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Human-induced stream channel abandonment/capture and filling of floodplain channels within the Atchafalaya River Basin, Louisiana

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ABSTRACT

The Atchafalaya River Basin is a distributary system of the Mississippi River containing the largest riparian area in the lower Mississippi River Valley and the largest remaining forested bottomland in North America. Reductions in the area of open water in the Atchafalaya have been occurring over the last 100 years, and many historical waterways are increasingly filled by sediment. This study examines two cases of swamp channels (<85 m^3/s) that are filling and becoming unnavigable as a result of high sediment loads and slow water velocities. The water velocities in natural bayous are further reduced because of flow capture by channels constructed for access. Bathymetry, flow, suspended sediment, deposited bottom-material, isotopes, and photointerpretation were used to characterize the channel fill. On average, water flowing through these two channels lost 23% of the suspended sediment load in the studied reaches. Along one of the studied reaches, two constructed access channels diverted significant flow out of the primary channel and into the adjacent swamp. Immediately downstream of each of the two access channels, the cross-sectional area of the studied channel was reduced. Isotopic analyses of bottom-material cores indicate that bed filling has been rapid and occurred after detectable levels of Cesium-137 were no longer being deposited. Interpretation of aerial photography indicates that water is bypassing the primary channels in favor of the more hydraulically efficient access channels, resulting in low or no-velocity flow conditions in the primary channel. These swamp channel conditions are typical in the Atchafalaya River Basin where relict large channel dimensions result in flow velocities that are normally too low to carry fine-grained sediment. Constructed channels increase the rate of natural channel avulsion and abandonment as a result of flow capture.

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1. Introduction

Intentional flow redirection and channelization have been a component of floodplains since humanity began irrigating crops and draining land for farming in floodplains. Remote and vast swamps and marshes were typically unaffected by channelization until the advent of excavation machinery (Kroes and Hupp, 2010; Schenk et al., 2011). Canals were dug to float timber out of high value stands in swamps like the Atchafalaya River Basin that were too wet to be drained or for railways to be installed. In the twentieth century, where reserves of oil and gas were discovered in deep swamps, exploration and development of that resource resulted in the excavation of numerous canals that were large enough to barge in drilling equipment. Pipeline canals were dug to move products into and out of the swamps as well as across rivers. Although smaller examples of unintentional flow redistribution exist in many locations, numerous large-scale unintentional, natural-channel abandonment resulting from access canals can be seen in aerial imagery (Google Inc., 2013) with the greatest density in the Atchafalaya River Basin, USA. Globally, aerial imagery appears to show this type of channel abandonment to a lesser degree in the wetlands of Centla and Terminos, Mexico, and the Niger River delta, Nigeria.

The Atchafalaya River Basin (hereafter the Basin) lies entirely within the Coastal Plain physiographic province (Hunt, 1967) and is the largest remaining forested wetland in the United States with an area of about 5700 km^2. This floodplain is typically inundated for several months annually. Sediment accretion rates on these floodplains could be among the highest of any physiographic province in the U.S. (Hupp, 2000). In 1927, the Mississippi River (hereafter Mississippi) experienced its flood of record and caused the cross-sectional area of the Atchafalaya River (hereafter Atchafalaya) to increase, resulting in its capturing greater amounts of flow from the Mississippi. The percentage of flow going down the Atchafalaya

Abbreviations: GIWW, Gulf Intracoastal Water Way; BP, Big Bayou Pigeon; P, Bayou Postillion; D2RB, Distributary 2 Right Bank; D3RB, Distributary 3 Right Bank; BLR, Atchafalaya River at Butte La Rose gage.

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continued to increase, and in 1963 the Old River Control Structure was completed in order to control the flow leaving the Mississippi into the Atchafalaya (Barry, 1997; Reuss, 2004).

Prior to 1850, the Basin existed as a back swamp of the Mississippi located between the Teche and the St. Bernard delta lobes (Kolb and Van Lopik, 1958). As such, the Basin had limited connection to the Mississippi and only received significant sediment during large floods of the Mississippi (Frazier, 1967). Because of this isolation from sediment, the Basin contained ~10% of its area as open water. After 1850, the Basin was permanently connected to the Mississippi and has experienced substantial amounts of sediment deposition leading to the filling of numerous channels (bayous), lakes, and backswamp areas within the last 80 years (Roberts et al., 1980; Tye and Coleman, 1989; McManus, 2002). Between the late 1800s to the mid-1950s, open water area decreased from 490 to 290 km^2; and from the 1950s until 2010, open water decreased from 290 km^2 to 190 km^2 (Hale et al., 1999; Y.C. Allen, U.S. Army Corp of Engineers, written communication, 2010). Much of this loss was from channels that accessed areas of historic, recreational, and economic significance. As upstream channels and floodplains filled and became hydraulically abandoned or isolated, sediment deposits begin to fill areas farther south where the Basin is subjected to prograding delta processes (Tye and Coleman, 1989). Water flow and sediment delivery in these swamps have been heavily modified by the construction of channels to enable movement of materials and people. Although it is largely unknown what the flow patterns could have been historically, the floodplain currently (2013) experiences flow reversals in many channels and across the floodplain, large areas of near-zero water velocities, and water with high sediment concentrations entering open water areas and deep swamps.

The hydrologic cycle on riparian floodplains has four phases: rising, peak, falling, and low-water. During the rising phase, the hydraulic gradient extends from the river to the floodplain, and water with high sediment content and typically a higher flow velocity enters the floodplain laterally. Once the floodplain and the river waters reach the same elevation, a peak phase occurs where flow is no longer lateral but downstream. If the river stage is above bankfull during peak phase, water could be exchanged bilaterally between the floodplain and the river channel as the channel crosses the river valley. During the falling phase, the hydraulic gradient extends from the floodplain toward the river. Water velocities are slow, and sediment concentrations are low. In a vast floodplain swamp like the Basin, water leaving the swamp could have sediment concentrations <10 mg/l. The floodplain is often dry during low-water phase, although local ponding could occur. Rainwater could also create flows that drain toward the river with low mineral sediment concentrations and high concentrations of dissolved organic material.

In the twentieth century, numerous large channels were constructed in the Basin to access oil and gas and for pipelines. These constructed channels likely changed the hydrologic patterns of the Basin and contributed to the abandonment of natural channels and the filling of deepwater habitats. These extra, constructed channels have contributed to a situation where the amount of water and sediment moving through the area does not have the flow velocity necessary to keep sediments in suspension and maintain the cross-sectional area of channels. This could have contributed to the abandonment and filling of swamp channels (natural channel branches of an anastomosing river system that go through a swamp forest). These channels are neither true distributaries nor tributaries to the main river because all flows come from and go back into the primary channel, often through discontinuous channels. The primary channel is the main channel of flow that other channels converge into or diverge from.

Channel avulsion (rapid whole-channel change) and abandonment (slower changing of channels where one channel expands and another constricts and becomes blocked) are relatively common occurrences in stream systems that have high sediment loads. The bulk of research on this topic has been conducted in braided, arid systems (Field, 2001; Ashworth et al., 2004), in humid systems in relation to channelization (Pierce and King, 2007; Hupp et al., 2009; Kroes and Hupp, 2010), and the Mississippi River oxbow lakes (Rowland et al., 2005).

1.1. Study sites

During 1984–2007, the Atchafalaya received on average 35% of the sediment and 25% of the discharge of the Mississippi (Arthur Horowitz, U.S. Geological Survey, written communication, 2010) as well as the entire flow of the Red and Black Rivers, in effect providing for the largest, although indeterminate, watershed in the United States. The Basin traps 4.3 billion kg of sediment annually, of which ~10% is organic material and thus a globally important carbon sink (Hupp et al., 2008). Deltas forming in the Basin and at the two Atchafalaya outlets to the Gulf of Mexico are the primary locations of land growth along the eroding and subsiding coastline of Louisiana (Couvillion et al., 2011). The average annual air temperature in the Basin is 20.1 °C and has an average annual precipitation of 1.56 m (U.S. Climate Data, 2013). The average discharge of the Atchafalaya from 1984 to 2011 was 6500 m^3/s measured by the U.S. Army Corps of Engineers gage (03045) at Simmesport, LA (U.S. Army Corp of Engineers, USACE, 2013).

Two typical examples of the channel filling that occurs in this area of the Basin are Big Bayou Pigeon and Bayou Postillion (Fig. 1). These two bayous were chosen to determine whether commonalities exist between two seemingly unrelated channels. They differ in orientation, flow patterns, cross section, and the area of swamp drained or filled; however, both of these channels demonstrate the effect of flow capture by access canals that have greater hydraulic efficiency than the natural channels and facilitate sediment deposition conditions associated with the prograding delta front. The 170-km^2 Bayou Pigeon/Postillion area contains ~2 km of dredged, constructed channels (>30 m in width) for every 1 km of natural channel (>30 m in width) (Google Inc., 2013). Bayou Postillion has filled, been abandoned, been dredged open, and has started to fill again; the same fate is likely in the near future for Big Bayou Pigeon as well.

Bayou Pigeon directly connects to the Gulf Intracoastal Water Way (GIWW), the primary conduit of water and sediment to the east side of the Basin. Big Bayou Pigeon diverges from Bayou Pigeon 5 km downstream of the GIWW. Bayou Pigeon continues past the divergence as Little Bayou Pigeon (Fig. 2). Normally all of these bayous flow away from the GIWW. In the Big Bayou Pigeon study reach, two access canals were excavated (30–50 m in width, 2–3 m in depth). The upstream access canal (D2RB) was begun prior to 1968 and was finished prior to 1978 (USGS, 1969, 1980). The next access canal in the reach (D3RB; Fig. 2) was excavated between 1968 and 1978. Vegetation along the channel of Big Bayou Pigeon shows that the bayou has been decreasing in width and depth for at least 20 years. As the channel narrowed and sediment was deposited on the channel edges, the pioneer species willow (*Salix nigra*) and cocklebur (*Xanthus* sp.) became established along its banks in cohort bands as the channel narrowed. At the time of study in 2010, the oldest cohort of willow was18–20 years old, and beaver suppressed the channel edge saplings for an indeterminate amount of time. As willow and cocklebur become established on banks and bars, they increase the resistance of flow in the primary channel (McKenney et al., 1995) and increase the relative hydraulic efficiency of the access channels. Over the last 10 years (2002–2012), navigation in the upstream portions of Big Bayou Pigeon during mid- to low-river stages has become limited to boats requiring <0.3 m of depth. The smallest cross section of Big Bayou Pigeon exists just downstream of D3RB (4 m^2). This appears to be the location of an imminent channel plug and abandonment.

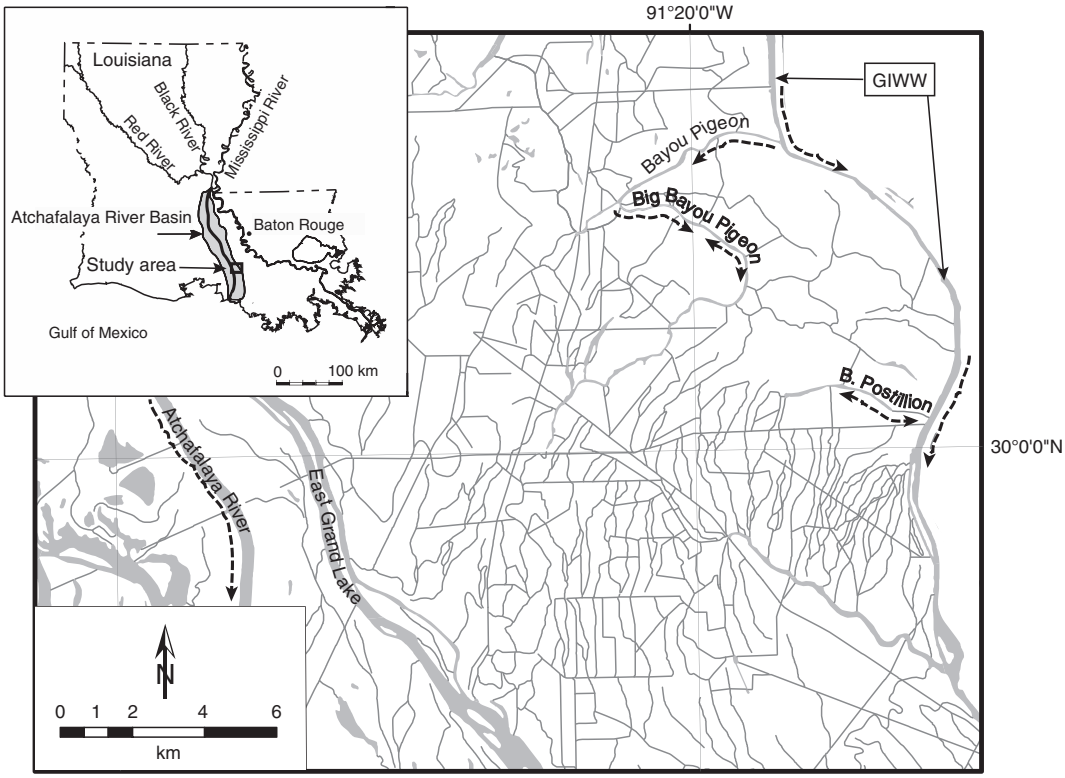

Fig. 1. Location of the Big Bayou Pigeon and Bayou (B.) Postillion study reaches in the Atchafalaya River Basin, Louisiana. Dashed arrows indicate observed flow directions. Straight lines on the map typically are constructed channels although many modified channels are not straight. GIWW = Gulf Intracoastal Waterway.

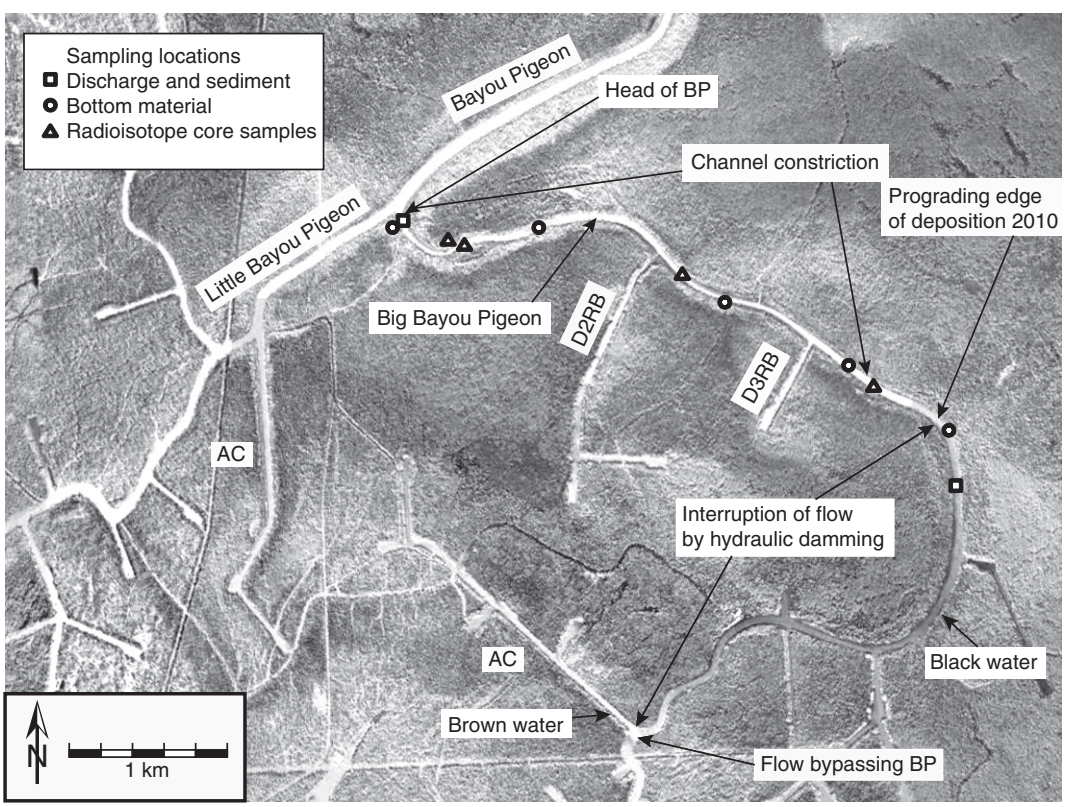

Fig. 2. Sampling locations in the Big Bayou Pigeon (BP) study reach, Atchafalaya River Basin, LA. Major constructed distributaries are identified: D2RB (distributary 2 right bank) and D3RB (distributary 3 right bank). Interruption of flow can be seen by black water bracketed by lighter, brown turbid water coming from BP and the access channels (AC) resulting in hydraulic damming. Imagery date 6 Feb. 2004.
Base map modified from Google Inc., 2013.

Channel widths that existed prior to the current filling (although very shallow) could be observed about 4 km from the top of the study reach as delimited by rows of large, channel-edge bald cypress (*Taxodium distichum*). The historic cross section (55 m^2, depth x width) exists downstream of the prograding sediment deposits. This study reach was 5 km in length and flowed to the southwest. The channel varied in width from 30 m at the upstream end of the reach to 70 m at the downstream end and varied from 0.5 to 2 m in depth from the top of bank. This reach was chosen to examine how access canals affect flow patterns and in-channel sediment deposition.

In the mid-1970s, access canals (30–50 m in width, 2–3 m in depth) were dug off of Bayou Postillion's channel into the adjacent swamp to the south in a downstream direction (USGS, 1969, 1980). Bayou Postillion is directly connected to and receives sediment from the GIWW. Over a period of 30 years, the access canals captured an increasing percentage of flow as Bayou Postillion filled with sediment to the point where navigation was only possible at high water. Bayou Postillion's channel remained open from the GIWW to the first access canal where a natural bayou from Postillion to the south had been deepened, widened, and extended (labeled 'Blocked canal' in Fig. 3) to connect to a pipeline canal. West of the access canal, the flow velocity through Bayou Postillion was probably insufficient to keep sediments in suspension and eventually led to sediment filling the channel at the point shown on Fig. 3. At low water, cocklebur and willow, species common to freshly deposited sediment, were prominent on the filled channel in aerial photos taken in February 2004 (Google Inc., 2013). Bayou Postillion was reopened by dredging in 2005 and the access canal was blocked. The study reach was 3 km in length and had east and west flow directions, depending on river stage. The channel was ~50 m wide and varied in depth from 1.5 to 5.5 m from the top of bank. In the study reach, Postillion had no junctions with constructed channels. This reach was chosen to examine what could be called natural sediment deposition within the channel as a result of high sediment loads and low water velocity.

Sediment deposition studies (Hupp et al., 2008) in the Basin floodplains north of the studied reaches have shown that connections with river flow, available sediments, and hydrologic setting are the major determinants of deposition on floodplains. In the vicinity of the study reaches, sediment deposition rates on the floodplain ranged from 8 to 26 mm/y (Hupp et al., 2008). However, no characterization has been made of sediment deposition within channels or of suspended-sediments moving off of the Atchafalaya through the floodplain in this anastomosing mix of swamps and open water. Numerous channels have been abandoned in this system. Currently several channels are filling in the 170-km^2 Bayou Pigeon and Postillion area of the Basin, along the length of the GIWW, and in other locations in the Basin. This study was conducted from 2008 to 2010 in order to clarify the processes that result in the human-induced abandonment and filling of Big Bayou Pigeon (BP) and Bayou Postillion (P) (Fig. 1) and to identify conditions that could accelerate future in-channel sediment deposition in other locations as the delta progrades down the floodplain.

2. Methods

The rate of sediment deposition within the channel was examined by (i) collection of suspended-sediment samples and discharges at a variety of water stages to characterize suspended-sediment loads entering and exiting the reaches; (ii) collection of sediment cores for radioisotope analysis; (iii) collection of bottom-material samples to characterize bottom material deposited within the channel; (iv) detailed bathymetric mapping; and (v) general flow pattern determination for the area by interpretation of aerial photography.

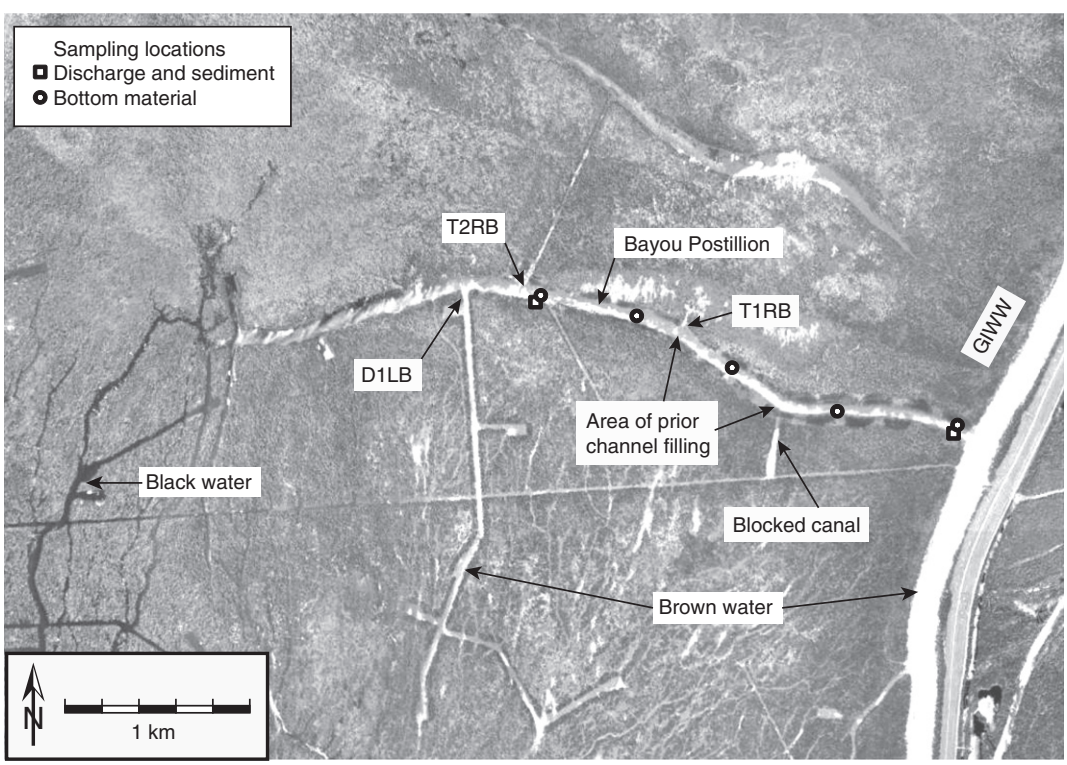

Fig. 3. Sampling locations in the Bayou Postillion (P) study reach, Atchafalaya River Basin, LA. Major tributaries and distributaries are identified: T1RB (tributary 1 right bank), T2RB (tributary 2 right bank), D1LB (distributary 1 left bank). GIWW = Gulf Intracoastal Waterway. Imagery date 17 May 2009.
Base map modified from Google Inc., 2013.

Suspended sediment samples were collected 50 m downstream of the head (the upstream origin of the channel) of BP near the point of divergence from Bayou Pigeon to characterize the sediment load entering the study reach. Samples were also collected downstream of the channel constriction (4.4 km from head) to characterize the suspended-sediment load exiting the study reach (Fig. 2). Suspended-sediment samples were collected at the eastern end of P, 50 m from the divergence from the GIWW. Samples were also collected at 2.5 km from the GIWW, to the west of the footprint of 2005 dredging (Fig. 3). Samples were collected on six occasions between May 2008 and May 2010 at stream stages representative of high (>4.26 m above the North American Vertical Datum 1988 [NAVD88]), intermediate (2.43–4.26 m), and low stages (<2.43 m) in the Atchafalaya River at Butte la Rose (hereafter BLR, USGS station #07381515; U.S. Geological Survey, USGS, 2013). Depth-integrated samples were collected using the multiple-vertical method (Guy and Norman, 1970). Samples were analyzed for total suspended-sediment concentration. Discharge measurements were made at the sediment sampling locations during sampling events using acoustic Doppler velocity profiler hardware and software (Simpson, 2001) to determine total suspended-sediment loads. Monitoring efforts also included two distributaries (2) and (3) from the right bank (D2RB and D3RB; Fig. 2) after observing flow conditions from the first sampling date. Discharge measurements were made in these two distributaries for the remaining five sample dates. Suspended sediment concentration and discharge data were used to calculate the loss or gain of suspended sediment and discharge within the reaches; only measured channel losses or gains of discharge were considered. Suspended sediment concentration comparisons were simple comparisons of concentrations flowing through primary channels. During sampling events when flow entered both ends of the reach, differences were not calculated because there were unmeasurable losses of flow and sediment (only observed in BP). In cases where flow in the channel changed direction as a result of hydraulic gradients (only observed in P), flow and sediment concentration were compared in relation to the flow direction on the sampling date.

In order to determine long-term sedimentation rates in BP, bottom-material cores (7.5 cm diameter) were taken to a depth of 2.5 m for radioisotopic analysis at three locations in and along the bayou using a vibracore and methods as described in McIntyre and Naney (1990). These three locations were near the head of the channel; mid-point of the filling area between D2RB and D3RB; and the downstream end of the filling area. Samples were also taken of freshly deposited sediment from a willow swamp, 23 m from the core at the head of BP at a depth of 0.3 m (Fig. 2) and freshly deposited sediment from a point bar at the intersection of Bayou Sorrel and the Atchafalaya (not shown). Analyses of radioisotopic activity of Cesium-137 (^{137}Cs), Lead-210 (^{210}Pb), Radium-226 (^{226}Ra), Uranium-238 (^{238}U), and Potassium-40 (^{40}K) were used to determine the depth of the 1963–1964 peak occurrence of atomic bomb-produced fallout and naturally occurring radioactivity in order to estimate the rate of sediment deposition (Craft and Casey, 2000; Stokes and Walling, 2003). Cores were split, manually inspected for grain size and material changes, cut into 2-cm sections, dried, and wood particles were removed. The remaining material was then finely ground in a mortar and pestle. Selected subsamples were analyzed for ^{137}Cs activity by placing 5 to 20 g of sample in a flat aluminum container and then placed on the flat surface of a J-type intrinsic high-purity germanium semiconductor. ^{210}Pb and other isotope activity were determined using 1 to 2 g of sample in a plastic container in a well-type detector. No radioisotopic samples were collected from P because the study reach was dredged in 2005.

Bottom-material grab samples were collected from the head of BP to beyond the filling reach (~4.4 km) at five locations spaced at 1000-m intervals to characterize grain size distribution and amount of organic matter in the substrate (Edwards and Glysson, 1999). Bottom material samples were also collected from P at five locations from the eastern end to the western end of the area dredged in 2005 (~2.5 km). Bottom-material and selected subsamples of core samples were analyzed using a Ro-tap sieve shaker stack for grain sizes from 1000 to 63 μm median grain diameter and hydrometer from 63 to 1 μm median grain diameter (Guy, 1969).

Water surface elevations were determined for use in the surveying of centerline and cross-sectional bathymetry of BP and P (150-m intervals and above and below major confluences). Elevation data were collected using an elevation-grade GPS (±2 cm) over two 4-hour periods on 28 January 2008 at BP and on 8 June 2010 at P. The data were post-processed using calculations by the National Oceanic Atmospheric Administration's Online Position User Service relative to NAVD88. Conventional surveying equipment was used to survey from the point of GPS-determined elevations to a tape-down to water-surface reference point. Bathymetry data were collected using a differential GPS-enabled survey grade digital recording fathometer (±2 cm) coupled with a computer.

Flow patterns in the area surrounding BP were examined by aerial photo analyses of nine clear images as compiled by Google Inc. (2013) of historical conditions from 1998 to 2011 representing an Atchafalaya River stage range at BLR of 0.77 to 5.16 m. In the Basin, moving fresh water from the river has high turbidity and suspended mineral sediment and appears light brown in color in comparison to stagnant and swamp-sourced water, which appears black when viewed in a body of water. Blackwater is rich in dissolved and particulate organic material and has very little mineral sediment (typically <10 mg/l). In aerial photography the high contrast between these waters is apparent. In the aerial images, if an area of reduced turbidity or blackwater dissected turbid water across the entire channel of BP for a distance of at least 10 channel widths (500 m), the image was deemed to show an interruption of flow resulting from hydraulic damming. When high concentrations of suspended sediment in flowing water enter an area of lower velocity water, rapid sediment deposition occurs. Hupp et al. (2008) found the highest measured deposition rates in the Basin to be associated with these conditions. Images were correlated to the Atchafalaya River stage at BLR to determine river stages when interruption of flow occurred.

3. Results

3.1. Water elevations and discharge

Samples were collected from the BP study site during stages ranging from 0.98 to 3.33 m (NAVD88). The highest sampled stages occurred on 1 June 2009. Water velocities at the downstream end of the BP area generally were <0.06 m/s and were never observed to be >0.15 m/s.

The flow patterns in BP were typical of a stream entering a ponded environment, with some notable exceptions. On 27 April 2009, during rising water, P (downstream of BP) had higher water levels than BP (Table 1). On this day, BP showed a partial flow reversal with negative discharge of 0.71 m^3/s at the downstream end of the reach. At the same time, the upstream end of the reach had positive discharge of 17 m^3/s. In a reach of the channel between the access canals D2RB and D3RB, discharge left the channel via overbank flow and entered the adjacent swamp. During this measurement, only 5% of the flow went into the two access canals (Table 1) and the remaining 95% of the discharge appeared to exit overbank into the swamp during this measurement. Although water elevations of P were higher than BP during 3 of the sampling events, no other events showed flow reversals in BP.

On 7 May 2008, during a falling phase at the second highest sampled stage, measured discharge at the downstream site on BP was substantially higher than at the upstream site as a result of additional water entering the BP channel from the swamp north and east of the channel. A comparable increase at the downstream site of BP was not

Table 1
Big Bayou Pigeon (BP) and Bayou Postillion (P) discharge (m^3/s) and suspended sediment concentration (mg/l).[a]

	7 May 2008		15 Aug. 2008		8 Oct. 2008		27 Apr. 2009		1 June 2009		3 May 2010		
Atch. stage at Butte la Rose (m)	5.64		2.49		2.00		4.34		5.75		2.56		
Stage at head of BP (m)	3.33		0.98		1.01		1.30		2.99		1.35		
Stage at West end of P (m)	3.08		1.22		0.96		1.63		2.84		1.39		
	7 May 2008		15 Aug. 2008		8 Oct. 2008		27 Apr. 2009		1 June 2009		3 May 2010		Average percent difference
	m^3/s	mg/l	m^3/s	mg/l	m^3/s	mg/l	m^3/s	mg/l	m^3/s	mg/l	m^3/s	mg/l	
BP upstream end	17	140	6.9	340	2.9	71	17	160	27	44	8.0	100	
BP downstream end	34	97	2.6	320	2.9	53	−0.71	62	21	34	4.1	41	
BP D2RB	(–)		2.2		0.79		0.76		1.1		1.6		
BP D3RB	(–)		0.89		0.45		0.06		2.7		0.65		
Sediment Conc% difference		(–)		−5.9		−25		(–)		−23		−59	−28
Percent of discharge lost to D2RB and D3RB	(–)		−44		−43		−4.8		−15		−28		−27
P east	−18	96	46	480	21	250	66	150	−27	39	22	99	
P west	−1.9	120	47	360	20	(–)	37	120	−0.57	38	28	69	
Sediment Conc% difference		−23		−25		(–)		−20		2.6		−30	−19

[a] Percent difference in suspended sediment concentration, and discharge loss from BP through major distributaries (not including overbank losses or gains). Atch = Atchafalaya River, (–) = no data or outlier, D2RB = distributary 2 right bank, D3RB = distributary 3 right bank. Stages are in meters NAVD88.

observed at the highest stage when water levels were at a peak phase on 1 June 2009.

Contribution or loss of discharge from BP by most of the tributaries and distributaries was observed to be minor with the exception of the two access canals, D2RB and D3RB. During the five sampling events when these two canals were measured, they captured an average of 27% of the total flow entering the BP study reach. During intermediate and low flows of the Atchafalaya (stage at BLR <3.00 m), these canals captured 38% of the BP flow (Table 1). On most of the sampling dates, the majority of flow loss was through D2RB and D3RB; minor losses and gains also occurred from the other tributaries and distributaries. The banks of BP were totally submerged at stages of the Atchafalaya River at BLR between 4.34 and 5.64 m, but no consistent pattern of flow loss or gain from overbank sources or sinks was observed.

The flow patterns in P were consistent with variable, alternating hydraulic head sources. The stage range in the Atchafalaya at BLR corresponded to a range of sampled stages in P from 0.96 to 3.08 m (NAVD88). During water stages of the Atchafalaya at BLR above 2.50 m, water from the swamps north of P contributed substantial flow to P and some discharge was lost from the channel to the south overbank (Table 1). Water typically flowed east to west in P away from the GIWW, but on two sample dates water was observed flowing west to east. At an undetermined stage of the Atchafalaya at the BLR gage between 4.34 and 5.64 m, flow in P stagnates at the western end of the study area and the swamps draining into P from the north force flow to reverse out of the eastern end of P into the GIWW. The water elevation in P was lower than in BP during the two sampled flow reversals. No clear pattern was found indicating whether these inputs and outputs at intermediate and low stages (<4.34 m) result in an increase in east to west flow through the bayou.

3.2. Suspended sediment

Suspended sediment concentrations at the head of the BP study reach ranged from 44 to 340 mg/l. Concentrations leaving the BP study reach at the downstream sampling site ranged from 34 to 320 mg/l. The average percent difference in sediment concentration entering and leaving the reach (not including any losses to D2RB or D3RB) was −28% (±23%) (Table 1). The sample set comparison from 7 May 2008 was discarded because large volumes of water were entering the channel from the swamp thus making the comparison an outlier. The sample set from 27 April 2008 when flow was entering from both ends of the study reach, was also considered to be an outlier and excluded from the average.

Suspended sediment concentrations at the eastern end of P ranged from 39 to 480 mg/l. Sediment concentrations in samples from the western end ranged from 38 to 360 mg/l. The average percent difference in sediment concentration was −19% (±13%) between the east and west sampling locations (Table 1).

3.3. Radioisotopic analyses

The upstream BP bottom-material core was collected from a known location of initial and current filling of the bayou. The core was primarily comprised of silt and clay (<63 μm) and abruptly ended at 1.9 m in dense clay and organic material. Radioisotopic analyses of this core resulted in low ^{137}Cs disintegration counts per minute per gram (<0.3 dpm/g) that were near detection limits and no usable dating data were obtained (Fig. 4). The core collected from the downstream end of BP was analyzed and also showed detection limit count levels. Because no usable dating data were obtained from the first two cores, analyses of the remaining core were discontinued. Samples of freshly deposited sediment and from the willow swamp also exhibited very

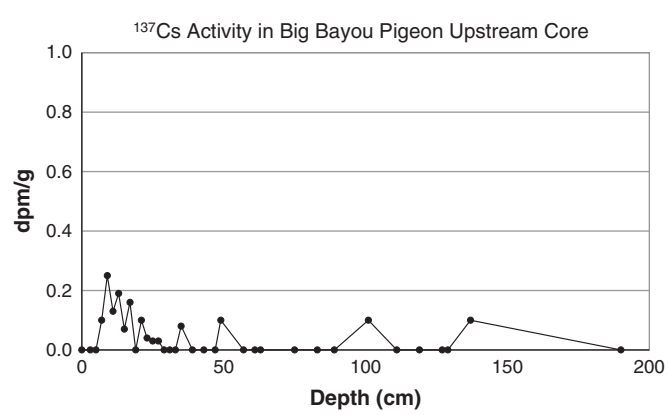

Fig. 4. Radioisotopic activity in the core taken from the upstream site of Big Bayou Pigeon, collected in January 2009. Cesium-137 activity was below dateable levels in the core.

low ^{137}Cs activity. These results indicate that the sediment deposited in this area could be more recent than 1963–1964. Alternatively, the sediment filling the bayou could have originated as resuspended material from channel dredging work or bed erosion.

3.4. Bottom-material samples

Grain size distributions of bottom material in BP were consistent with the flow patterns, with the slower water carrying and ultimately depositing finer sediment. Grain size analysis showed a range of sediment with diameters from 250 μm (fine sand) to smaller than 1 μm (very fine clay). The median diameter of sediment collected at the head of BP was 46 μm. Median diameters decreased in the downstream direction and abruptly decreased in grain size from 25 to 8 μm between D2RB and D3RB. This sudden change in grain size suggests a change from slowly flowing to ponded water. The bottom material collected at the downstream end of the reach had a median diameter of 7 μm.

The grain size distribution of bottom material in P ranged from 1 to 177 μm. The bottom material did not show consistent trends. Median diameters in the P study reach ranged from 46 μm at the eastern end, 44, 21, 35, to 25 μm at the western end. These data indicate that the channel cross section still could have been adjusting to channel dredging that resulted in unstable erosional and depositional patterns.

3.5. Bathymetry

Cross-sectional areas in BP ranged from 15 to 24 m^2 from the head to 2000 m downstream of the head (Fig. 5). At 2200 m, the channel decreased to a cross-sectional area of 6.3 m^2, equal to the cross-sectional area (6.3 m^2) of the access canal D2RB at 2100 m. The cross-sectional area of BP increased to just over 9.3 m^2 at 2500 m, decreased to 6.8 m^2 just upstream of D3RB, then decreased further to 4.3 m^2 at 3400 m, immediately downstream of D3RB. At 3400 m the cross-sectional area of BP is half the cross-sectional area of D3RB (11 m^2, 3300 m). By 3900 m from the head of BP, the cross-sectional area of BP begins to increase again, and by 4700 m, appears to be back to an unfilled, cross-sectional area (55 m^2) as of May 2008.

The largest cross-sectional area of P was 154 m^2 at the eastern end of the channel (Fig. 6B); to the west, the channel cross-sectional area averaged 114 m^2. The smallest cross-sectional area of P (96 m^2) was measured at 2890 m west of the GIWW which was immediately downstream of access canal D1LB on the southern bank (Fig. 6).

3.6. Photo interpretation

Nine aerial photos of the Big Bayou Pigeon vicinity taken between 1998 and 2011 show interruption of flow in images taken when the stage of the Atchafalaya at BLR was below 1.0 m or above 2.7 m. Three aerial photos that were taken when the Atchafalaya River stage was between 1.2 and 1.4 m show no interruption of flow. In the interrupted flow images, zones of black water were frequently present between the area of channel constriction and where access channels enter the bayou at ~7200 and 8300 m from the head of BP. In Fig. 2 the black water zone between BP's constriction at 3300 m from the head and the aforementioned channels indicate flow conditions with little or no velocity (Fig. 2).

Analyses of the two aerial photos of P taken in 1999 and 2004 prior to dredging show little turbidity west of the channel blockage. Six photos taken from 15 October 2005 through 2007 show turbidity extending to the west end of P. One photo taken on 17 May 2009 when the stage of the Atchafalaya at BLR was 5.2 m, showed turbid water leaving P through an access canal D1LB at ~2900 m; west of the access canal the water in P was black water (Fig. 3).

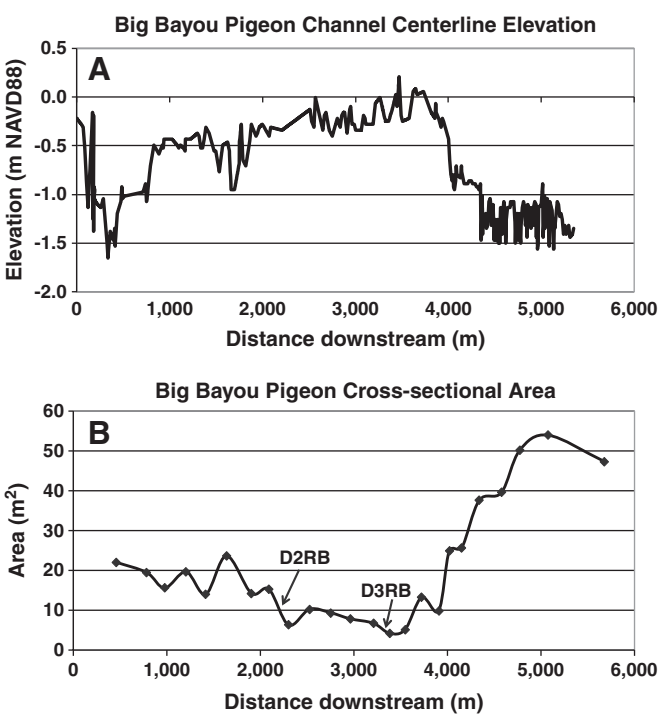

Fig. 5. Plots of (A) channel centerline elevation and (B) cross-sectional area in Big Bayou Pigeon in relation to distance downstream. Locations of distributaries and their cross-sectional areas are noted on (B). Constructed channels are D2RB and D3RB. The first channel cross section was measured at 500 m, ~10bankfull widths from the head.

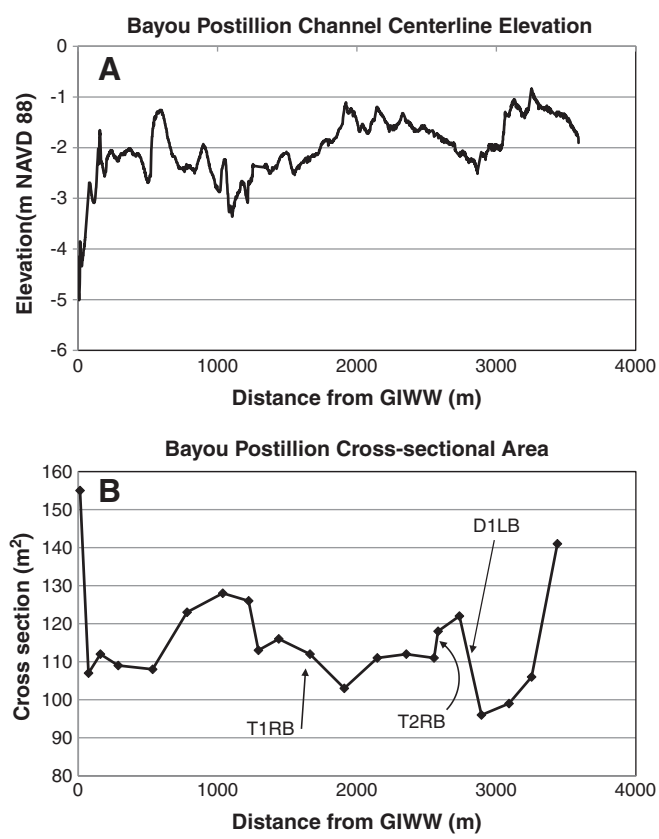

Fig. 6. Plots of (A) channel centerline elevation and (B) cross-sectional area in Bayou Postillion in relation to distance from the GIWW (Gulf Intracoastal Waterway). Tributary 2 right bank (T2RB) and distributary 1 left bank (D1LB) are access channels.

4. Discussion

These results indicate at least three causes of channel filling along Big Bayou Pigeon; they are, in descending order of their contribution to in-channel sediment deposition: high suspended sediment load, flow loss to access canals, and hydraulic damming. The most important factor was the high suspended sediment to BP from the Atchafalaya through the GIWW. In swamp channels in the Basin just south of the study area, sediment concentrations are often < 10 mg/l where waterways are not directly connected to a sediment source. Some of these channels are large (300–600 m^2) and exhibit no apparent sediment filling despite flow rates that are commonly < 0.1 m/s, with numerous access channel intersections (Kroes, unpublished data).

Sediment in the radioisotope cores from BP was comprised primarily of silt and ended abruptly in layers of dense clay and organic material. The sediment stratification indicates low water velocities and low suspended sediment concentrations existed prior to an abrupt change in suspended sediment composition and load, and possibly increased flow velocity. The connection of the Atchafalaya River to the Mississippi River (beginning in 1830) and the construction of the GIWW (1950s) has provided a conduit for sediment transport that historically only existed during great floods. In P, 19% of the suspended sediment entering the study reach was deposited in the reach. This in-channel deposition of sediment is a result of water velocities that are too low to keep silt in suspension. Bayou Postillion is similar to many channels in the Basin and exemplifies the process by which channels throughout the Basin could eventually fill. Even if access channels were not part of the situation, flow velocities would probably not be sufficient to maintain the water/land ratio in the Basin.

The second most important cause of filling in BP was the loss of flow caused by the access channels D2RB and D3RB. These channels captured an average of 27% of the flow of BP, which resulted in a decrease in water velocity sufficient to induce channel filling and reduce the cross-sectional area of the channel immediately downstream of these distributaries.

Although significant, the least important cause of channel filling was hydraulic damming conditions common downstream of D2RB induced by the introduction of water from access channels that enter BP downstream of the study reach (Fig. 2). As high-velocity, high-suspended-sediment-content water enters an area of low or no velocity water, a portion of the sediment load is deposited. Big Bayou Pigeon channel before filling could have carried sufficient discharge to prevent the hydraulic damming induced by tributary access channels. In BP, 28% of sediment entering the reach did not leave the reach. Compared to P, BP lost an additional 9% of its sediment load.

This study did not clarify what percentage of sediment deposition resulted from flow loss to the access canals or from hydraulic damming conditions, the losses could be magnified by the interaction of the two. Apparently the flow in the first 2 km of BP had enough velocity to maintain an 18-m^2 average channel, and if the two access canals had not captured as much discharge, then the BP channel likely would continue to extend into the historic BP channel cross section with a cross section averaging 18 m^2, as it had formed from the head of BP to D2RB.

Channel abandonment in swamp channels like BP (maximum recorded flow 34 m^3/s, ~0.002% of total river discharge measured at Simmesport, USACE gage 03045) does not appear to have been previously published. However, this multifaceted, complicated process is similar to what can be observed in other riparian systems (Field, 2001; Ashworth et al., 2007; Kroes and Hupp, 2010). As long-term flow is reduced in a primary channel, sediments are deposited in the channel and vegetation grows on the deposited sediments. This growth increases flow resistance in the primary channel forcing more flow into a secondary channel (a branch or distributary), continuing until the primary channel is filled. Here, the process is further accelerated by the presence of backwater conditions dominated by variation in the Atchafalaya stage and hydraulic damming where flowing water enters an area of counter flow or stagnant water (Hupp et al., 2008) as a result of access canals in the vicinity. Backwater and counter flow conditions have been observed in the vicinity of D2RB. Higher stages could result in backwater upstream of D2RB. Flow direction in this system is complicated by the variable hydraulic gradients that are driven by the interactions of the river, pipeline canals, GIWW, access canals, and whether the swamp is in a rising or falling phase. Sedimentation within BP could be reduced by increasing the downstream flow velocity. This could be achieved by restricting flow loss through the distributaries (D2RB and D3RB), increasing BP's channel dimensions, and blockage or restriction of flow entering other access canals in the vicinity of BP (Fig. 2).

5. Conclusions

These channels filled as a result of the interaction of three conditions: high sediment load, flow capture, and backwater conditions. In the Atchafalaya River Basin, high sediment loads have been introduced within the last 150 years. In the last 70 years, numerous channels were dug through deep swamp for navigational access. As these more efficient channels were dug, the flow velocity in natural channels was reduced. In systems like this where sediment load is an existing problem, any decrease in flow velocities will contribute to the filling of channels and open water.

Trends in the Atchafalaya River suggest that it is becoming increasingly incised with decreasing percentages of water leaving the river and passing into the swamp. Despite the fact that open water has been reduced by 75% since the 1800 s, the Atchafalaya Basin (2013) does not exhibit the flow velocity necessary to prevent open water filling for the amount of water and sediment moving through the system. Channel filling will continue to occur until flow velocities are sufficient to transport silt. In the Atchafalaya River Basin, numerous channels and lakes are filling as a result of high sediment load and low flow velocities within channels that are too slow to transport fine silts and clays. This floodplain system formed as a back swamp of the Mississippi and its precursors without significant mineral sediment loads. Now that suspended mineral sediment is a constant component of this system, the interface between faster and slower flowing waterbodies is experiencing rapid sediment deposition. If a more hydraulically efficient alternate flow path is created, like a canal, water will leave the natural channel to follow the more efficient path. This will usually result in the filling of the abandoned channel unless suspended sediment concentrations are extremely low, as currently exist south of the BP and P study sites. As oil and gas exploration expands into other parts of the Basin and other wetland areas such as the Niger Delta, the concepts that access canals can result in open water habitat loss, access loss as a result of channel filling, and can create abnormal hydrologic conditions with unknown results need to be considered.

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Disclaimer

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.geomorph.2013.06.016. These data include Google map of the most important areas described in this article.

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