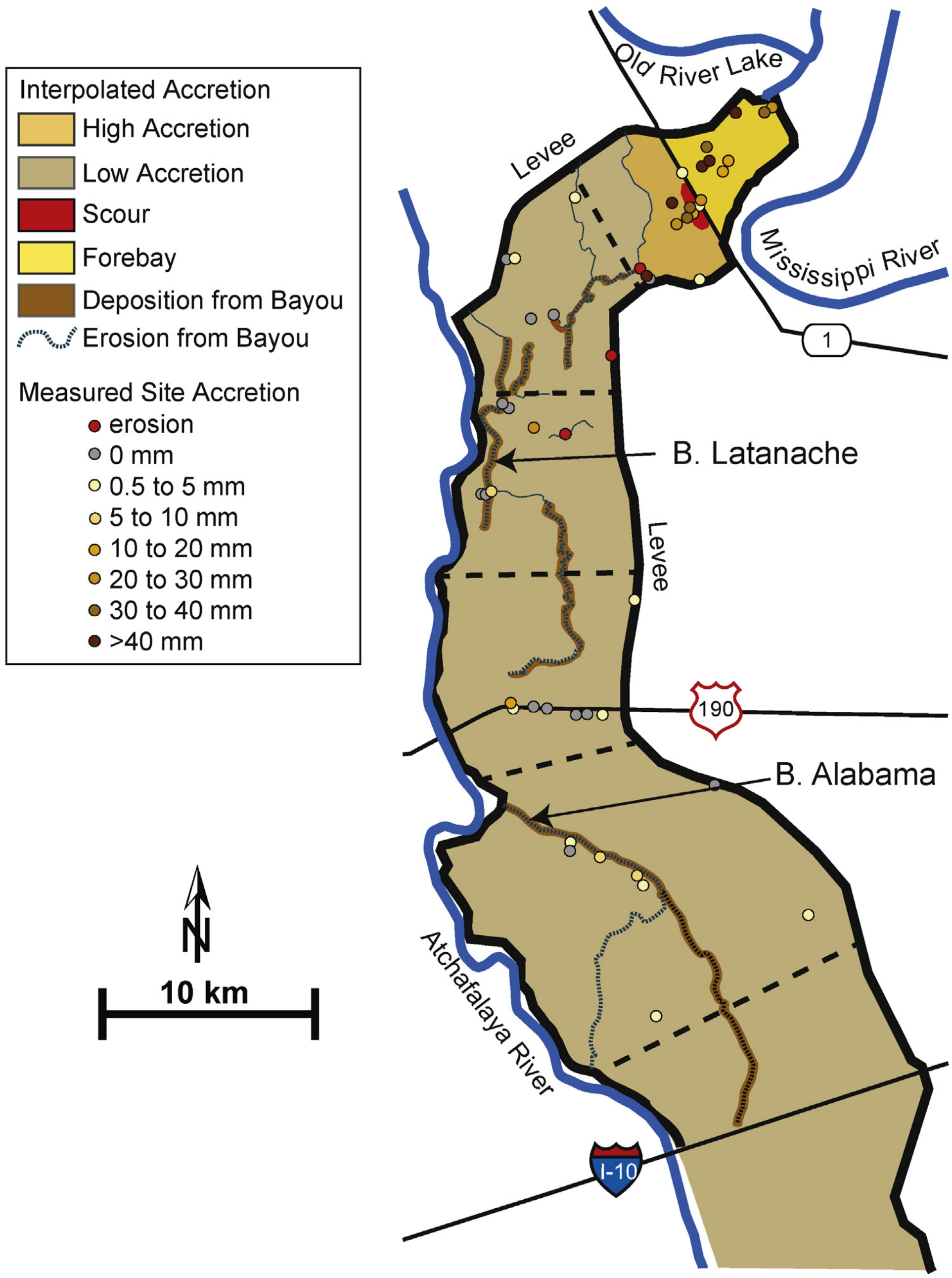

Fig. 6. Sampling locations and accretion amounts. Interpolated accretion and probable stream scour reaches are indicated. Dashed lines indicate distance groups.

(0–4 km), C:N ratio of deposited sediment was comparable to that of suspended sediment in the Mississippi main channel near St. Francisville (USGS, 2012c). In contrast, scour hole sediment C:N ratio was lower than that of deposited sediment. Farther down the Floodway, from 12–30 km, the C:N ratio of deposited sediment increased to values between that of Mississippi sediment and floodplain tree leaf fall (Fig. 8).

Nutrient deposition decreased with distance down the Floodway. Deposition of sediment, C, N, and P deposition had similar longitudinal trends, suggesting that gradients in nutrient accumulation were more influenced by spatial variability in sediment deposition rather than nutrient concentration (Fig. 5). The mean depositional masses on the Morganza Spillway from the 2011 flood were 2.47 kg-sediment/m^2, 78.4 g-C/m^2, 7.19 g-N/m^2, and 1.8 g-P/m^2.

5. Discussion

The opening of the Spillway during the 2011 Mississippi River Flood resulted in an influx of sediment and associated nutrients that, per area of floodplain, was higher than for most floodplains and resulted in a much greater depositional mass than annual deposition mass in other floodplains (Craft and Casey, 2000; He and Walling, 1996; Noe and Hupp, 2009; Hupp et al., 2013; Wolf et al., 2013; but see Steiger and Gurnell, 2003). For comparison, the depositional mass on the Morganza Spillway was more than twice the annual floodplain deposition of the lower Roanoke River, the largest floodplain on the U.S. East Coast (Hupp et al., 2015). Deposition on the Morganza Spillway during the 2011 flood was less than annual trapping in the Basin as a result of the much larger area of the Atchafalaya floodplain and as a result of several large

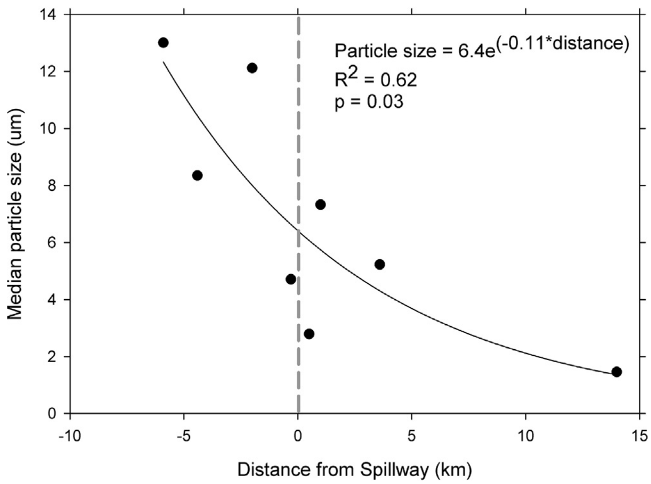

Fig. 7. Median sample particle size as a function of distance from the Spillway.

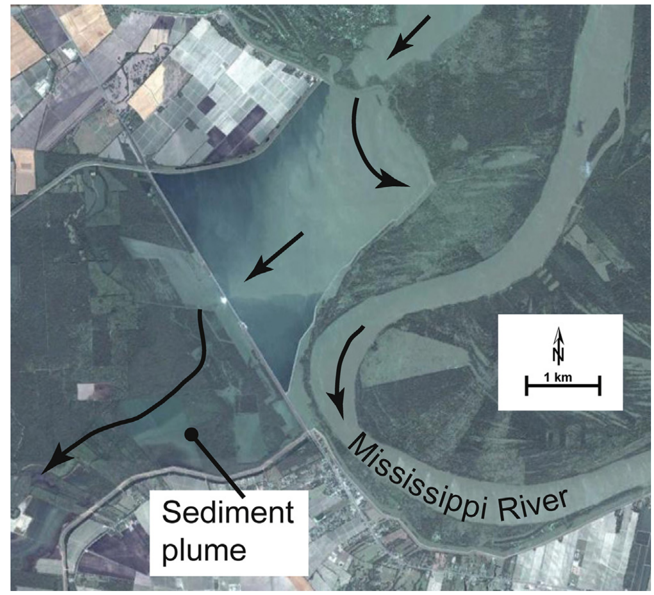

Fig. 9. Aerial photograph taken during the first day of the Spillway opening showing sediment plumes in the dominant flow paths. Date of imagery May 14, 2011 (base map modified from Google Inc., 2013).

distributary channels and a much longer hydroperiod with typically higher SSC (Hupp et al., 2008).

If the SSC of the Mississippi River at Vicksburg, Mississippi was maintained into the Morganza Spillway and only the flow that passed through the structure were considered, this would equate to a maximum 0.70 Tg of sediment. The net deposition on the Morganza Spillway was 0.77 Tg, 63% (0.49 Tg) was deposited in the Forebay. The high accretion in the Forebay was partially a result of its location and flow patterns. The Forebay is located on the inside of a river bend. When Mississippi flood water reached the elevation of the Forebay lip, it began to circulate through the Forebay. In aerial photography this can be seen on May 14, 2011 (Fig. 9) where water from the oxbow lake enters the Forebay and arcs back toward the river. In this pattern, much more sediment laden water crossed the Forebay than the 7.3 km^3 that went through the Spillway.

There were few locations farther than 4 km downstream of the Spillway that had accretion greater than 10 mm (Fig. 5). Clay ball deposition indicates that some scour-hole material was deposited within 2 km thus increasing the deposition amounts in that area.

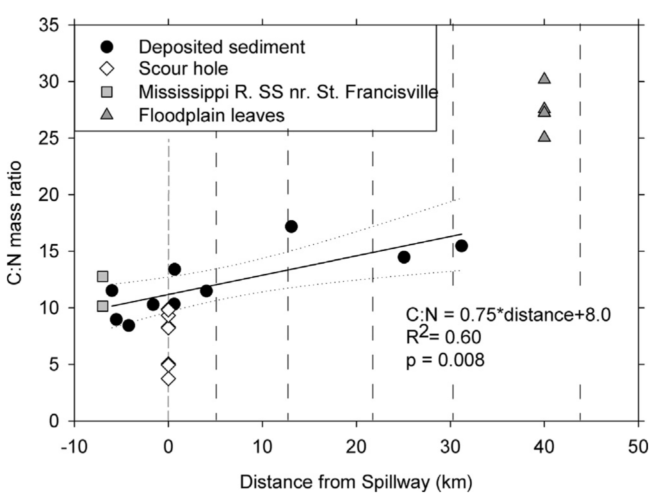

Fig. 8. The ratio of TC to TN in newly deposited sediment, suspended sediment in the Mississippi River during flooding, and senesced leaves of floodplain trees. Distance groups are noted by dashed lines. Dotted lines indicate 95% confidence interval (SigmaPlot 11.0, Systat Software Inc., San Jose, CA).

Suspended sediment concentrations during the Mississippi River Flood of 2011 (<150 mg/L) were lower than during normal high water flows (>300 mg/L; USGS, 2012a). With higher sediment loads and the same flow rate it would be reasonable to infer that accretion would be greater with a similar pattern of deposition.

There were no measurements of the SSC in the water entering the Forebay or what went through the Spillway, but by the time flood water traveled from the river, through the Spillway and reached the cross-section of flow measurement and suspended sediment collection, (U.S. Highway 190 bridge, 28 km down Floodway), the concentration of suspended sediment had decreased by 83%. Of the 0.106 Tg of suspended sediment that passed Hwy 190, 63% was deposited in the 30–44 km reach. This percentage would leave a mean SSC of approximately 3–10 mg/L in the water leaving the Floodway, and is consistent with downstream samples collected by Kroes (USGS) (Carlson et al., 2011). It is reasonable to infer that almost all of the sediment that passed through the Spillway structure was deposited on the Floodway.

The particulate percentage of the TP load (55%) was five times higher than the TN load (11%) resulting in a suspended particulate N:P mass ratio of 2.3. Of the Mississippi TN and TP during the 31 days following the opening of the Spillway, 0.94% of TN and 1.97% of the TP load was trapped on the Morganza Spillway. The Morganza Spillway trapped 0.17% TN and 0.33% TP load of the 2011 annual Mississippi load. The N:P ratio of the deposited sediment was 4.9, indicating enrichment from an autochthonous source of N, likely leaf redistribution on the floodplain. Nitrogen trapping associated with deposition on the Morganza Spillway was twice that of nitrate removal rates in both small and large scale floodplain diversions (Mitsch et al., 2005). Although N and P trapping associated with deposition does not represent permanent removal of nutrients from rivers, it does decrease downstream loading to sensitive waters for time scales relevant to ecosystem management (Noe and Hupp, 2009).

Despite the large amount of erosion near the Spillway (0.259 Tg), it does not appear that the material from the scour holes was a major component of the downstream deposited material. The C:N ratios in the samples of deposited material in the

0–4 km reach were 10.3 (similar to river values) whereas the mean ratio of material from the scour hole material was 7.4. It is unlikely that the eroded sediment could have gained enough carbon in that distance to match the deposited sediment's ratio. Sediment on the Spillway had increasing C:N ratios with distance, indicating that the deposited material was a mixture of Mississippi River sediment and entrained leaf litter or organic material from the Floodway (Fig. 8). It is likely that there was some organic material exported from the Spillway into the Basin.

Flow reached a velocity of 0.64 m/s in the reach of Floodway that was mostly agricultural fields (4–12 km). The water velocity in this reach resulted in minor erosion, but was not sufficient to break the herbaceous root layer. ADCP measurements in the reach indicate that flow was not evenly distributed across the Floodway. The flow disparity was reflected in erosional and depositional patterns (Fig. 6). Erosion was observed on the eastern side, while most locations on the western side showed no deposition and no disruption of the leaf pack. This indicates a flow preference to the eastern side which had nearly continuous agricultural fields in this reach. Observers and aerial imagery confirm this flow pattern (Fig. 9). Water that went to the west side appears from aerial imagery to be low in mineral sediment (black water). This indicates that even though large volumes of water were moving through the Spillway, discharge and the associated sediment showed flow preference to the dispersed fields of the south side of the 0–4 km reach. This flow preference translated to flow preference in the 4–12 km reach and was likely strengthened by the longer down-valley fields along the eastern side of the reach.

In the 12–21 km reach, an increase in deposition was observed (1.4 mm). This reach had reduced water velocity and lower turbulence as a result of increased forest vegetation (Nepf, 1999). The drop in velocity and the erosion of sediment from the 4–12 km reach probably contributed to increased deposition in the 12–21 km reach. In the 12–21 km reach stream channels in the Floodway began to show increased accretion with larger particle sizes near the banks. This pattern of scour and accretion appears to have occurred primarily along channels that were parallel with the flow direction in the Floodway. The 21–30 km reach had low accretion (0.4 mm). However, the leaf pack was intact in all locations and showed no signs of erosion. Increased accretion along parallel, open stream channels indicates that during the initial surge of water, these channels may have experienced water flow rates that resulted in channel scour (Fig. 6). The discharge and sediment sampling teams measured fairly consistent flow rates across the Floodway at Hwy 190 and water samples indicate that SSCs were consistent across the wetted width which would not be consistent with channel scour. However, measurements were not made during the initial flush of water.

5.1. Implications for large restorations

The operation of the Morganza Spillway has offered an opportunity to study floodplain restorations in grand scale. The scale of this temporary floodplain restoration allowed us to explore the maximum depositional effect of a single, temporary hydraulic input. The volume of water moved by this flood diversion was much greater than any that has been proposed for the sole purpose of wetland restoration with depths exceeding 7 m.

Despite the large volume of flow and sediment, 86% of total deposition occurred in the 6 km of the Forebay and within the first 4 km downstream of the Spillway. Beyond this distance, accretion was minor except in proximity to downstream oriented channels and the zone of depositional influence from those channels was limited. Erosional patterns in the 4–12 km reach indicated preferential flow to the lower resistance fields of the eastern side of the Floodway (Fig. 9). Within the first day of opening, water that went to the west side appears from aerial imagery to be low in mineral sediment (black water). These observations indicate that once water was in the forested, high flow resistance areas there was little intermixing between the higher SSC water and the low SSC water that was in place, functionally equivalent to the self-sharpening jet described by Falcini et al. (2013), and similar to perirheic zone of swamps that have standing water present prior to floods (Mertes, 1997; Kroes et al., 2007). However, this floodplain did not have standing water, was in a local drought prior to and during the flood, and no significant groundwater leakage from the river has been observed into the Floodway.

The majority of sediment was very fine sediment (13 μm at the start of the forebay to 1.5 μm). The slowest water velocity (if only the water passing through the Spillway is considered) was in the Forebay (0.21 m/s) and the majority of sediment was deposited there. Deposition occurred in the 0–4 reach where the calculated maximum velocity was 0.48 m/s. Flow rates of 0.64 m/s showed minor erosion and if that rate were maintained for a longer time would likely have resulted in substantial erosion or channel formation since the Floodway's base material is fine silt and clay. All other segments had lower flow velocities ($\leq$0.34) but received low deposition, indicating that the sediment that remained in suspension was very fine and required very low water velocities and turbulence for deposition to occur.

6. Conclusions

The effective trapping of sediment and nutrients by the Morganza Spillway floodplain during the flood illustrates the effectiveness of floodplain reconnection as a management technique to improve water quality. Although caution is required when interpreting the results from a single, infrequent flood, the findings of this study suggest that floodplain spillways that increase connectivity to the Mississippi River could effectively reduce nutrient loading to eutrophied coastal ecosystems and the northern Gulf of Mexico. The mass of sediment deposited during the period of the Morganza Spillway flow was substantial, but likely less than if SSC were at the recent "normal" high water concentrations.

Reduction in the delivery of nutrients to eutrophied waters is often a goal of restoration and reconnection of floodplains. If the results of the nutrient deposition from this Spillway opening were extended to a reduction of Mississippi River particulate N load of 40% as suggested by Mitsch et al. (2001, 2005) it would require 34,000 km^2 of restoration / reconnection. Although numerous other dissolved nutrient transformations and uptakes occurred (Scott et al., 2014), it is evident from the results that the particulate nutrient and sediment trapping ability of the Morganza Spillway was limited because suspended sediment was quickly deposited along the flow path and not refreshed by incremental water exchanges between the Atchafalaya River (the western boundary) and the Floodway. Rather, there was one source of water with a particulate nutrient and sediment supply that was rather quickly depleted. If the Spillway was a restoration project, the nutrient and sediment trapping potential would be improved by creating additional points of hydraulic connection with the River, allowing sediment starved water to leave the floodplain and sediment rich water to enter. Simply adding more water at the same location would increase deposition mass, but would likely not result in a more equitable distribution of deposited materials.

Because of the vastness of large river floodplains it is unrealistic to expect hydraulically distal areas to have large depositional mass (per m^2) because of poor hydraulic connectivity with sediment rich water. In restorations that act as distributaries with a single input of river water, like the lower Mississippi River diversions, this study indicates that there is a limited spatial range of depositional effect even with large discharge and fine sediment.

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2015.04.056.

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