The Evolution of a Tie Channel

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ABSTRACT: Tie channels connect lakes with rivers along many lowland floodplains allowing the exchange of sediment and water. The channels which are characteristically narrow, leveed and stable represent a unique example of a self-formed channel created by a sediment-laden current entering still water. How such channels form and evolve is poorly understood. The Raccourci Old River tie channel, located 65 km upstream of Baton Rouge, is one of the largest and best documented tie channels on the globe. Through a detailed study of the Raccourci Old River tie we attempt to gain insights into the processes that control channel formation. The tie channel forms from a jet that preferentially constructs levees from the coarsest fraction of the incoming load through a combination of processes. Large massive rotational failures control channel width and the suspended sediment load of the Mississippi has been the dominant control on channel advancement.

1 INTRODUCTION

Once cut off from the main stem of the river, oxbow lakes commonly remain connected to the active river through narrow self-formed channels which evolve at the time of lake formation. These channels, referred to here as “tie channels” (Blake and Ollier 1971), allow the regular exchange of water and sediment; flow enters the lake when river stage exceeds lake stage and drains from the lake as river stage drops. Remarkably, these channels rarely become plugged with sediment and remain active for hundreds to thousands of years. We estimate that 65% of the floodplain lakes on the lower Mississippi River remained connected to the river through tie channels prior to large scale alteration of its floodplain; today a handful remain and few are in an unaltered condition.

How a tie channel or any channel created by a sediment-laden current entering still water forms and evolves is poorly understood. We undertook the study of a tie channel in the Raccourci Old River oxbow lake, Louisiana, USA (Figure 1) with the goal of characterizing its morphology and documenting its evolution in order to develop a model of channel formation. Critical to such a model is the identification of the processes that control the construction of levees, regulate channel width, and determine the rate of channel advancement.

The Raccourci Old River (ROR) tie channel is uniquely suited to address these questions. In addition to being the largest known tie channel on the planet, it is probably the best documented. Regular hydrographic surveys of the channel date to the late 1800s, aerial photographs cover it since the 1940s, and airborne laser swath mapping (ALSM) was performed in 2003. On field visits to the site in 2002 and 2005, we conducted topographic and bathymetric surveys, and collected sediment samples and cores for particle size distribution analysis and optically stimulated luminescence (OSL) dating.

2 SITE SETTING

Located 65 km upstream from Baton Rouge, LA USA at 30°54.7’N, 91°36.62’W, the ROR oxbow lake has the first functioning tie channel upstream of the delta on the lower Mississippi River (Figure 2). In 1848 humans cut off a 30 km bend in lower Mississippi River and by 1851 the cutoff bend had become the oxbow lake (Gagliano and Howard 1984). Since 1851 the tie channel, locally known as a “batture channel”, has extended itself 9 km filling approximately 24% of the lake.

The lower Mississippi River drains over 3.2 million km^2 of North America with a mean annual discharge of 18,400 m^3/s (Mossa 1996). The slope of the Mississippi River just upstream of this reach, at Natchez, MS has been measured at 5.2 x 10^{-5} (Biedendharn et al. 2000). The study site lies 27 km downstream of the Old River Control Structures where presently 30% of the Mississippi River flow is diverted into the Atchafalaya system.

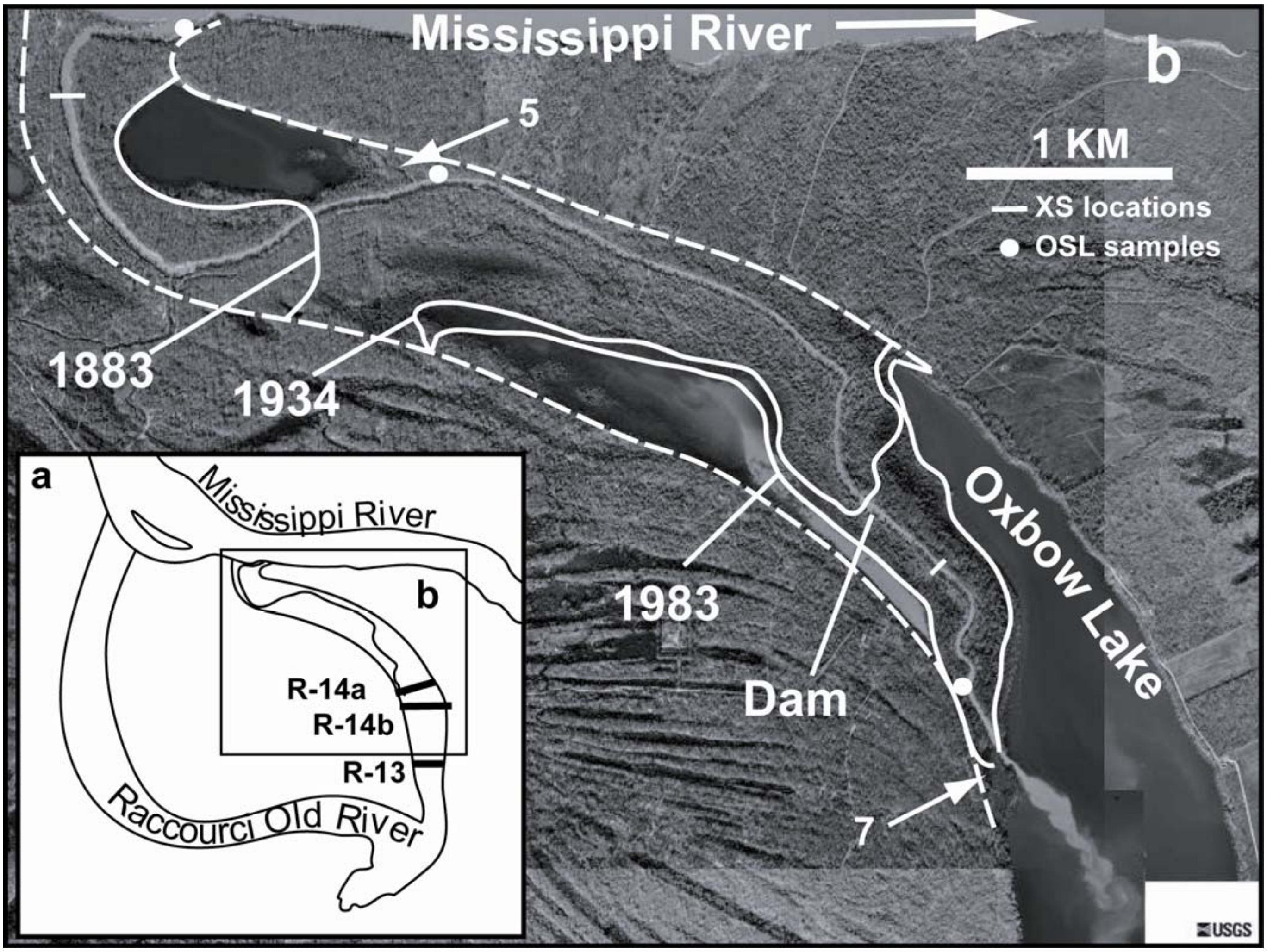

Figure 1. Raccourci Old River tie channel. a) Location sketch showing tie channel in relation to the entire oxbow lake and the Mississippi River. Labeled lines indicate locations of bathymetric cross sections. b) 1998 aerial photograph of the tie channel entering the downstream limb of the oxbow lake. The channel is 9 km in length. At the time of the photograph sediment was entering the lake via the tie channel; note the jet of sediment-laden water in the lower right. The dashed lines mark the original banks of the cut-off meander bend and the solid lines indicate the extent of lake infilling in 1883, 1934 and 1983. Also shown is the location of the dam, OSL sample locations, and locations of 2 cross-sectional surveys shown on Figure 4. Arrows point to areas of detail shown on Figures 5 and 7.

Fine sands dominate the river bed material in this reach and suspended sediment concentrations average 420 mg/l (measured between 1950 and 1991) (Mossa 1996) of which 45% is clay (< 4 μm) sized. Kesel et al. (1992) estimate that a 70% decrease in the Mississippi River suspended load has occurred since peak concentrations in the 1850s. Deceases began in the 1930s with the introduction of soil conservation measures across the Mississippi River watershed. Significant additional decreases have been documented since the 1950s in response to dam construction on major tributaries, bank stabilization, and diversion of flow at the Old River control structures (Mossa 1996; Keown et al. 1986; and Kesel et al. 1992). Keown et al. (1986) also note that downstream of the of Old River Control Structure the bed of the Mississippi is aggrading in response to the Control Structures.

The ROR oxbow lake lies in a unique "naturally" functioning portion of the floodplain. The lake formed after construction of the main line Mississippi River levees in this area. Following meander cutoff, the levees were not relocated to the new banks of the river. As such, the lake and its adjacent floodplain still receive periodic flood waters when

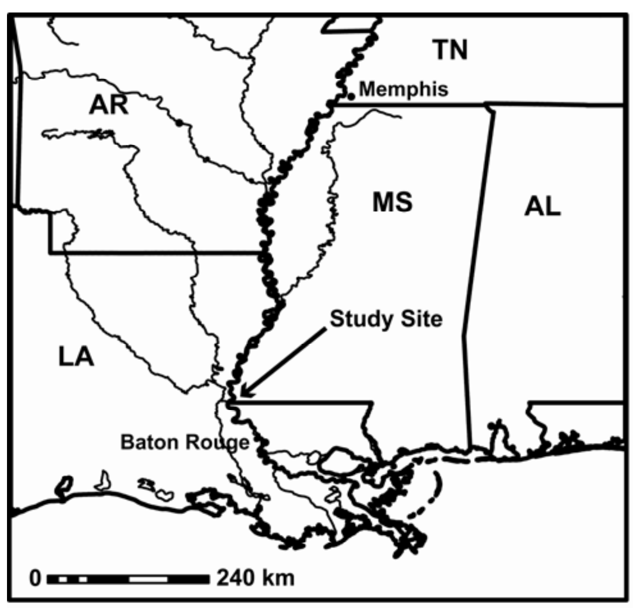

Figure 2. Location map of study site on lower Mississippi River.

the river crests its natural levees. The tie channel itself is unique; unlike many of the remaining tie channels on the lower Mississippi this tie channel has not been dredged or straightened to improve navigation into the lake. The only human alteration of the channel appears to be a low-head dam installed in 1965. The dam maintains a minimum lake level to facilitate boating and recreation during low water summer months. Located 6.5 km (all reference distances are given as measured along the channel, not straight line distances) lakeward of the Mississippi River, the dam has a crest elevation of approximately 7.4 m above mean sea level (amsl), 6.7 m below the local bank crests. We estimate that the dam raised the minimum lake levels by 1.4 m. While the impact on channel morphology appears limited, data suggest the dam may have influenced the rate at which the tie channel advances lakeward. Such flow control structures, however, are not without a natural analog; beavers commonly control lake levels by constructing dams across Alaskan tie channels.

3 TIE CHANNEL MORPHOLOGY

In an attempt to understand process through form, we look at both along-channel and across-channel characteristics of the tie channel. The tie channel is narrow, leveed and moderately sinuous; the channel is 9 km long but only occupies 6.5 km of the lake. Despite this sinuosity (1.3), successive maps and photographs dating to the 1800s show minimal to no migration of the channel centerline over time. This lateral stability in channel location allows for the study of the development of channel morphology by trading location for time, because the morphological "clock" has not been reset by migration of the channel. The spatial tradeoff for time is made by recognizing that the oldest section of the channel lies closest to the active Mississippi River and the youngest at the opposite end entering the lake. Assuming that the fundamental processes forming the channel have not changed over time we can examine how the channel develops by moving up and down the channel length. Moving along the channel in this manner reveals systematic changes in channel width, and levee morphology with distance.

Both levee crest elevation and channel width decrease with distance from the Mississippi (Figure 3). Figure 3 presents levee elevation versus channel distance from the river for both the left and right banks (defined looking into the lake) of the tie channel. Both levees decrease at an average rate of 0.5 m/km though the rate varies along the channel. For the first 1.3 km (left) and 2 km (right) the levees maintain relatively constant elevations equal to that of the Mississippi River levees. For the majority of the channel length the left levee decreases in elevation by 0.6 m/km and the right levee at 0.5 m/km. Over the last 2 km the slope of the left levee doubles and the right levee slope increases to 1.8 m/km. For a small section, from 5 to 6 km along the channel, the left levee crest gains in elevation, increasing in height at 0.3 m/km; what causes this reversal in slope is not known.

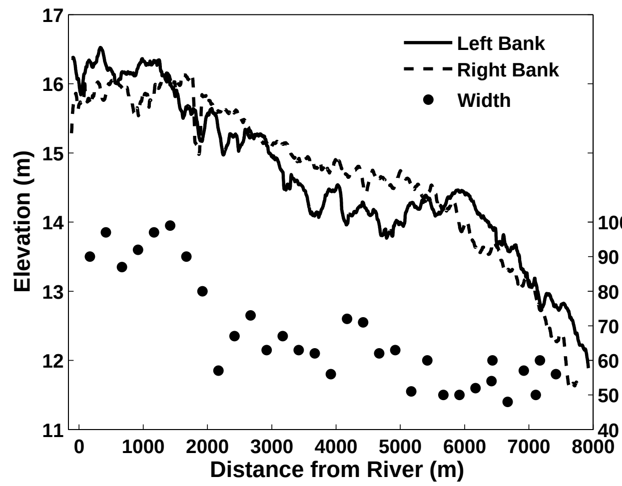

Figure 3. Long profile of tie channel levee crest elevations and channel widths measured between crests. Data from 2003 ALSM survey of site. Elevation data smoothed by averaging over a 100 m window. Width measurements made approximately every 250 m along the channel. Source of data: Concepts, Watershed 2005.

The trends on Figure 3 indicate three aspects of tie channel development: 1) levees progressively grow in height over time; 2) maximum levee heights are set by the main stem river levee heights; and 3) disparities in levee height on opposing banks occur along the entire channel but vary with location.

Channel widths also appear to increase with channel age and have a maximum value of approximately 90 m. The correspondence of a relatively stable maximum width with the section of the channel that has constant levee elevations suggests that there is a feedback between levee height and channel width. The general slope of the width trend with distance (a decrease of 5.3 m/km) also supports a relationship between channel height and width. The change in width, however, shows a variability that is not well correlated to local levee height. A final trend we observe in the field and on aerial photographs is a widening or flaring of the channel width in the last 1 km as the levees grade into the lake. Along this section of channel widths increase from a minimum value of 40 m to 60 m at the end of the channel. Figure 3 does not cover this section of the channel because the lake covered the last 1.5 km of the channel at the time of the ALSM survey.

The high lake levels also limited the ability of ALSM to collect elevation data inside the channel itself. To characterize channel geometry we rely on 5 field surveys conducted in 2002. Figure 4 shows two of these surveys which could be paired with ALSM derived cross-sections at the same locations (locations shown on Figure 1). The tie channel is deep relative to its width. The aspect ratio (width/depth) of the channel ranges between 4.7 and 8.3. Of the two cross-sections shown on Figure 4, the one closest to the river has a W/D ratio of 8.3 and the second one located just lakeward of the dam measured 5.4.

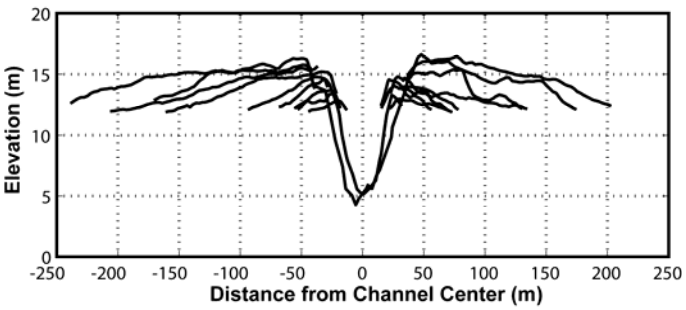

Figure 4. Cross-sectional surveys s approximately 1000 m intervals along the channel. Vertical exaggeration 10x. Levee topography and the upper portion of the channel banks extracted from 2003 ALSM survey of channel. Water level at the time of the ALSM survey was approximately 12 m obscuring much of the channel and the distal portions of the levees. Two field surveys from 2002 showing the entire channel cross-section were paired with ALSM data to provide complete sections (locations shown on Figure 1).

The link between channel height and width appears to relate to bank stability. In the field, we observe that channel width adjusts by a process of widening by massive (up to hundreds of m in length) bank failure and narrowing by deposition of sediment drapes over failure scarps. Failures occur as large-scale rotational blocks. Blocks are not immediately removed by the flow, but gradually slide down the banks toward the center of the channel. Fresh failures are marked by planar scarps and tension cracks along the levee crest. Older failures scarps, though smoothed by a combination of erosion and sediment drape deposition, still remain distinct due to the presence of back rotated trees and abrupt steps in the channel banks. Failures commonly occur on both sides of a channel cross-section. We speculate that a failure block along one bank may locally force flow towards the opposite bank, in turn triggering failure of that bank. This process of alternating failures would promote lateral stability, as the channel widens about a centerline rather than migrating by failing on one side and accreting on the opposite.

The uniformly low width to depth ratios along the channel point to a critical slope for bank stability. This slope will depend on the bulk material properties of the banks and the lake hydrology. Failure occurrence may be most prevalent during falling river stages when water levels in the channel drop faster than the lake. Under these conditions higher water levels on the back side of the levees and saturated banks may result in high pore pressures and reduced bank stability.

In addition to the two field surveyed cross-sections, Figure 4 presents cross-sections extracted from the ALSM data at approximately 1000m intervals along the channel. The sections predictably range in size from the smallest nearest the lake (youngest) to largest (oldest) near the river. The figure provides a view of channel cross-section evolution. As the channel evolves it becomes wider, deeper and the levees increase in height and broaden, filling more of the lake. This progressive broadening is reflected in the reduction in the slope of the levees away from the channel. The levee back slope ranges from 0.06 to 0.10 on the youngest banks to 0.006 to 0.01 on the most developed levees.

Critical to this process of levee broadening may be the common occurrence of splays along the channel length. Figure 5 presents examples of crevasses along the channel levee from the ALSM survey data. These crevasses erode material along the crest of the levee and deposit sediment in lobes further down the levee flanks. The size and length of features appear to increase with increasing channel size. The level of standing water (lake level) on the backside of levee likely controls the location of splay deposition by preventing further runout.

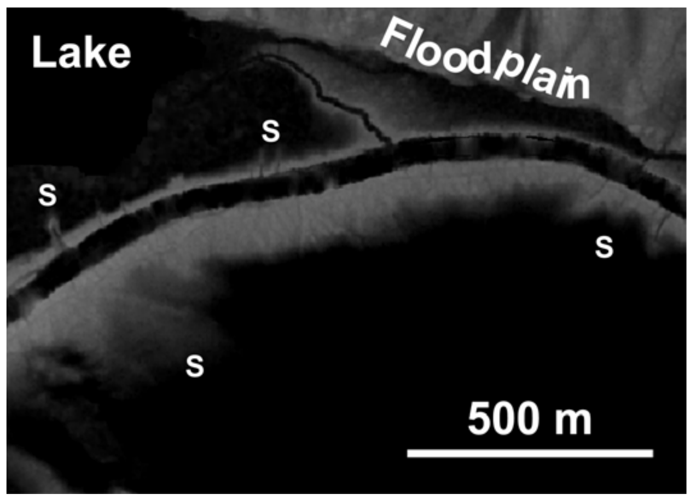

Figure 5. Image map of a section of tie channel 3.5 km from the river generated from ALSM data. The location is shown on Figure 1. The tie channel runs across the photo with the levees appearing as lighter areas bordering the channel. S – indicates location of splays. Crevasses appear as dark lines perpendicular to the tie channel and the splay lobes appear as light areas extending away from the levees. The asymmetry of levee development between the left and right banks is also visible. The large secondary channel in the upper middle of the figure is a secondary channel connecting the small lake visible in Figure 1 with the tie channel. It may in fact be a tie channel to the tie channel. Data Source: Concepts, Watershed 2005.

4 OUTLET BATHYMETRY

Understanding how tie channel levees start to build at the channel outlet into the lake is essential to developing a complete model of tie channel formation. Due to near continuous inundation, however, data sources such as aerial photographs and ALSM surveys provide little information on morphology of the channel outlet. To examine this portion of the tie channel we used a handheld Global Positioning System (GPS) and basic depth sounder to map the bathymetry of the channel outlet. This data collection involved making a series of bathymetric profiles along the channel into the lake and across the lake bed perpendicular to the channel at various distances from the outlet.

From this data we are able to get a general picture of the morphology of the lake bed in the vicinity of the channel outlet. The surveys show distinguishable levees extending approximately 200 m into the lake beyond the ends of the exposed, vegetated levees. Similar to the exposed levees, the submerged levees show uneven development between the two sides the channel. The left or eastern levee is more extensively developed; its exposed levee or subaerial portion extends approximately 150 m further into the lake than the opposite levee. In the lake, the crest of this levee is more pronounced and lies at a higher elevation than the right levee. This asymmetry in levee development appears to arise due to a progressive realignment of the channel course from a southeasterly to a more southerly trend. Flow out of the channel appears to be directed against the left levee, resulting in greater deposition on that side of the channel

Bathymetric profiles running along the channel axis show a sharp topographic transition from the channel into the open lake. Figure 6 presents a bed survey of the channel centerline from the low-head dam to 1.2 km into the lake. The profile shows a distinct change in bed slope leaving the channel entering the lake. From the dam to 500 m from the end of the channel the channel bed slopes downward toward the lake with a gradient of 0.8 m/km, approximately the same as the average gradient of the levees but about half that of the last 2 km of levees. For the next 750 m the bed rises 4 m and then decreases in elevation lakeward. The crest or peak elevation coincides with the end of the subaqueous bars. Lakeward of the crest no distinct topographic break marks the end of a delta front and by 500 m out from the crest the slope steadily drops at a rate of 3.4 m/km.

Two additional long profile surveys conducted along the edges of the channel show a similar trend in bathymetry, but with bed elevations 0.5 to 1 m lower than the centerline profile.

The overall morphology of the channel outlet bears a strong similarity to Wright's (1977) illustration of the bed topography associated with friction-dominated river-mouth effluents. The idealized friction-dominated delta is characterized by a triangular 'middle ground' bar located at the end of the subaqueous levees. According to Wright (1977), this bar causes the flow out of the channel to shoal and separate leading to deepening of the channel between the bar and the levees. The positive feedback of shoaling and deepening results in bifurcation of the channel and development of deltaic distributaries on either side of the 'middle ground' bar. Aside from a perpendicular split in the channel visible on 1941 aerial photographs but gone by 1949, the ROR tie channel has no persistent bifurcations and is presently a single thread channel for its entire length.

Army Corps of Engineers surveys of the lake bed at several cross-sections provide a limited picture of changes in lake bed topography over time. The Army Corps has maintained 2 cross-sections for repeat surveying. The two cross sections, R-14 (a,b) and R-13, are located 5.8 and 8.2 km from the Mississippi River; R-14 was relocated 750 m further lakeward in 1963 due to encroachment of tie channel on the original location (locations are shown on Figure 1a). Surveys were conducted in 1935, 1950, 1963, 1974 and 1991.

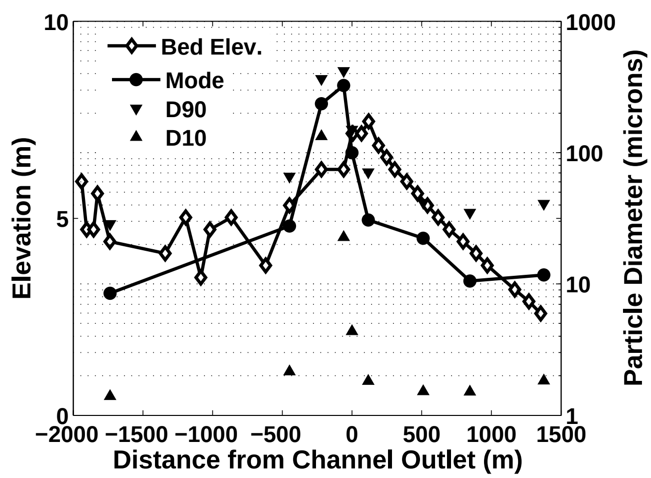

Figure 6. Bathymetric survey from the channel into the lake and grain size characteristics of bed samples collected along the survey. The 0 location on the distance axis marks the end of the exposed channel levees. The prominent rise in the bed at the channel outlet marks the mouth bar which lies between the channel levees at the outlet. The slope of the channel bed is 0.0008, and the slope on the delta front (the last 1000 m) is 0.0034.

The surveys show three morphological trends: 1) near the channel outlet, deposition leads to an increase in bed topography; 2) deeper into the lake, deposition reduces bed topography by filling in lows; and 3) the slope of the lake bed away from the tie channel has increased since 1974. Surveys conducted at locations R-14a and R-14b both show broad (300 to 600 m) areas of greater deposition lakeward of the tie channel outlet. The location of these maximums changes over time in correspondence to the shifting of the channel outlet position.

Using the paired cross-sections we calculate a bed slope from the center of the depositional highs on the R-14 surveys to the R-13 survey. The three pre-dam surveys show consistent bed slopes: 2.5 m/km (1935), 2.5 m/km (1950) and 2.3 m/km (1963). Post-dam, 1974 surveys show little change (2.5 m/km), however, the surveys show limited to no deposition at either cross section on this date. In 1991, however, the bed slope increased to 3.2 m/km. The difference between the 1991 and 1963 slopes (0.9 m/km) is equivalent to the additional slope created by adding 1.4 m in elevation difference (the dam induced rise in base level) between the survey cross-sections. The 1991 bed slope is also consistent with the 2005 field surveyed bed slope of 3.4 m/km (Figure 6). Based on these surveys it appears delta front has steepened 34% since dam installation.

5 STRATIGRAPHY AND SEDIMENTOLOGY

In addition to studying tie channel morphology we have attempted to characterize the channel stratigraphy and sedimentological properties to gain insights into the material properties of the channel banks and morphodynamics of their formation.

The majority of sediment entering a tie channel from the river is likely in suspension. This is due to two factors: 1) tie channels connect to the main stem at an acute angle, causing water and sediment entering the channel to be diverted in an upstream direction, and 2) channels do not generally grade to the bed of the main stem requiring sediment to be above the bed to enter the tie channel. A comparison of the sediment load of the Mississippi River and the particle size distributions of tie channel deposits (Table 1) suggests that the channel effectively sorts the incoming load by size. The Mississippi River data was collected at Tarbert Landing, located 14 km upstream of the ROR tie channel, between 1974 and 1991 (Catalyst Old River Hydroelectric Limited Partnership 1999). Tie channel data comes from sediment samples collected from channel deposits in 2002 and 2005.

Deposits exposed in the banks of the tie channel consist of alternating layers of sand and mud. Primary sedimentary structures are limited to faint planar laminations. No cross-bedding or ripple marks are visible. The particle size distribution of coarse layers indicate sediments ranging in size from fine to medium sand, abundant silt and a small fraction of clay. The mud layers are dominantly silt with up to 20% clay and a few percent organic litter. The layers range in thickness from a few centimeters to tens of centimeters. No subsurface cores have been collected, but on the levee surface the thickness of the sand layers appears to diminish with distance down the levee back slope while the mud layers increase in thickness.

We interpret the stratigraphic layering as the result of alternating depositional processes. The sand and coarse silt settle from suspension along the channel margins during active inflow to the lake. Following lake inundation and flow cessation, the finer silt and clay settle from suspension in relatively quiescent waters, blanketing inundated portions of the channel and lake. The ability of tie channel processes to sort the incoming sediment load from the river is highlighted by noting that while sand sized sediments comprise approximately half of the deposits exposed in tie channel banks, sand makes up only 20% of the suspended load of the river.

Table 1
Sediment Grain Size Characteristics for River and Tie Channel

	Size in Microns				Percent		
	Mode	D50	D90	D10	Sand	Silt	Clay
Location							
MR Bed	300	300	800	150	99.5	0.5	0
MR SS	94*	4.5	150	< 4	20	33	47
TC Levee Coarse	111	90	204	8	66	27	7
TC Levee Mud	53	22	94	2	21	60	19
TC Bed at Delta	362	353	515	235	100	0	0
Lake Bed	12	10	41	2	4	72	24

MR – Mississippi River at Tarbert Landing averaged over 1974-1991 for stages > 9m.
SS – Suspend sediment sample
TC – Tie channel
* represents the peak of the coarse mode, distribution undetermined at sizes < 3.9 μm.

Coincident with the bathymetric survey we also collected a series of grab samples from the bed along the same transect (Figure 6). Bed sediment increases in size as the bed rises into the mouth or ‘middle ground’ bar and systematically decreases over 1 km lakeward of the bar. The peak grain size (325 μm), however, occurs 175 m before crest of the bar. Near the crest of the bar the mode of the bed sediment decreases to 30 μm and by 1 km from the channel the bed reaches a constant mode of 11 μm. To the east of the mouth bar crest, along the crest of the subaqueous levee the particle size distribution coarsens and the levee crest is capped by fine sand with a mode of 111 μm.

The abrupt decrease in grain size at the crest of the mouth bar may reflect a sudden decrease in jet strength over the crest of the bar during inflow. Alternatively, it may, arise from erosion of sediment within the channel during outflow. The fines may blanket coarse bar sands during the waning stages of inflow. During outflow, erosion of the loosely consolidated muds only occurs where the flow is confined by channel levees. Diffuse flow over the crest is insufficient to expose sands. The latter interpretation would be consistent with the depositional patterns shown in Wright’s (1977) model in which peak grain sizes occur at peak bed elevations.

Cohesive muds comprise the channel bed upstream of the mouth bar. At the upstream edge of the mouth bar, the bed consists of coarse silt with 19% clay. Just lakeward of the dam the bed material is even finer with a mode of 9 μm and 36% clay (Figure 6). Both samples are similar in size to the most distal lake bed sample on Figure 6 (Table 1). Near the dam, the cohesiveness of the bed rendered it largely impenetrable to a grab sampler. The lack of mobile sands on the bed of the channel may reflect high in-channel velocities that keep all sediments in suspension until the flow reaches the lake. It may also, however, be an artifact of the dam preventing the movement of bed material load into the last 2 km of channel. Sampling of the bed upstream of the dam was not possible at the time of data collection to test this possibility.

At the time of a field visit in 2002, the river end of the tie channel also had limited sand on the bed. The lack of mobile bed material in this region, however, is not surprising given observations and measurements of high outflow velocities and bed scour along tie channels in Papua New Guinea (Dietrich et al., 1999). Dietrich et al. (1999) have speculated that strong and possibly infrequent outflow events may be responsible for the removal of stored sediments from the channel bed and prevent channel plugging by excessive sedimentation.

6 CHANNEL EVOLUTION AND RATES OF DEVELOPMENT

6.1 *Channel Evolution*

Based on our observations of tie channel morphology, sedimentological characteristics, and the records of channel advance from hydrographic surveys and aerial photographs we present a synthesis of our understanding of channel evolution.

The oxbow lake formed by 1851 following an 1848 cut off of the meander bend (Gagliano and Howard 1984). Since 1851 the tie channel has advanced 9 km into the lake. The first hydrographic survey following tie channel formation, however, occurred in 1883, at which time the channel had already advanced a minimum of 2.8 km into the lake.

To describe the process of channel formation immediately following meander cutoff, we draw on observations of tie channels in Alaska, USA and the Fly River, Papua New Guinea. In these locations we observe that following cutoff of a meander bend coarser sediment begins to fill the limbs of the oxbow, increasing the bed height. In one or occasionally both limbs, flow into and out of the cutoff maintains a narrow channel across the developing plug. Flow only through this developing channel occurs at river stages below the plug crest, while at higher stages flow passes across the entire plug. The focusing of flow through the developing channel results in sedimentation at its outlet into the lake. Our observations suggest that this focusing of flow and localized deposition becomes a self-reinforcing process leading to development of a leveed channel that builds lakeward from plug. Over time, the plug deposit aggrades to the elevation of the main stem levee leaving the newly formed tie channel as the only connection between river and lake at river stages below bankfull.

Following establishment, the tie channel advances lakeward by a continual process of levee growth. Levees initially form as subaqueous bars along the margins of the jet; these bars progressively grow in elevation becoming emergent and vegetated at low lake stage. The development of levees appears to constrain the jet, limiting its expansion and maintaining the higher flow velocities of the channel. This feedback likely leads to erosion of the mouth bar such that the location of the bar progressively advances lakeward in conjunction with the lengthening channel. The mouth bar, in turn, may aid or enhance the growth the subaqueous bars by causing flow to diverge over its crest and focusing flow and sediment toward the margins of the jet.

The continued growth of levees following emergence occurs as a combination of processes. These processes vary depending on lake stage and water elevation in the channel. As the lake fills, the channel levees progressively become submerged and flow in the channel is no longer entirely constrained by the channel banks. We have not observed these conditions in the field, but draw on observations of laboratory experiments and tie channel morphology to speculate about possible morphodynamics.

In the laboratory we observe that levee sedimentation occurs in a narrow zone along the levee crests where intense shear between flow in the channel and the ambient lake waters cause an abrupt transition in fluid turbulence and rapid sedimentation. This mode of deposition leads to narrow well-defined levees similar to the smallest levees on Figure 4.

Local disparities in the height of levees on opposite sides of the channel (Figure 3) also suggest another mechanism for sediment transfer to the levees under inundated conditions. These elevation discrepancies occur along the length of the channel, but are particularly prominent on the outside of the tie channel bends. For example, within the last 2 km of the channel, the levee crest elevation on the outside of a sharp bend exceeds the opposite crest by up to 2.5 m. To maintain such a discrepancy in bank height, flow must preferentially exit the channel over the outside bank. This is only possible under inundated conditions because if lake levels were below the levee crests, flow would exit the channel over the lowest bank first, leading to more frequent deposition which would in turn tend to equalize the bank elevations. This process appears to broaden the levee as a whole. This effect can be seen on Figure 5.

The prevalence of splays along the length of the channel (Figure 5) is evidence of a depositional process that occurs along the channel prior to levee inundation by the lake. Splays form when water in the channel breaches the levee crests and runs down the back side of the levee. Splays tend to locally erode the levee crests and deposit sediment in lobes when the flow encounters standing water. This process broadens levees and reduces the slope away from the channel.

Numerous irregularly spaced bends mark the course of the ROR tie channel (Figure 1). These bends vary greatly in curvature and radius, ranging from broad gentle sweeps to abrupt, near perpendicular realignments of the channel course. Given the apparent absence of lateral migration of the bends in successive aerial photographs, we hypothesize that the bends form as the channel forms and advances lakeward. Unobstructed, the jet will build a straight channel until it becomes deflected by irregularities on the lake bed, the lake margins or its own deposits.

Broad gentle bends likely represent the progressive steering of a steadily advancing jet. Abrupt high angle (often perpendicular) bends may reflect short term stalls or retreats in the overall channel advancement due to channel outlet plugging or migration into a lake margin.

Figure 7 shows the development a breach in the channel levees that led to the development of a high angle bend near the current terminus of the channel. The aerial photograph taken in 1983 shows the breach located approximately 150 m upstream of the 1962 channel outlet. The channel has since built outward from this breach. It appears that the breach resulted from plugging of the channel outlet with sediment. Due to the location of this breach near the maximum extent of the channel in 1962, it may be related to the sudden change in base level caused by the dam. In Papua New Guinea, however, we have observed similar outlet plugging and breach development in unaltered channels. One possible cause may be infrequent high magnitude events that lead to deposition of large quantities of potentially coarse sediment that the channel subsequently fails to remobilize.

6.2 *Rates of Development*

The rates at which the tie channel advances lakeward, constructs its levees vertically, and fills the lake with sediment all provide insights into the processes of channel development. Changes in these rates over time offer the potential to evaluate the relative importance of various controls on tie channel development.

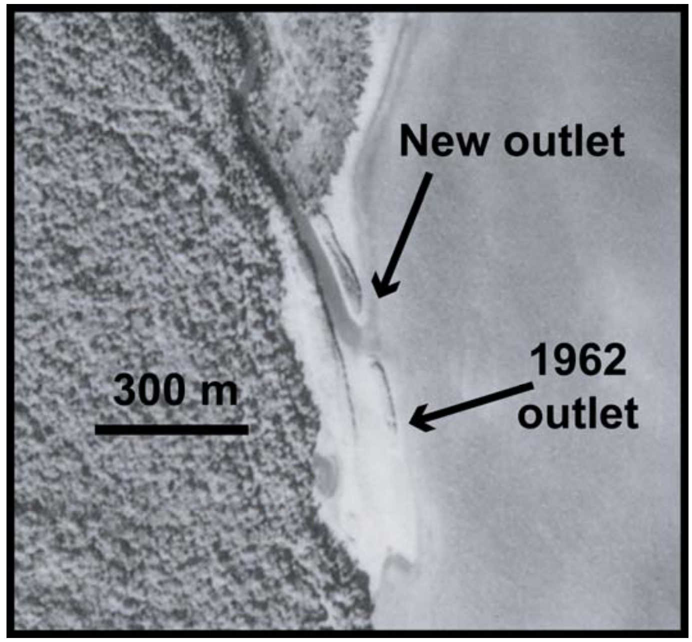

Figure 7. 1983 aerial photograph of channel outlet showing breach in left channel levee that became the present day channel course. The maximum extent of the channel in 1962 is shown with the arrow. Note the minimal advancement of the channel lakeward since 1962. This hiatus of channel advancement appears to be in response to the increase in channel base level due to dam construction in 1965.

We estimate advancement rates in two ways: 1) measurements of channel length on successive hydrographic surveys and aerial photographs and, 2) OSL dating of deposits. The determination of channel advancement rates from aerial photographs is inherently problematic. Channel lengths measured on any particular date represent the length of the channel exposed at the time of the photograph. This length varies according to lake level; given levee slopes on the order of 0.5 m/km, a 0.5 m difference in relative lake levels between photographs can represent a significant apparent variation in channel length. If the time interval between photographs is short, this discrepancy may have a significant effect on the rates calculated. In order to minimize this source of error we selected photographs taken at times of low river stage (direct measurements of lake stages are not available) and excluded photographs that showed a loss of channel length that could not be explained by channel realignments. For OSL, the error in rates arises from uncertainty in determining ages of recently deposited sediments (for discussion see Rowland et al., in press).

Figure 8 graphically displays the tie channel advancement rate with measured channel lengths plotted against the date of the survey or aerial photograph used for the length measurement. From this plot, we estimate advancement rates by determining the slope of a linear regression of the channel length over time. The rates pre-dam (before 1962) and post-dam (after 1983) show a clear change in rates, decreasing from 76.4 ± 2.6 m/yr (slope ± standard error (SE)) to 17.7 ± 6.2 m/y, respectively. The rate for 1962-1983 is assumed to be approximately 0 m/yr given the channel retreat and breach formation observed on Figure 7. Closer examination of the rates, however, indicates another change in rates, for the period before 1934 and 1934-1962. The slope of the data for 1851-1934 gives a rate of 83.9 ± 1.5 m/yr versus 53.3 ± 5.9 m/yr for 1934-1962. OSL dating also suggests a change in rates after 1930. Bases on dates provided by Rowland et al. (in press) we estimate rates 97 ± 23 m/yr (rate ± SE) for 1851-1888, 101 ± 31 m/yr for 1888-1930, and 20 ± 9 for 1930-1962 (sample locations shown on Figure 1).

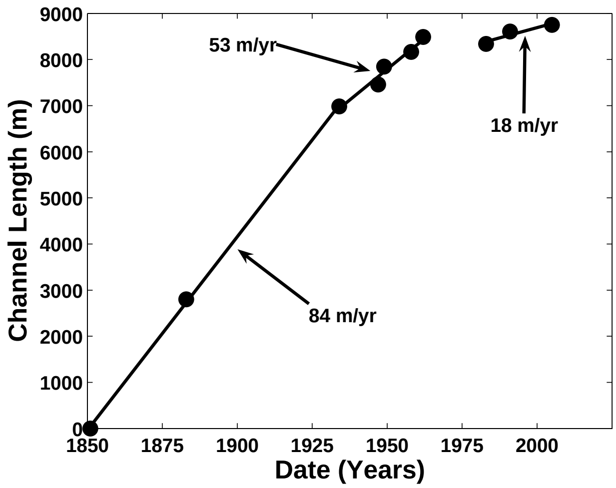

Figure 8. Channel length by date. Figure shows the progressive lengthening and advancement of the tie channel into the lake as measured from aerial photographs and hydrographic surveys. The slope of the best fit linear regression lines represents the advancement rates of the channel. Three time periods are shown: 1851-1934, 1934-1962, and 1983-2005. The lack of channel advancement between 1962 and 1983 appears to be due to channel aggradation in response to dam construction on the channel in 1965.

We examine the rate of vertical levee growth using OSL dating and a combination of aerial photographic data and ALSM data. Based on paired OSL samples, Rowland et al. (in press) made estimates for vertical accretion rates for three time periods. The rates show little variation with time: 3.4 ± 1.2 cm/yr (rate ± SE) (1930-1965), 5.8 ± 1.5 cm/yr (1965-2002), and 4.5 ± 0.6 (1888-2002). For comparison, we estimate an average accretion rate based on the ALSM data. Using the long profile (Figure 3) we determined the levee elevation at the transition between constant elevation and decreasing elevations (16 m), subtracted our estimate for minimum pre-dam lake level of 6 m and divided the result by the estimated time since channel formation at this location based on Figure 8 (~1870). The minimum level is estimated from the water level at the time of 1963 Hydrographic Survey conducted after the river had dropped to and stayed near or below 6 m for three months prior to the survey. From this analysis we obtain an estimate of 7.5 cm/yr.

We estimate lake sedimentation rates at both the local scale from Army Corps hydrographic surveys and for the entire lake by examining the total accumulation of tie channel sediments in the lake. Lake bed sedimentation rates were determined by differencing the average lake bed elevations between successive cross-sectional surveys and dividing by the time elapsed (Table 2). Both sets of cross-sections record the highest rates of deposition between 1935 and 1950 and also show a cessation of sedimentation between the 1963 and 1974 surveys. Deposition rates increase again by 1991 with rapid deposition occurring locally at R-14 as the tie channel outlet advanced to within 200 m of the survey line. The maximum measured rate was 22 cm/yr.

Table 2. Lake Bed Sedimentation Rates

	Average Rates (cm/yr ± standard error) by Cross Section		
Survey Dates	R-14a	R-14b	R-13
1935 – 1950	12.5 ± 1.4		9.9 ± 3.3
1950 – 1963	*	*	4.0 ± 2.6
1963 – 1974		0.64 ± 0.61	-0.71 ± 2.1
1974 – 1991		6.8 ± 0.48	3.0 ± 1.2

* survey line relocated due to tie channel advancement over R-14a

At present, deposition related to the tie channel has filled 6.5 km of the lake. Using the 1950 survey at location R13 as representative of the lake as a whole, we estimate a cross-sectional volume of 11,000 m^2. This representative cross-section and the 1998 USGS 30 m DEM allow for the determination of total tie channel sedimentation. On the DEM, the elevation of the lake water level lies at 6 m. The volume of sediments above this elevation is determined using common mapping software that determines the volume enclosed by map contours above a specified datum. Below the 6 m contour we assumed that sediment completely fills the cross-section to a height of 6 m for the entire length of tie channel deposits. This assumption overestimates sedimentation in distal regions of the tie channel belt, but seems reasonable for two reasons: 1) cross-sectional surveys near the terminus of the active tie channel show much of the cross-section filled to 6m, and 2) fine sediments conveyed further into the lake than the active channel region are not directly accounted for in this estimate, balancing overestimates within that region.

Based on these assumptions, the estimated volume of sediment introduced to the lake between 1851 and 1998 is 57 million m^3 or ~24 % of the total lake volume. Assuming a sediment bulk density of 1.2 gm/cm^3 the total mass of sediment is 68 million metric tons for a rate of 450,000 tons/yr.

Maps covering the lower Mississippi River from Baton Rouge, LA to Memphis, TN show evidence of 24 lakes that were at one time connected by tie channels. If we assume that all were active prior to river alteration and all received sediment at a similar rate as the ROR tie channel, the total loss of suspended sediment to lakes would be 4 % of estimated pre-1963 load (Keown et al. 1986). The assumption of 24 active tie channels seems valid in light of Matthes' (1947) estimate that 13 to 15 meander cutoffs a century occurred on the lower Mississippi River prior to significant engineering controls.

7 INFLUENCE OF SUSPENDED SEDIMENT LOAD ON CHANNEL ADVANCEMENT RATE

The observed decreases in tie channel advancement rates over the life of the channel suggest significant changes in the controls on channel development. To gain greater insight into the processes of tie channel formation we examine the relative roles of four possible controls. These controls include: 1) the 1965 installation of the low-head dam; 2) the progressive loss of lake volume due to tie channel sedimentation; 3) change in river hydrology decreasing magnitude and/or frequency of inflow events; and 4) a change in the suspended sediment load of water entering the lake. Based on our analysis, the concentration of suspended sediment entering the lake from the river appears to be the dominant factor in determining the rate of tie channel advancement.

The possible effect of the dam on advancement rates is limited to time after 1965. Aerial photographs suggest that channel advancement largely ceased between 1962 and 1983 likely in response to the dam-induced rise in minimum lake level. Since 1983, channel advancement has clearly resumed though at a much reduced rate compared to the period of 1934-1962. The dam may continue to influence the rate of channel advancement but the effect is likely small. A rise in the minimum lake level would reduce the volume of water entering the lake and hence reduce the quantity of sediment deposited. We estimate the rise in base level to be 1.4m, a relatively small fraction of the total range in lake stage (10 m).

The second possible control, progressive lake infilling, also assumes that advancement rate is related to the volume of water entering the lake. As the tie channel has advanced into the lake it has filled a portion of the lake with sediment reducing the lake volume. Even under the assumption the lake volume is directly proportional to sediment input, the estimated 24% reduction in volume since 1851 is far less than the measured 80% decrease advancement rates over this time period.

We examine two aspects of river hydrology to look for possible changes in the frequency and magnitude of inflow to the lake. First, we look at the annual maximum stages recorded from 1851 to 2004 to gain some insight into the occurrence of high magnitude events. Second, using daily stage data collected since 1935, we derive an estimate of the yearly inflow volume to the lake. Both sets of stage data were collected at the Red River Landing gauging station located approximately 8 km upriver from the entrance of the ROR tie channel and made available by the Army Corps of Engineers (daily data: http://www.mvn.usace.army.mil/cgi-bin/watercontrol.pl?01120; annual maximums in hard copy from the New Orleans District office).

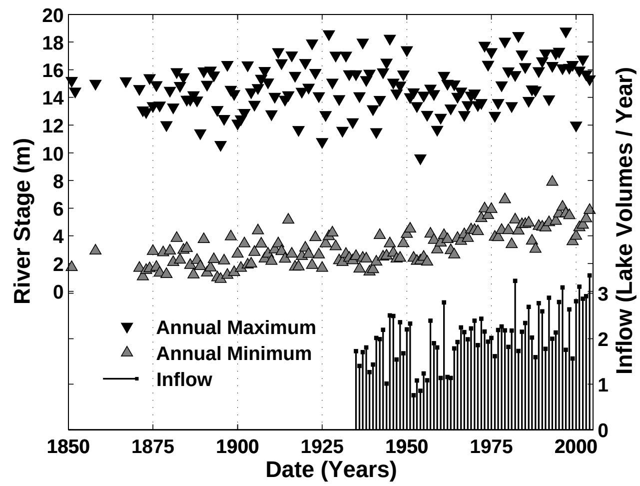

Figure 9. Yearly maximum and minimum river stages and lake inflow. River stages measured at Red River Landing 8 km upstream of the tie channel. Inflow represents the number of times the oxbow lake fills over the course of the year and is derived from daily stage data. The stage data show a progressive rise in both the minimum and maximum elevations over time. The average yearly inflow is two lake volumes but also shows a slight increase over time.

The yearly maximums (Figure 9) present a distribution of high magnitude events over the life of the tie channel, but do not, however, capture important aspects of the flood record such as the rate of rise, duration of flood conditions, or multiple large events in a single calendar year. Qualitatively the distribution of yearly high stages does not suggest a trend that would result in a decrease in sedimentation rates between the late 1800s and the present day. The trends of both the maximums and minimums show increasing stage elevations over the period of record.

As a proxy for inflow to the lake we look at rises in river stage. We assume that all incremental rises in stage, regardless of relative elevation, represent an equal volume of water entering the lake. To calculate an annual inflow volume we evaluate each daily river stage. If the stage is greater than the previous day's value and above 6 m but below 16.2 m the daily increase in stage is recorded. The sum of these rises for the year is then divided by the specified range in stage (10.2 m). The minimum represents the lake levels at the time of the 1963 hydrographic survey (discussed above) and the maximum is the average maximum tie channel levee height; above this elevation the entire floodplain becomes inundated and flow through the tie channel ceases.

The mean inflow value for the period of record indicates that the two lake volumes of water are exchanged with the river each year with a slight increase over time (Figure 9). These estimates likely represent an overestimate of water entering the lake because 1) all changes in stage do not represent an equal volume, let alone an equal quantity of sediment, and 2) lake stage lags the river, thus no inflow occurs when the river is rising, but is below the stage of the lake, or when the river stage drops prior to the lake reaching peak stage. Regardless of the inherent error in the analysis, the overall trend in river hydrology does appear to explain the observed changes in channel advancement rates.

Abundant historical data indicates that suspended sediment concentrations on the lower Mississippi River have significantly declined since the 1850s (Mossa 1996). Decreases began in the 1930s in response to soil conservation measures (Mossa 1996) and significant declines in suspended sediment load followed the construction of dams in the 1950s and 60s and the diversion of flow at the Old River Control Structures in 1963 (Keown et al. 1986; Kesel et al. 1992). Kesel et al. (2003) report a 70% decline in annual suspended load since this time and Keown et al. (1986) document a 50% decrease. This decrease in load occurred in association with a 30% decrease in discharge implying a drop in suspended sediment concentrations. While reporting an average concentration of 420 mg/L, Mossa (1996) notes that annual average suspended sediment concentrations measured between 1950 to 1991 range from 174 mg/L to 948 mg/L, but have been decreasing at a rate of 13 mg/L annually since 1950. Also of importance to tie channel evolution, Mossa (1996) reports that the percentage of sand in suspension measured at Tarbert Landing between 1950-1982 was 50% less than earlier periods.

Given the large variability in suspended sediment concentrations and the uncertainty in magnitude and timing of changes in the early 20th century, we do not attempt to calculate a decrease in tie channel advancement rates due to sediment loading. The timing and magnitudes of changes in sediment loading on the lower Mississippi River exhibit trends that match the measured trends in ROR tie channel advancement rates. This correlation and the lack of another plausible mechanism strongly suggest that the quantity of sediment entering the ROR Lake has been the dominant control on the rate of tie channel advancement.

8 DISCUSSION

Our study of the ROR tie channel suggests a number of key characteristics that must be taken into account in order to develop a model of tie channel formation and evolution. First and foremost the model must have sedimentation from a jet entering still water that promotes levee formation. This requires a pattern of deposition that is greater on the jet margins while limited along its centerline. This marginal deposition must progressively build in elevation while at the same time advancing the jet condition basinward. Data from the ROR tie channel indicates that this process represents a hydrodynamic balance between the jet and the sediment load of the tie channel.

Once evolved, the channel growth and stability requires the incorporation of processes that both build the channel vertically and widen it laterally. Observations from the ROR tie channel indicate that sedimentation on the levees occurs under conditions of complete levee submergence and as crevasse-splays across a subaerially exposed levee crest. The lateral stability of tie channels appears directly related to mass failure processes that control the width. These processes point to a critical bank angle that presumably depends on a combination of bank material properties and lake hydrology. Finally, the long-term stability of tie channels must take into account the hydrodynamic balance that allows the channel to transport large quantities of sediment without plugging. This balance likely requires an understanding of flow conditions both into and out of the lake.

Unfortunately, our understanding of the role of this bi-directional flow, as well as the process by which levees become emergent from the lake remains limited. In addition to the physical processes of controlling sedimentation on the levees, the role of vegetation in trapping sediment and promoting levee growth needs further exploration.

9 CONCLUSIONS

The ROR tie channel has advanced 9 km and filled 24% of the lake with sediment in 155 years. The channel is narrow, leveed and stable. This stability is achieved through a balance of deposition and re-entrainment of sediments by a sediment-laden jet created by the channel. The jet sorts the sediment load. The coarsest particles form levees whose continued growth propagates the channel lakeward as a prograding delta. The finest sediments, the majority of the load, settle in deeper portions of the lake and blanket the coarse sediments adding cohesion and strength to the channel banks. This strength results in narrow width to depth ratios and a channel cross-sectional geometry controlled by a combination of massive failures and sediment drapes.

The channel has remained active and stable despite significant hydrological and physical alterations of the parent river. Largely in response to significant decreases in sediment loads on the lower

Mississippi River the rate of channel advancement has decreased by 80% since the late 1800s.

At present the ROR tie channel represents a rare geomorphic feature along the lower Mississippi River. At one time, however, 65% of the lakes along the lower Mississippi River connected to the river via tie channels. Our analysis shows that these channels likely played a significant role in floodplain sedimentation, annually transferring up to 4% of the total suspended load of the river.

ACKNOWLEDGEMENTS

This work was supported in part by a grant from the Institute of Geophysics and Planetary Physics (IGPP) through Los Alamos National Laboratory, by the American Chemical Society Petroleum Research Fund, and The National Center for Earth-Surface Dynamics (NCED). We thank Jacques LaCour, Sam Bentley, and Joel Chaky for assistance with field logistics. Thanks also to Wes Lauer, Mary Power, and Christine May for assistance in the collection of field data. Luke Patterson assisted the archival research of aerial photographs.

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