

OXBOW LAKES AS INDICATORS OF GEOMORPHIC CHANGE IN SOUTHEASTERN
MISSISSIPPI

By

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To the family, friends and teachers who sparked my interests and nurtured my dreams,
this milestone would not be possible without their support and the inquisitive nature they
instilled in me

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This research encompasses a number of topics, but all relate to a relatively understudied landform, the oxbow lake. The work utilizes oxbow lakes to ascertain the extent and nature of change in a river's form, focusing on the effects of post 1950s floodplain gravel extraction on the geomorphology of the Leaf River in southeastern Mississippi. It also looks at the incidence of oxbow lakes and alluvial cutoffs across a watershed, examining the spatial-temporal distribution of these landforms for a pattern of clustering. Finally the research investigates sedimentation in oxbow lakes of varying size and condition with an eye toward defining the relationship between the lakes attributes and its longevity as a landform on the floodplain.

In-stream and floodplain gravel mining often have noticeable effects in the immediate vicinity of the activity. However, it is difficult to establish a connection between mining and dynamic channel conditions that are far removed from the explicitly impacted area. The river and oxbow lakes of a 5 km reach of stream of the Leaf River in southeastern Mississippi, USA were examined for the effects of floodplain and in-channel gravel mining. Information from 12 cross sections suggests that the current river is 35% wider and 12% shallower than the cross sectional geometry in the cutoffs.

This examination also utilized alluvial cutoffs to measure the bed elevation change of the river from roughly 1911 to 2006. Field measurements reveal that the Leaf River was relatively stable from at least 1911 to the early 1940s but has since undergone an average of 2.65 meters of degradation in the study reach. Survey data from a nearby USGS stream gage show that the river degradation began abruptly in the mid 1970s, most likely as a result of upstream mine pit avulsions that occurred at that time and have since deprived the reach below the mined area of much of its sediment load.

Oxbow lakes are the result of alluvial cutoffs. Research on meanders and alluvial cutoffs has demonstrated that such forms are complex and exhibit non-linear behavior in their development. It has been argued that these are also the result of internal processes that compel the river system to self organize. In the case of river meandering this self organization ostensibly takes the form of increasing reach sinuosity over time, which eventually moves the reach to a critical state where cutoffs are produced, thereby reducing the reach sinuosity and returning the system to a sub critical state where the movement toward the critical sinuosity resumes. This study examines more than 1000km of stream over 50 years, establishing a quantitative link between channel sinuosity and the development of alluvial cutoffs. To that end, it follows decadal changes in sinuosity and records the formation of 127 alluvial cutoffs in the Pascagoula River Basin of southeastern Mississippi, finding evidence of both spatial-temporal clustering in cutoffs and also deriving an empirical estimate of the critical threshold in reach sinuosity whereupon cutoffs begin to occur in the Pascagoula Basin.

Once these cutoffs occur, sedimentation follows and over time the cutoff is either filled or becomes an oxbow lake. Existing research on the formation of oxbow lakes

focuses on the conceptual aspects of these sedimentary processes. This work examines 156 oxbow lakes on the floodplains of the Leaf and Chickasawhay Rivers of southeastern Mississippi, finding that despite potentially mitigating factors like differing geology and regional landuse, there is a significant negative correlation between lake surface area loss and drainage area. Simply put, lakes in the lower basin have substantially longer spans on the floodplain than lakes in the upper basin. I also examine the bathymetry and sediment volume in a handful of lakes and find that the aforementioned trend with respect to basin area can only be used as a rough guide. High variability is the rule and not the exception, with local conditions driving the rates of sedimentation in these lakes to a degree that we find that the longevity of adjacent lakes as landforms differs by nearly an order of magnitude.

CHAPTER 1 INTRODUCTION

The focus of this work is not entirely topical. In lieu of limiting the scope of this effort to a series of connected research hypotheses regarding a single topic, this dissertation is driven by the study of one particular landform and the processes that create and destroy it. As such, the range of topics and hypotheses addressed in the writing that follows is broad and may appear to be disparate or only loosely related. But this appearance is deceiving in that all of the material is an examination of the different aspects of the fluvial process that prompt streams to meander, cutoff, and thereby spawn and fill in the oxbow lakes that are found on floodplains around the world.

Oxbow Lakes as Indicators of River Channel Change

Chapter 2 of this work is the most applied of the three research chapters. Its focus is on delivering an example of how alluvial cutoffs and their resulting oxbow lakes provide insight into past river channel conditions. The application of this work in this case is to determine how floodplain and in-channel gravel mining near Hattiesburg, Mississippi has altered the cross-sectional geometry and bed elevation in the Leaf River.

The stated research hypotheses for this chapter ask if oxbow lakes can be used as instruments for measuring geomorphic change in the cross-sectional geometry and bed elevation of rivers. We resolve these questions by using traditional survey methods on the rivers and floodplains of the Pascagoula Basin of southeastern Mississippi, measuring both channel geometry and relative changes in bed elevation and channel slope with a survey level.

The inspiration for this approach to assessing geomorphic change in rivers came from a paper by Marston et al. (2003) that described how gravel mining on the Malnant River in the French Alps prompted intense channel incision. During the course of this incision, local authorities attempted to arrest the resulting bank erosion by placing concrete structures into the banks along the affected reach of stream. However, the structures did not stop the erosion and as the stream incised further, they were left high above the river, serving as an indicator of the change in bed elevation since the time they were constructed.

A similar usage of alluvial cutoffs and oxbow lakes as indicators of geomorphic change is found in Erskine et al. (1992). Erskine's group did work on cutoffs created over a 60-year span along the Hunter River of southeastern Australia. Their efforts were largely sedimentological, but they did record the bed elevation of the channel cutoffs and compare them to the elevation of the present day river.

This research successfully uses a handful of oxbow lakes to help resolve the stated research questions on whether these lakes are reliable indicators of geomorphic change, finding that the lakes reveal change in both the bed elevation and channel geometry of the river over time by recognizing recent incision by the stream in the area with a precision of at least $\pm 5\text{cm}$ while also finding evidence of significant change in the cross-sectional geometry in the same reach. Furthermore, the lakes also address the larger question of what impact floodplain gravel mining has had on the Leaf River over the past 50 years, helping to ascertain the amount and spatial extent, while using the timing of the formation of the oxbow lakes to determine when changes began to occur.

Sinuosity and the Clustering of Alluvial Cutoffs

Chapter 3 of this work is largely theoretical in its focus and deals with the relationships surrounding the development of alluvial cutoffs. The processes surrounding stream meander evolution and alluvial cutoffs are well studied. However the past decade has introduced a systems-theory-based perspective to understanding how the planform dimension of rivers change over time and space. The chapter specifically asks if there is evidence of self-organization and critical thresholds in river meandering.

The hypothesis questioning the existence of self organization in planform river dynamics is approached by examining aerial imagery captured over the rivers of the Pascagoula Basin at multiple times looking at stream channel sinuosity and the incidence of alluvial cutoffs. Stolum (1996 and 1998) describes meandering in streams as a self-organizing process with an attractor in the system located at the threshold where alluvial cutoffs occur. Meaning that as the sinuosity of reach of stream increases, the rate at which it increases will also increase until one or more alluvial cutoffs occur. If we find that cutoffs occur in clusters where channel sinuosity was formerly high, we find empirical evidence for self organization.

The hypothesis on the existence of critical thresholds in river meandering is also addressed using aerial imagery. But in this case the focus is on cutoff clusters and global changes in sinuosity in the Pascagoula Basin over time. The origin for examining cutoff clusters is in Hooke's (2004) paper on a cluster of cutoffs along the River Bollin in northwest England, United Kingdom. Hooke focused upon a reach of stream 800m long and a recent spate of activity occurring there. This study extends the ideas derived from Hooke's single reach of cutoffs to an entire basin, thereby ascertaining if the results

reported on the River Bollin were unusual or out of place while assessing the cutoffs in the Pascagoula Basin for spatial and temporal clustering.

This research successfully manages find reasonable evidence for the formation of cutoffs being tied to high sinuosity. More importantly, it empirically derives the critical threshold for sinuosity and cutoff inception in the Pascagoula, thereby providing an additional basis for the existing theoretical work on river planform change.

The Infilling of Oxbow Lakes

Chapter 4 of this work encompasses a broad range of investigations on how floodplain lakes fill in and what factors influence the persistence of these landforms on the floodplain. We examine the hypothesis on the persistence of oxbow lakes using aerial imagery of the river floodplain, lake sediment cores and lake bathymetry measurements. This effort utilizes geographic information from the floodplain of the two major rivers in the Pascagoula Basin and also employs paleolimnological field data techniques that help explain the history of sedimentation in four oxbow lakes along the Leaf River.

Oxbow lake sedimentation has attracted some attention in geomorphology. Erskine et al. (1992) describes the sedimentological basis for how these lakes form, while Gagliano and Howard (1984) and Einsele and Hinderer (1997) describe how they fit into the longer-term evolution of floodplains. Recent work by Rowland and Dietrich (2005 and 2006) is particularly useful in that they use optically stimulated luminescence (OSL) to date single grains of deposited sediment, thereby following the progress of a batture channel as it fills the Raccourci Old River cutoff on the Mississippi River with sediments.

This work uncovers a number of different factors involved in oxbow lake sedimentation, providing insights into how watershed-wide processes combine with factors that are reach- or even lake-specific, creating a very diverse range of outcomes in lakes of similar size and location. Overall, this section of the larger work found that there are general trends in how oxbow lakes fill in but as a rule these lakes are highly variable, defying description through simple hypotheses. But even so, the scope of topics addressed and the general impressions garnered from the application of paleolimnological techniques to geomorphological questions make this chapter a useful addition to the existing body of work on oxbow lakes.

CHAPTER 2 OXBOW LAKES AS INDICATORS OF RIVER CHANNEL CHANGE

Introduction

The purpose of this work is to determine if oxbow lakes can be used as indicators of geomorphic change. Our research hypotheses ask if the cross-sectional geometry of the Leaf River in southeastern Mississippi differs from the alluvial cutoffs and oxbow lakes created by the river over the past 100 years and if the bed elevation of the Leaf River has changed since the formation of the alluvial cutoffs and oxbow lakes in the study.

We resolve these questions by utilizing field surveying techniques to determine the changes in channel geometry and bed elevation. The application of these techniques in this case is directed towards ascertaining what impacts floodplain gravel mining has had on the river over the past half century where we use the oxbow lakes as proxies for the former predisturbance river.

Measuring River Channel Change

It is difficult to assess the “baseline” or predisturbance character of many rivers (Kuhnle et al., 1996). This is because the changes that occur often destroy the old channel and any evidence of predisturbance conditions. Schumm (as cited in Erskine et al., 1992) notes that most studies of river metamorphosis are inhibited by the channel change itself. Because the old channel and any basis for comparison with current conditions are destroyed in the process of change, it is necessary to look for other means of comparison.

Research on earlier river conditions has utilized paleochannels in the sediment record (Schumm, 1968), floodplain deposits (Knox, 2001; Owens, 2002), and point bar

deposits (Brooks, 2003) as proxies for former channel conditions. These techniques have been employed to determine the channel geometry, bed materials, and flow conditions of streams in the past. Such techniques, augmented with historical evidence in the form of maps and aerial photographs, can provide a window into past channel conditions (Uribelarrea et al., 2003).

Allen (1965) describes the processes operating after a stream avulsion prompts the abandonment of a section of channel. The former channel is eventually separated from the new channel by the deposition of bed load materials at the ends of the cutoff in contact with the river. Once this occurs, the lake becomes a zone of quiet water and begins to fill with sediments in suspension delivered during overbank flows. The end result is the filling of the cutoff with material that differs sedimentologically from the material in the bed of the original river channel. This, in essence, makes each oxbow lake a record of a river's bed elevation and form.

Erskine et al. (1992) assessed the usage of alluvial cutoffs as indicators of former channel conditions. In that study, four cutoffs that occurred between 1890 and 1956 on the Hunter River in southeastern Australia were used successfully to compare former and current bed elevations and bed material sizes with past conditions recorded in the morphology of the cutoffs. Erskine et al. (1992) found evidence of about 0.1 m of bed elevation rise on the Hunter River in southeastern Australia between a cutoff in 1890 and the 1987 channel. In the same study, he found 1 m of degradation between a 1956 cutoff and 1987, showing that this technique for utilizing cutoffs to measure changes in bed elevation was able to discern both a long period of relatively slow aggradation and the relatively intense 30-year period of degradation that followed. This study adopts a

similar approach to determine change in riverbed elevation after the inception of the lake as well as comparisons of the cross-sectional geometry of the lake as a relict form of the river.

Factors Affecting River Channel Change in the Study Area

The Leaf River in southeastern Mississippi has been exposed to a variety of human impacts near the study area at Hattiesburg, Mississippi. Timber harvesting, agriculture, and urbanization have all played some role in the metamorphosis of the Leaf River since European settlement in the area. Agriculture and deforestation are generally associated with increased erosion in stream basins (Knox, 2001), filling channels and valleys with sediment. Knox (1972) noted the historical increase in floodplain alluviation in southwestern Wisconsin streams as valleys in agricultural areas filled in with silt-loam sediments.

Urbanization is typically associated with prompting a reverse effect, whereby a stream's sediment load is reduced relative to its capacity to transport sediment out of the basin. Regardless of the land use impacting the stream, we generally expect that aggradation of the bed is associated with widening of the channel, whereas degradation of the bed prompts narrowing of the channel. The exact effect that occurs is dependent on the nature of the impact and whether it results in an increase or decrease in the delivery of sediment to the river. That said, it is clear that in the case of this study, the aforementioned impacts are overshadowed by the extensive effects of gravel mining on both the floodplain and the channel itself.

In-channel and floodplain extraction of gravel can affect river form and process in multiple dimensions, causing the channel to move laterally by inducing channel cutoffs or avulsions (Mossa and McLean, 1997). Near-channel gravel mining can encourage

channel shift in the planform, causing the channel to move laterally by increasing erosion (Davis et al., 2000). Gravel extraction can also force changes in cross-sectional form. Kondolf et al. (2002) found that gravel extraction on the Drome River in France reduced bed load supply and fostered a channel incision of between 2 and 5 m in over one-third of the study area. This degradation caused the channel in formerly wide and braided reaches to narrow by 60% from 1947 to 1970. Another effect of in-channel or floodplain gravel mining is the instigation of channel degradation both upstream and downstream of the mine site (Davis et al., 2000). Marston et al. (2003) recorded 7 m of incision in 25 years above a gravel pit in a small stream in the French Alps.

The effects of in-channel gravel mining on the geomorphology of a stream often propagate up and down the stream from the site of the mining. The slope on the upstream side of the extraction pit is often increased locally. This increase in slope can be accompanied by an increase in the erosion rate as the channel incises headward toward a new graded profile (Galay, 1983). The downstream side of the pit undergoes a transformation similar to stream reaches found on the downstream side of a dam. The pit acts as a reservoir that traps incoming sediment (Kondolf, 1994). This reduction in the input of sediments from upstream reaches increases erosion rates locally as the stream reacquires its sediment load (Kondolf and Swanson, 1993). Degradation in the channel above and below the site of extraction can propagate in tributaries both upstream and downstream as the perturbation in the longitudinal profile of the stream moves through the system. The effects of channel incision are manifest in increased bank erosion (Kondolf, 1994). The effects of channel incision can also cause an increased suspended load and channel instability (Mossa and McLean, 1997)

throughout the drainage network. The incision can also be accompanied by channel widening as exposed banks are subjected to an increased likelihood of failure (Collins and Dunne, 1990).

Sand and gravel aggregate in many areas is obtained from alluvial deposits, either from pits on the river floodplains and terraces or by in-channel mining. These are preferred sources of gravel because of the ease of access as well as the quality of the material (Davis et al., 2000). Sand and gravel subjected to prolonged transport in rivers is particularly desirable as a source of aggregate because the materials remaining are durable, rounded, and well-sorted gravels (Barksdale, as cited in Kondolf, 1997). In-stream gravels are of the highest quality and are suitable for use in the production of Portland cement (Barksdale, as cited in Kondolf, 1997).

In-stream mining also directly alters channel geometry and bed elevation. It can be carried out by excavating trenches or pits in the gravel bed or by scalping or planning gravel bars to a lower slope from the summer waterline. In the Leaf River, the gravel bars in the study reach were largely removed during the 1980s (S. Barefield, Pat Harrison Water Management District, personal communication, August 2006), prompting substantial geomorphic adjustment in the reach. In many cases, the existing channel morphology is directly disrupted, and the local sediment balance is severely altered (Kondolf, 1997). These direct effects can disrupt the continuity of sediment flow and prompt channel incision, bed coarsening, and lateral channel instability in surrounding reaches (Kondolf, 1994). The disruption of the balance between sediment supply and the stream's transport capacity affects the local geomorphology, so a local

sediment deficit will promote incision both upstream and downstream of the area of mining.

In-channel mining alters the longitudinal profile of the stream, creating a headcut at the upstream end, which can develop into a nickpoint with sufficient excess stream power to begin migrating headward. These nickpoint migrations have been recorded propagating upstream for several kilometers, both on the main channel and in tributaries to the mined stream (Germanoski and Ritter, 1988; Stevens et al., as cited in Kondolf, 1997). Gravel pits trap much of the incoming bed load sediment, creating the same effect as a dam and reservoir. This typically causes erosion downstream, as the stream attempts to regain a portion of the lost sediment (Kondolf, 1994). An example of mining-induced nickpoint migration occurred in 1992, when an air photo of Cache Creek, California, showed in-stream mining up to the miner's property boundary. The mining activity ended at the property boundary with a 4-m-high headwall. After the 1993 winter flows, the headwall nickpoint had migrated 700 m upstream at a depth of over 3 m. By 1995, the migration had moved 1400 m upstream, where it nearly caused a bridge to fail (Kondolf, 1997).

The direct effects of mine-induced incision can include the undermining of bridges and other river structures. This seems to be so widespread that in 1995, the U.S. Department of Transportation issued a notice that federal funds would no longer be available to repair bridges damaged by gravel mining (Kondolf, 1997). Such longitudinal change can disrupt the existing equilibrium channel form and have lasting effects on channel stability in the planform. Incision can cause undercutting or oversteepening of banks, thereby increasing lateral migration. These effects often propagate both up and

down the main channel and tributaries, causing channel widening and increased delivery of sediment to the main channel (Harvey and Schumm, 1987).

Another subtle effect of gravel mining on stream geomorphology in the southeast coastal plain is that the removal of the gravel from streams increases the proportion of sand and finer material, prompting a predominately sand bed channel substrate, which is more easily eroded. The removal of coarse material increases the mobility of the channel bed, further increasing erosion rates and promoting incision. It was noted that in the pregravel-mined Leaf River Basin, the gravel component of the bed served as armor for the rest of the finer components of the bed (U.S. Army Corps of Engineers, Mobile District, 1983). It has also been said that the removal of gravel bars by in-channel mining can eliminate hydraulic control for the reach upstream, causing scour and eventual washout in the upstream riffle.

Extraction of gravel from the channel and floodplain typically results in a wider and shallower streambed, leading to increased water temperatures, modification of the pool-riffle distribution, and alteration of both the plan and longitudinal forms. These effects are long-lasting because of the severity of the disruption to sediment transport in the system. In-stream mining extraction rates often exceed the natural sediment supply by 1 to 2 orders of magnitude (Kondolf and Swanson, 1993).

Floodplain pit mining transforms large areas of the floodplain into open ponds, often at the same water level as the nearby stream. A narrow strip of unmined land is often all that separates these ponds from the river, so stream and pit interactions are likely. Existing pits are often steep-sided to maximize the gravel yield, so they offer little in the way of floodplain or wetland habitat. Pit capture commonly occurs when the

narrow strip of land between the pit and river is breached by lateral channel erosion or floodwaters (Kondolf, 1997). This turns floodplain mines into in-channel pits, which usually are accompanied by in-channel mining effects, notably the propagation of incision both upstream and downstream of the pit.

The Yakima River in Washington State was diverted by two floodplain pits in 1971 and undercut the highway for whose construction the pits had originally been excavated (Dunne and Leopold, 1978). An off-channel pit avulsion occurred on the Clackamas River in Oregon in 1996. This avulsion and capture of an off-channel pit resulted in 2 m of incision up to 1 km upstream (Kondolf, 1997). Once the pits are formed, they are likely to remain and impact the geomorphology of the river over the human span of time because refilling the pits is prohibitive due to the cost involved. The proposed cost of filling two pits on the Tuolumne River in California was \$5.3 million (Kondolf, 1997).

While there is already a strong body of work on the effects of mining on stream geomorphology, there is the opportunity to utilize direct comparisons between the current channel and past channels to obtain detailed measurements that will explain exactly how much change has occurred and over what length of time. The purpose of this study is to assess the effects mining has had on the geomorphology of the Leaf River by measuring the geometry of the channel before the mining occurred. This study documents changes in the geomorphology of a 5 km reach of stream over the past 100 years.

Regional Setting

The Leaf River Basin

The Leaf River Basin drains 9280 km² of the Longleaf Pine Belt Region of the southeastern Coastal Plain in Southeastern Mississippi. Elevations in the basin range

from 150 m above sea level at the head of the basin to 10 m above sea level where the Leaf flows into the Pascagoula River. The Leaf River generally flows southward, until it joins with the eastward flowing Bowie River. After this confluence, the river continues first south, then southeastward, and finally eastward, until it joins with the Chickasawhay River to form the Pascagoula River.

The study area is a 12 km reach located immediately downstream of the confluence of the Leaf and Bowie rivers at Hattiesburg, Mississippi (Figs. 2-1 and 2-2). The combined drainage area of the Leaf and Bowie at the study area is approximately 4550 km². The Bowie River drains roughly 1750 km² (nearly 40% of the total drainage area). The floodplain elevation in the study area is approximately 35 m with the areas overlooking the river rising to as high as 50 m. The floodplain in the study area is generally 1–3 km wide but is only a few hundred meters wide as it flows past Hattiesburg.

The local geology includes the Pliocene- to Pleistocene-age gravels of the Citronelle Formation; the Miocene-age Hattiesburg and Pascagoula formations, comprising clays, sand clays, and sands; and the Eocene-age Chickasawhay Limestone of the Vicksburg Group. The river interacts with both the Citronelle and Hattiesburg formations in the study area, with the Citronelle Formation providing the source for the reworked fluvial gravel that is extracted in the region.

Both the Leaf and Bowie rivers are alluvial streams with dynamic floodplains. The Leaf River channel in the study area displays the signs of regular lateral migration, experiencing five meander cutoffs in the last century. The bed material for the Leaf River was classified as 78% well-graded sand and 22% small- to medium-sized gravel

in the study area, while the Bowie River near the study area has a substantially coarser bed material of 30% sand and 70% gravel (U.S. Army Corps of Engineers, Mobile District, 1983).

The upland vegetation is predominately pine and oak. The longleaf pine *Pinus palustris* was the dominant tree species in the region but is now long gone after being timbered out during the timber boom in the late 1800s and early 1900s. Floodplain vegetation is bottomland hardwoods and has traditionally been sweet gum, *Liquidambar styraciflua*; sweet bay, *Laurus nobilis*; red maple, *Acer rubrum*; black willow, *Salix nigra*; and bald cypress, *Taxodium distichum*. At this time, the study area floodplain is overrun with the recent addition of the invasive Chinese privet *Ligustrum sinense*.

The climate in the region is semitropical and humid, with hot summers and cool winters. The mean temperature for 105 years of record is roughly 20°C. Annual rainfall is approximately 140 cm and is nearly evenly spread across the year, with fall being the driest season and spring being the wettest season (U.S. Army Corps of Engineers, Mobile District, 1983). The main rainmaking mechanisms in the region are winter and spring frontal precipitation, summer convectional precipitation, and summer tropical storms.

Of these mechanisms, only winter and spring fronts produce serious flooding in the Leaf River. A U.S. Army Corps of Engineers, Mobile District (1983) study lists seven major floods of record for Hattiesburg, Mississippi, between 1900 and 1974. The April 1974 flood crested over 10 m at the Hattiesburg stream gauge at the upper end of the study area. The estimated peak discharge for this event was over $3400 \text{ m}^3 \text{ s}^{-1}$. Since

the 1983 study, there have been three floods (April 1980, April 1983, and May 1990) with greater than $1500 \text{ m}^3 \text{ s}^{-1}$ discharge (Fig. 2-3).

Land Use History

The history of European land use in the study area begins with settlement in the early 1800s, but the town of Hattiesburg was not founded until 1884. At that time, the town became a rail and transportation hub, and the surrounding area began to be utilized for lumber and, to a lesser degree, agriculture. Timber production was at its peak between 1890 and 1930 (Howe, 2001). Over time, timber production has declined, yet it remains a major source of revenue in the region.

Sand and gravel extraction began on the rivers in the area in the 1940s. Historically, the primary area of mining operations was on the Bowie River, just upstream of its confluence with the Leaf River. The American Sand and Gravel Company began mining operations on the floodplain in this area in 1946, but over time, the Bowie River has occupied the extensive pit areas on the floodplain. The mining operations in this area occupy over 7 km^2 of the floodplain. The total volume of the material removed is difficult to assess, but the company reported that it planned to remove $2,000,000 \text{ m}^3$ from this area between 1981 and 1986 at a rate of $400,000 \text{ m}^3 \text{ a}^{-1}$ (U.S. Army Corps of Engineers, Mobile District, 1983). This estimate, when extrapolated over the 50-year span during which mining was allowed in this area, provides an estimate of nearly $20,000,000 \text{ m}^3$. The yield of material per year was most likely much less prior to the 1980s, but it is not unreasonable to assume that several million tons of gravel have been removed from the area.

There are other gravel operations in the area, but they are comparatively smaller. Local landowners, in partnership with gravel companies, have mined most of the Leaf

River floodplain gravel deposits in the study area. During the late 1970s and early 1980s, the gravel bars and channel of the study reach were extensively mined (S. Barefield, personal communication, August, 2006). In-channel gravel mining was forbidden in 1995 (Mossa and Coley, 2004a), so current gravel extraction in the study area is limited to gravel bars on the interior of former channel cutoffs.

The Study Reach

Field measurements were taken from one specific reach of stream less than 5 km south of Hattiesburg, Mississippi (Fig. 2-2, focus area). This reach of the Leaf River is approximately 5 km long, with a strongly alluvial character and a dynamic channel with an active floodplain. In the study reach, five meander cutoffs have occurred in the past century, each resulting in an oxbow lake. This cluster of alluvial cutoffs was created over roughly 50 years, with the first occurring in the early 1900s and the last occurring between 1955 and 1960. Of the five oxbows formed in the reach, only four were available for study. The fifth and most recently formed lake was removed in a gravel operation in the late 1980s. The other four lakes vary in age and in their exposure to the gravel operations in the area.

The uppermost of the remaining four lakes is Aldrich Lake. Its formation predates air photos and available maps for the area, but botanical evidence from bald cypress *Taxodium distichum* tree cores suggest that the inception of the lake is 1911 ± 10 years. The lake is located on private land in an area set aside for hunting and fishing. In the last 40 years, numerous gravel operations have occurred in the area, but not in the immediate vicinity of the lake, which remains surrounded by deciduous forest.

Immediately downstream of Aldrich Lake and on the opposite bank side of the river is Owens Bluff Lake. This lake is so named because it rests against the valley wall

or bluff created by the Leaf River. This lake also predates air photos but is estimated through botanical evidence to have formed in 1927 ± 10 years. This lake also rests on privately owned land. However, the landowner began extracting gravel roughly 30 years ago and continued for approximately the next 20 years, before shutting down operations in the vicinity. This has had a noticeable effect on the lake in that gravel was removed from the point bar of the cutoff meander and then replaced with sand spoils from the surrounding area.

Further downstream is Wedgeworth Lake. This lake is estimated to have formed between 1926 and 1942, but after Owens Bluff Lake. The lake is privately owned at the moment but used to be a popular fishing area for the local community. It is unique among the four lakes in the study in that it has a small creek flowing into it. Over the past 70 years, sediment from this creek created a bar that is now forested and completely separates the oxbow. Wedgeworth Lake now suffers badly from a handful of invasive exotic water plants, including one of the first recorded outbreaks of giant salvinia, *Salvinia molesta*, in Mississippi.

The final lake in the study is Sims Lake. This lake is located furthest downstream and was formed last of the four lakes in the study. It was formed between the 1942 and 1955 sets of aerial photographs, most likely in the earlier portion of this time period. The lake is completely contained in a privately owned plot of land, with surrounding forest being largely undisturbed. The lake is used for recreation, and as a result, the landowner has made some alterations, partially dredging the shallow, point bar side of the lake in the 1980s and constructing a concrete sill at the outflow of the lake, raising the lake surface by nearly a meter.

The Leaf River in this area displays a shallow and wide channel geometry, with wide sandbars exposed along the channel margin during the low-flow summer months. The channel form is predominately a single channel in summer, with short, braided sections at many riffles. A braided morphology is uncommon in the Leaf River both spatially and over time but occurs regularly in this area, suggesting that the reach is disturbed, with a much higher width depth than is customary in the region. During winter and spring high flows, the river occupies more of the traditional floodplain and covers over most of the sandbars but leaves high areas dry enough to be colonized with riparian vegetation.

Materials and Methods

Stream and Cutoff Cross Sections

The study compares the current stream cross-sectional geometry with the past geometry in the stream stored in the cross-sectional form of the oxbow lakes created by past stream cutoffs. This is accomplished through the use of 24 surveyed cross sections, four from each of the four oxbow lakes and another eight cross sections from the Leaf River.

The lake cross sections were surveyed at regular intervals on the downstream limb of the oxbow. The downstream limbs were selected because the upstream limbs in the two oldest lakes are now sediment-filled swamps, whereas the downstream limbs in all four lakes have remained relatively open. The first cross section was located whenever possible at the apex of the former meander, with each subsequent cross section being roughly two channel widths below the last cross section. Each cross section began well up on the now vegetated point bar of the former river and ended atop the high, steep bank on the outside bend of the former meander. Both the water

level and the often submerged river bankful level were identified on the cross sections whenever possible to generate cross-sectional geometry comparisons free of the effect of changing water levels. All depth measurements in each cross section included both the water depth to lake sediments and the total depth to the original riverbed.

River cross sections were collected from four meanders, two from each river meander closest to each oxbow lake. The first cross section was located at the apex of the meander whenever possible and the second cross section was placed between two and four channel widths downstream of the first cross section. Each river cross section began at the upper vegetated portion of the river point bar and ended well up the high, steep bank on the opposite side of the meander.

Cutoff and Lake Age Estimates

Each of the four cutoffs of the Leaf River used in this study appears to have occurred in the first half of the 20th century. All but one of those meander cutoffs predates the air photos available for the area, making it difficult to establish even relative dates for the origination of each of the cutoffs. This study utilized both information from aerial photographs and botanical evidence to estimate the age of each oxbow lake (Table 2-1). We obtained the 1955 series of air photos for the study area and have a report (U.S. Army Corps of Engineers, Mobile District, 1983) on this reach and its cutoffs that includes information on the cutoffs relative to the 1942 series of air photos.

The botanical evidence comes in the form of Harper's hypothesis (Harper, 1912). Harper used trees in a study also located on the southeastern Coastal Plain to establish the age of oxbow lakes. He used tree cores from the oldest bald cypress *Taxodium distichum* tree growing on the bar deposits between the river and the oxbow lake. His

study has recently been tested and was found to give decadal-scale precision on the age of oxbow lakes (Shankman, 1991). Shankman found that after a meander cutoff, the bar deposits in the southeastern Coastal Plain are colonized by black willow *Salix nigra* first, but are rapidly replaced after about 60–80 years by bald cypress.

We searched each of the forested areas occupying the bars that formed at the ends of each oxbow lake for bald cypress trees and then collected tree cores at breast height from 10 trees in each stand. The age of the oldest tree in each stand plus 70 years provides an estimate of the closing of the lake to continuous river flow ± 10 years.

With aerial photography information, we can deduce that Sims Lake occurred after 1942 but before 1955. The river in the 1942 photos occupies the meander that is now Sims Lake. By 1955, the cutoff has occurred, and the lake is completely detached from the river, with vegetation covering the scars of the old river channel. This suggests that the cutoff forming Sims Lake occurred very early in the period between 1942 and 1955.

Wedgeworth Lake predates both the 1942 and 1955 photos, but in the 1942 photos, the cutoff that formed the lake is still connected to the river, suggesting that it occurred only a few years before the photograph. This argument for an origin in the late 1930s is supported by the absence of bald cypress seedlings in the area. At the time of the study, only 64 years had elapsed since the photo showing that the cutoff joined with the Leaf River.

Both Owens Bluff and Aldrich lakes were well established as cutoffs detached from the Leaf River in the 1942 air photographs. Both have established stands of bald cypress on the bar deposits that separate each lake from the river. The oldest bald cypress found on the deposits at Owens Bluff Lake was 9 years old and the mean of the

stand was 6.8 years. These data suggest that Owens Bluff was separated from the river around 1927 ± 10 years. The oldest bald cypress on the deposits at Aldrich Lake was 25 years old and the mean of the stand was 21.6 years, yielding a date of origin of 1911 ± 10 years.

Lake Bed to Riverbed Elevation Changes

This study attempts to determine the change in riverbed elevation since the time of each cutoff. We accomplish this by surveying from the water surface of the lake to the water surface of the river and then up or down the water surface slope along the riverbank to the location of the current river channel cross sections. Because of the distance and number of turning points involved as well as the density in vegetation and uneven terrain, each survey path from lake to river was cleared of vegetation and then surveyed as a closed loop repeatedly until the result was reproduced three times in succession. The results of these calculations were then applied to the survey data from the cross sections to determine the relative difference in bed elevation between the mean depth of the current river cross sections and the mean depth of the lake cross sections that represent the river elevation in the recent past.

The field-based data have been supplemented by additional data from the U.S. Geological Survey (USGS) stream gauge on the Leaf River at Hattiesburg, Mississippi. These data come from the repeat surveying of the cross section at the USGS stream gauge located roughly 6 km upstream of the study reach. These survey cross sections serve to record the aggradation or degradation of the Leaf River at the one location over the past century.

Results

Channel Cross-Sectional Geometry Measurements

The results from the channel cross sections display a marked contrast between the current river channel and past river channels that are recorded in the morphology of the oxbow lakes. While there is some variation in cross-sectional geometry from lake to lake, the between-lake variation is smaller than the lake-to-river variation. Table 2-2 shows the width, mean depth, cross-sectional area, and width:depth ratio for the Leaf River at its field-estimated bankful stage.

The most noteworthy portion of the summarized data on the Leaf River is the presence of the second cross section as an outlier. The other seven cross sections have mean depths of greater than a meter and relatively narrower channels than the outlying cross section. This particular cross section has a mean depth of only 0.7 meters and a width:depth ratio that is nearly three times greater than the other cross sections. It is known that in-channel gravel mining disturbed the area, and it appears that much of the point bar in this area was removed, leaving a disrupted channel morphology with braided characteristics. At present, a mid-channel bar has developed where the former edge of the point bar resided. This bar is isolated from the rest of the point bar by a relatively minor second channel similar to a chute cutoff. This channel is present even at low flows, and recent high flows have not been great enough to inundate the bar, so it has now been stabilized with vegetation, creating an island that is likely to remain for the near future.

The lake cross sections are displayed in Table 2-3. Each lake has a decidedly different character, but overall, the lake cross sections are narrower and deeper than the river cross sections. Aldrich Lake has relatively deep cross sections. This lake is the

least disturbed in the study, and its cross section provides good insight into the character of the Leaf River nearly a century ago. Although the cross sections show some variability, all are narrower than the current river and overall have comparable to greater mean depths. As a result, the width:depth ratio of Aldrich Lake is significantly less than the bankful width:depth ratio of the Leaf River.

Owens Bluff Lake is also highly variable in its cross section metrics. This particular lake has a strongly disrupted character, with the point bar deposits on the inside bend of the oxbow serving as the site of a gravel-mining operation for over 20 years. As such, sandy stockpiles from the site have filled the channel, potentially making the cross section measurements an underestimate of the overall channel size. Despite this, the narrower cross sections tend to have comparable to deeper mean depths than the current river, and the one largely undisturbed cross section displays metrics very similar to the relatively undisturbed Aldrich Lake.

The Wedgeworth Lake cross sections are also summarized in Table 2-3. This lake possesses three fairly shallow cross sections due to sediment inflow from a local creek that now drains into the oxbow. These sediments are nearly indistinguishable from the Leaf River bed sediments at the bottom of the lake, so the depth of the cross sections may be underestimated slightly. In all cases but one, the channel preserved in the oxbow lake is relatively narrower than the current river channel.

Sims Lake has the deepest cross sections in the study, but much of this can be accounted for by the lake owner's decision to dredge the shallow portion of the point bar, creating a much more symmetrical cross section than would be expected from a well-developed meander. Of all the oxbow lakes in this study, Sims Lake provides the

least information about the cross-sectional geometry of the past Leaf River. Its disturbance makes direct comparisons troublesome.

Bed Elevation Measurements

In addition to the assessment of cross-sectional change in the Leaf River over the past century, this study also looks at the change in bed elevation over that time span. We do this by measuring the relief from the bottom of the lacustrine sediments in each oxbow to the bottom of the riverbed. This is accomplished by surveying from the lake water surface to the river water surface and then accounting for the mean depth in each water body. It is important to note that the depth data displayed in Table 2-4 are the wetted mean depth of the Leaf River and not the bankful mean depth displayed in earlier tables.

Fig. 2-2 shows the location of each oxbow lake and each modern meander that was measured in the study. The comparisons were not always direct with regard to the axis of the river valley, but Aldrich, Owens Bluff, and Wedgeworth lakes were all compared to the Leaf River meander that occupies the same segment of the Leaf River Valley. Sims Lake happens to be located in a valley segment with a nearly straight reach of stream, so it was compared to the channel geometry of the meander immediately upstream. The water surface slope for that reach of stream is 0.0002 m m^{-1} , so the 500 m of stream distance represent 10 cm of rise from the area of the lake to the meander to which it was compared. The results shown in Table 2-4 account for these 10 cm of rise from the lake to the river.

The results show that all four lakes sit well above the current Leaf River. This shows that the last 50 years have seen a substantial amount of channel degradation. The fact that the Leaf River bed sits 2–3 m below all the cutoffs that occupy the former

channel bed also suggests that channel degradation was most likely negligible before the Sims Lake cutoff. If this were not the case, then we could expect the elevation change from the Aldrich Lake cutoff to the river to be substantially greater because of the additional 40 or so years between these two cutoffs.

Rates of degradation, when averaged over the entire span, are fairly consistent at 30–60 mm a⁻¹. But it is likely that most of the degradation occurred post-1960. This places the rates for Sims Lake noticeably higher than the denudation rates inferred for the other three lakes. The assessment that the results in Table 2-4 are largely recent and not spread across the entire span of the century covered in this study is conjecture when taken alone. Fortunately, there is ample supporting evidence for relative stability in the bed elevation in this portion of the Leaf River during the first 60–70 years of the 20th century.

The USGS maintains a stream gauge at Hattiesburg, Mississippi. This gauge is located roughly 6 km upstream from the focus study area (Fig. 2-2). The gauge is immediately downstream of the Leaf and Bowie river confluence and has been in operation since 1938. Its cross section has been measured at roughly monthly intervals by the USGS during the past 70 years. This repeated at-a-station sampling of the Leaf River's thalweg elevation is shown in Fig. 2-4. The individual markings denote each observation, while the heavy gray line denotes a five-sample moving average for the observations. The heavy black line marks out a yearly moving average for the entire set of observations. The most noteworthy facet of this figure is the relatively stable thalweg elevation prior to 1978, contrasted with the oscillating series of measurements since 1978. The fluctuation in thalweg elevation at the gauge cross section was largely in a 3

m range for the first 40 years of observations. But during the past 30 years, the oscillation has covered a range of over 6 m, and the series seems to have settled about a thalweg elevation that is a full 3 m less than the average condition in the 30 years before. We will discuss bed elevation changes at the gauge and in the study area in greater depth in the discussion section that follows.

Discussion

Changes in Channel Geometry

When the cross sections from each lake and the Leaf River are averaged, we find that the river tends to have a higher width, a higher channel area, and a mean depth comparable to the oxbow lakes. The averages for these metrics as well as the width:depth ratio from the river and each of the four lakes are summarized in Table 2-5.

It is important to recognize that the river metrics are representative of the bankful discharge as estimated in the field. When the wetted dimensions of the channel are considered, the differences between the four oxbow lakes and the current river are far more striking because the summer flows in the Leaf River are well below the flows encountered during the rest of the year, particularly in the spring.

Such a comparison is inappropriate because the oxbow lakes' wetted dimensions appear to be fairly consistent throughout the year and reasonably close to the former river's bankful stage, as evidenced by the geomorphic break. In each of the lakes, there was a relatively stable outlet during the 12 months during which they were under observation. Local landowners who observe each oxbow regularly further confirmed the stability of lake surface levels in recent years.

The relative consistency of the lake surface belies another important difference between water surface levels in cutoffs and water surface levels in the river: the

absence of a water surface slope. This absence of slope is manifested in the tendency for some of the uppermost cross sections to display a water level slightly below the defined geomorphic break. By the same token, the lower cross sections in some lakes were inundated above the bankful level, making it difficult to recognize subtle geomorphic features. This difficulty was also compounded by the disturbance to some of the lakes.

Despite these difficulties, the average conditions are generally representative of the samples. Each lake's individual character is displayed in the summary, and the Leaf River average represents seven of the eight cross sections very well. Fig. 2-5 shows a scatter plot of cross-sectional width versus cross-sectional depth. Each lake tends to occupy its own region of the graphic, with the partially dredged Sims Lake displaying the highest mean depths and widths overall. The other lakes show some within-lake variability, but overall, they are narrower than the cluster of measurements from the modern channel. With the exception of two lake observations, the Leaf River measurements are wider than or just as wide as any of the lake measurements.

By the same token, Fig. 2-5 shows that the estimated bankful depths found in the Leaf River are generally shallower than the depths found in the cutoffs. This comparison is quantified with a Wilcoxon rank sum test. The Wilcoxon is a two-sample nonparametric test that is designed to work with ranked observations. In this case, the $m = 16$ lake cross section observations were compared to the $n = 8$ river cross section observations using a large-sample approximation of the rank distribution for $N = 24$ observations. The results of these tests are shown in Table 2-6, with both the z -score and the resulting p -value for each metric. The Wilcoxon was used because it is a robust

test that is not strongly influenced by outliers like Leaf cross section 2 or cross sections in the dredged point bar area of Sims Lake.

Table 2-6 can be read to provide the following interpretation: The bankful channel width of the current Leaf River differs significantly from past channel conditions recorded in the oxbow lakes. The Leaf River is significantly wider than it was in the past; this is at odds with what was reported in the River Drome by Kondolf et al. (2002) and most likely the result of in-channel gravel mining, which only ceased a decade ago. At the same time, the recent channel area of the Leaf River does not differ significantly from past channel conditions. This is the case because the channel area has largely been conserved by a nearly significant adjustment in channel mean depth, where the Leaf River is now perceptibly shallower than it was in the first half of the 20th century. Finally, these two effects are evidenced best by the miniscule p -value for the width:depth ratio comparison. Despite any variation in their age, surrounding land use, or land cover, the four oxbow lakes, as a combined sample, have a significantly lower width:depth ratio than the current Leaf River.

Changes in Bed Elevation

As stated earlier, the Leaf River channel bed is currently at least 2 m below the channel bed of the cutoffs. Despite the 40-year span between the first cutoff and the fourth cutoff, all the cutoffs are located 2–3 m above the current riverbed, indicating that the degradation has taken place since the formation of the last cutoff in the early 1940s. Evidence of a similarly timed episode of degradation is found at the USGS stream gauge located 6 km upstream, where the gauge had a relatively stable bed elevation for roughly 4 decades before undergoing 6 m of degradation in the late 1970s and then

oscillating about before coming to rest roughly 3 m below the predisturbance elevation (Fig. 2-6).

Episodes of channel degradation are common in areas with gravel mining. Marston et al. (2003) reported 7 m of incision on Malnant Creek, and Rinaldi et al. (2005) provides a nice review of studies that have reported upstream and downstream incision as a morphological effect of sediment mining in alluvial channels. The U.S. Army Corps of Engineers, Mobile District (1983) also recorded 2.5 m of degradation at the Glendale Bridge over the Bowie River, located just 4 km upstream of the USGS gauge and just 10 km above the reach where this study is focused. At that time, the degradation was attributed to the American Sand and Gravel Company's operations on the floodplain in this area. These operations began in 1946, and since that time, the Bowie River has been transformed into a series of pits 4 km long and covering the entire floodplain.

On April 15, 1974, the mean daily discharge for the Leaf River at the Hattiesburg gauge was over $3400 \text{ m}^3 \text{ s}^{-1}$ (Fig. 2-3). This flood was the largest in the historical record, and during the flood, the Bowie River occupied the entire floodplain. During that flood, it seems that the Bowie River adopted a course through a series of pits. Since that time, all bed load transport through the reach has stopped. Over the past 30 years, evidence of the capture of the bed load sediments can be found in the sizable delta that has developed on the channel inflow to the uppermost of the pits.

The implication of the Bowie River occupying these pits is substantial. Recall that each pit creates a reservoir effect that disrupts sediment flow through the system, creating a sediment deficit downstream of the impacted area (Kondolf, 1994). The

USGS stream gauge that figures so prominently in this study is located only 250 m below the last pit on the Bowie River. The Bowie joins with the Leaf River just upstream of the gauge, and the Leaf River both upstream and downstream of this confluence appears to be severely disrupted. The reach above the confluence is the most dynamic reach on the Leaf River and had the highest rates of planform change in the 164 km of stream analyzed by Mossa and Coley (2004b).

The timing of these effects at the confluence of the Leaf and Bowie rivers is within the period when the degradation occurred in the study area. But it is difficult to establish a direct link. The effects may extend 6 km downstream to the study reach, or they may be largely unrelated and the result of local effects. But it seems the timing of the degradation at the confluence and downstream in the study reach is more than coincidental and may be tied together. Kondolf (1997) reported a nickpoint migration of 1400 m, nicely illustrating the far-reaching impacts of gravel extraction. It is highly likely that the more subtle indirect effects associated with a disruption to the sediment flow of a stream can extend much further.

This disruption to the flow of sediment in the Bowie River is particularly relevant because 78% of the bed material for the Leaf River is finer than 2 mm, whereas only 30% of the bed material for the Bowie River is finer than 2 mm (U.S. Army Corps of Engineers, Mobile District, 1983). These pits on the Bowie River are depriving the lower Leaf River of its primary supply of the coarse material. It is this material that serves to armor the sandy bed of the river, thereby slowing the rate of erosion.

Given the rate of sedimentation in the upper pit and the depths of the pits in the area, which approach 17 m (Mossa et al., 2006), it is unlikely that supply of Bowie River

sediments will be restored in a human span of time, meaning that the channel degradation occurring in this area of the Leaf River is unlikely to cease altogether anytime soon, and its effects on the geomorphology of the Leaf River are expected to become more extensive over time.

While the large changes occurring at the Leaf River and Bowie River confluence are a likely factor in the degradation at the study reach, in-channel gravel mining in the reach also plays a large role. In the U.S. Army Corps of Engineers, Mobile District (1983) report on the Leaf River, the longitudinal profile of the study reach is described in detail. These observations were made before in-channel gravel-mining operations began in the reach.

This report describes the thalweg slope for the upper portion of the study reach as being roughly 0.0012 m m^{-1} . This is specifically mentioned as one of the steeper slopes found in the Hattiesburg area and is likely a result of the shortening of the channel via the multiple cutoffs in the reach. Measurements from the lower portion of the study reach are categorized as being adverse in the area downstream of Wedgeworth Lake, before sloping downward at 0.00039 m m^{-1} to the Sims Crossing Bridge.

Our measurements in the field were on the water surface slope, but we found a similar trend where the river in the vicinity of Aldrich Lake had a slope of 0.0005 m m^{-1} , before decreasing to as little as 0.0001 m m^{-1} in the area below Wedgeworth Lake, and then finally increasing to 0.0002 m m^{-1} at the lower end of the study reach. The water surface slope and the location of the oxbow lakes relative to the river are displayed in Fig. 2-7. First note that as was described earlier, all the lakes are well above the Leaf River. But also note the adverse slope between the third cutoff (Wedgeworth Lake) and

the fourth Cutoff (Sims Lake). The overall shape represented by the four cutoffs mirrors the longitudinal form described by the U.S. Army Corps of Engineers, Mobile District (1983) report. This adverse slope appears to have been largely eliminated in the modern Leaf River, with the water surface slope remaining fairly constant over the bottom half of the study reach. This could mean that the degradation and changes to the slope in the reach have occurred as recently as the 1980s.

We would expect that a nearly 3-decade-long episode of channel degradation would create an incised channel with a fairly low width:depth ratio. But this is not the case in the study area, and in fact, the reverse is true. Rinaldi et al. (2005) reviews 27 studies on streams impacted by gravel mining; in this review, incision and channel narrowing are reported together seven times, whereas channel incision and widening are reported only rarely (Kondolf, 1997). The high width:depth ratios found in the study reach of Leaf River may stem from local effects and the recent in-channel gravel mining on the point bars, whereby the bar material was removed as it was exposed by incision. But it also may be that the degradation that occurred in this area is largely a result of a shock to both the volume and composition of the sediment flow in the Leaf River. Meaning that upstream gravel mining that occurred decades ago on the Bowie River was the real impetus for the disturbed character of this reach of stream.

Conclusion

Regardless of the forces inducing change in this portion of the Leaf River, the geomorphology of the channel differs significantly from the form displayed in the four cutoffs that span 30–40 years of the first half of the 20th century. We can explicitly state that the evidence from the oxbow lakes reveals a river that has undergone relatively rapid change both in cross-sectional form and in bed elevation; proving that these

landforms are indicators of past channel conditions and can be utilized as measuring sticks for geomorphic change.

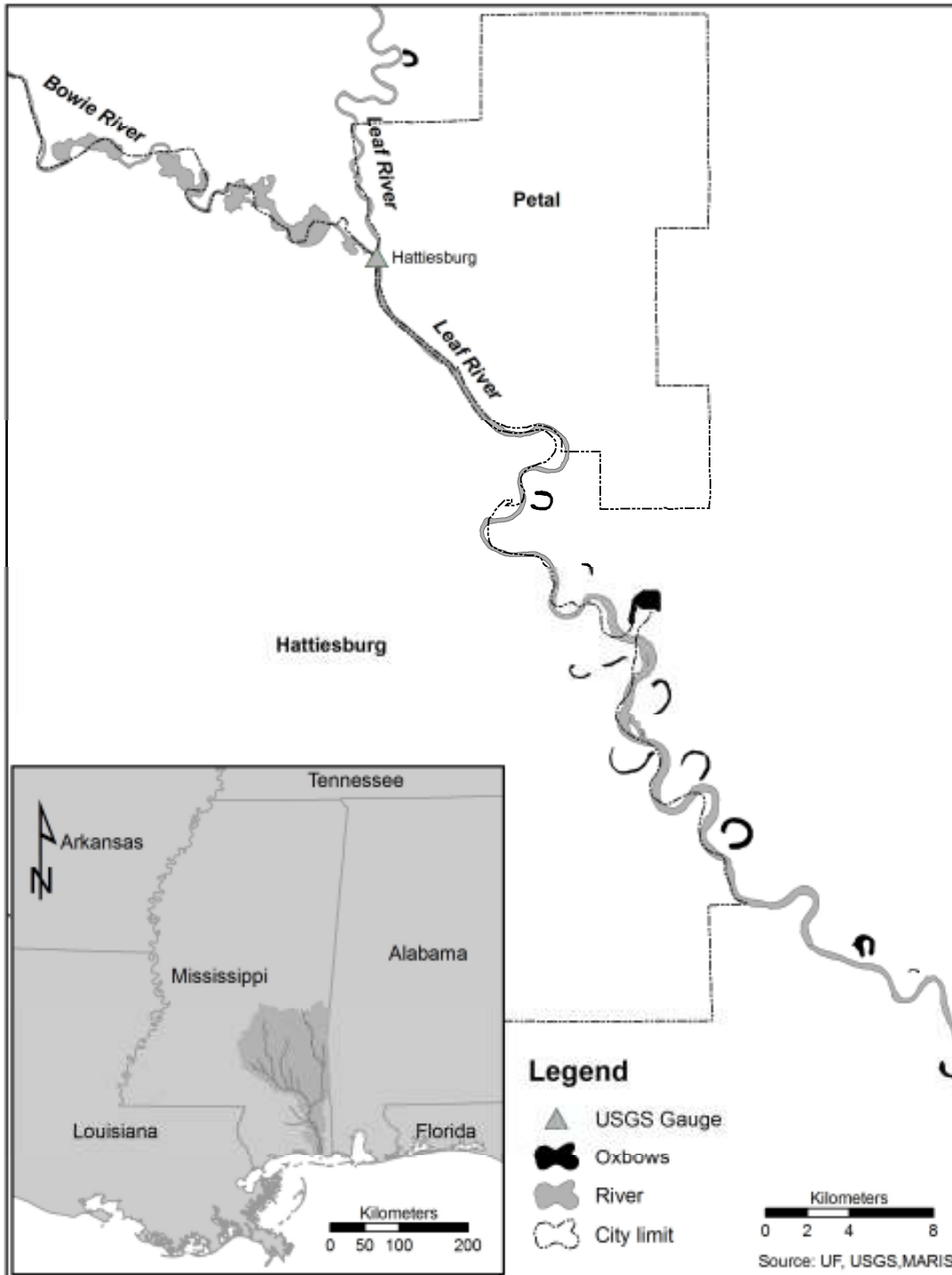


Figure 2-1. Map of the study area, showing the Leaf River near Hattiesburg, Mississippi, and the location of the U.S. Geological Survey (USGS) stream gauge

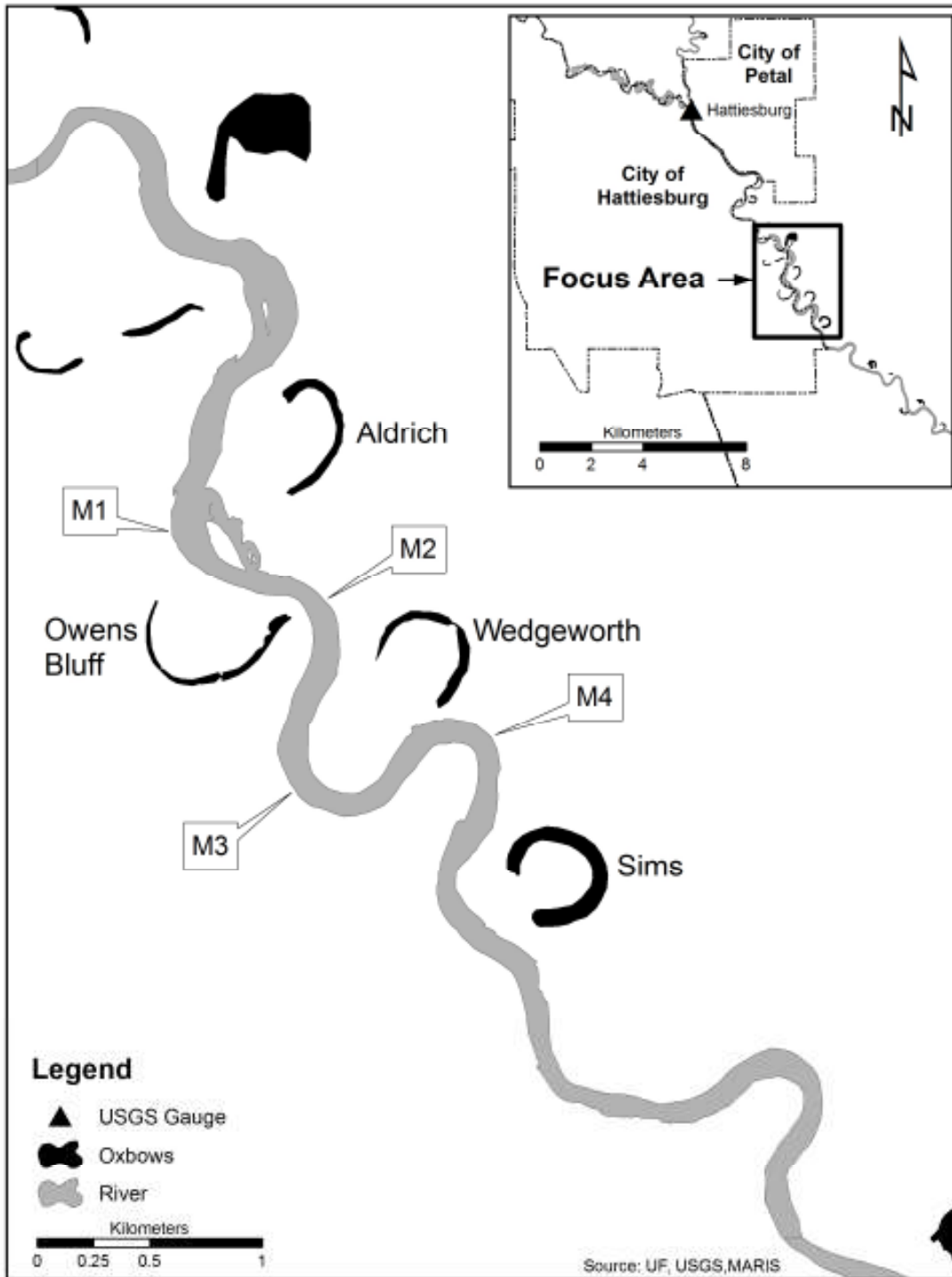


Figure 2-2. Study area map showing four oxbow lakes and Leaf River meanders along with the location of the USGS stream gauge

LEAF RIVER AT HATTIESBURG

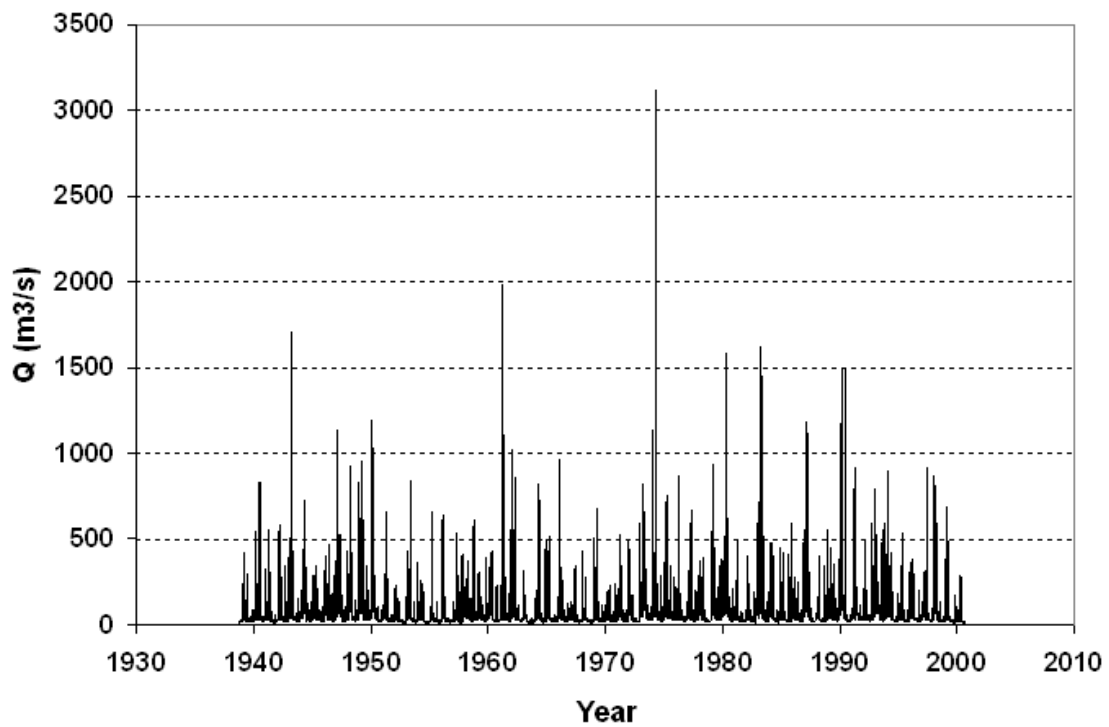


Figure 2-3. Sixty years of daily streamflow data for the Leaf River at Hattiesburg, Mississippi

Table 2-1. Bald cypress *Taxodium distichum* tree ring data and lake age estimates

Oxbow Lake	Time of cutoff	Dating method	Bald cypress stand
Aldrich	1911 ± 10 years	Tree core	Oldest 25 years, mean 21 years
Owens Bluff	1927 ± 10 years	Tree core	Oldest 9 years, mean 7 years
Wedgeworth	Late 1930s to 1942	1942 aerial photographs	No cypress trees present
Sims	Mid 1940s to 1955	1955 aerial photographs	No cypress trees present

Table 2-2. Summary of the river cross sections

Cross section	Meander	Width (m)	Area (m ²)	Mean depth (m)	Width:depth
Leaf River 1	M1	56	62	1.12	50
Leaf River 2	M1	88	62	0.71	124
Leaf River 3	M2	59	85	1.44	41
Leaf River 4	M2	65	87	1.35	48
Leaf River 5	M3	54	69	1.28	42
Leaf River 6	M3	50	60	1.20	42
Leaf River 7	M4	58	63	1.08	53
Leaf River 8	M4	62	82	1.33	47

Table 2-3. Summary of the lake cross sections

Lake	Cross section	Width (m)	Area (m ²)	Mean depth (m)	Width:depth
Aldrich	1	34	64	1.92	17
Aldrich	2	40	81	2.01	20
Aldrich	3	35	41	1.15	31
Aldrich	4	29	33	1.11	26
Owens	1	22	17	0.77	28
Owens	2	19	22	1.18	16
Owens	3	24	20	0.80	30
Owens	4	77	96	1.24	62
Wedgeworth	1	46	39	0.86	53
Wedgeworth	2	51	42	0.82	62
Wedgeworth	3	82	111	1.35	61
Wedgeworth	4	37	35	0.92	41
Sims	1	67	128	1.91	35
Sims	2	66	121	1.85	35
Sims	3	62	120	1.95	32
Sims	4	55	97	1.74	32

Table 2-4. Showing cutoff to riverbed elevation change

Lake	Mean depth (m)	Relief from lake surface to river surface (m)	River	Wetted mean depth (m)	Total difference (m)	Years (est.)	Rate (mm a ⁻¹)
Aldrich	1.13	2.51	Meander 1	0.49	3.15	95	0.033
Owens	1.02	2.07	Meander 2	0.91	2.18	79	0.028
Wedge	1.14	1.87	Meander 3	0.97	2.04	65	0.031
Sims	1.85	2.37	Meander 4	0.98	3.24	57	0.057

Thalweg Elevation at USGS Gauge, Hattiesburg, MS

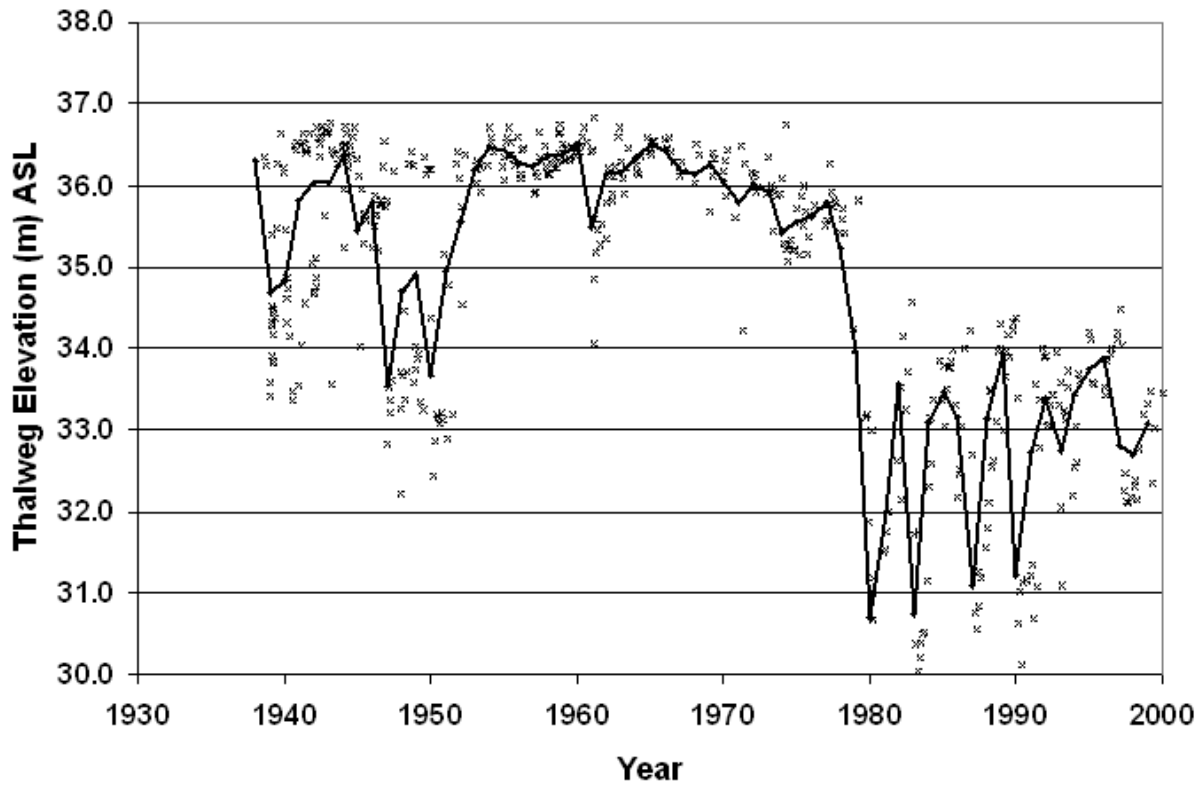


Figure 2-4. Thalweg elevation changes up to the year 2000 at the USGS stream gauge, Hattiesburg, Mississippi. The heavy black line denotes the 12-sample a^{-1} moving average.

Table 2-5. Showing lake and river averages for width, area, mean depth, and width:depth

Cross section	Age	Width (m)	Area (m ²)	Mean depth (m)	Width:depth
Leaf River	Current	62	71	1.19	56
Sims Lake	1940s to 1955	62	116	1.86	34
Wedgeworth Lake	1930s to 1942	54	57	0.99	54
Owens Bluff Lake	1927 ± 10 years	35	38	1.00	34
Aldrich Lake	1911 ± 10 years	35	55	1.55	24

Channel Cross sections

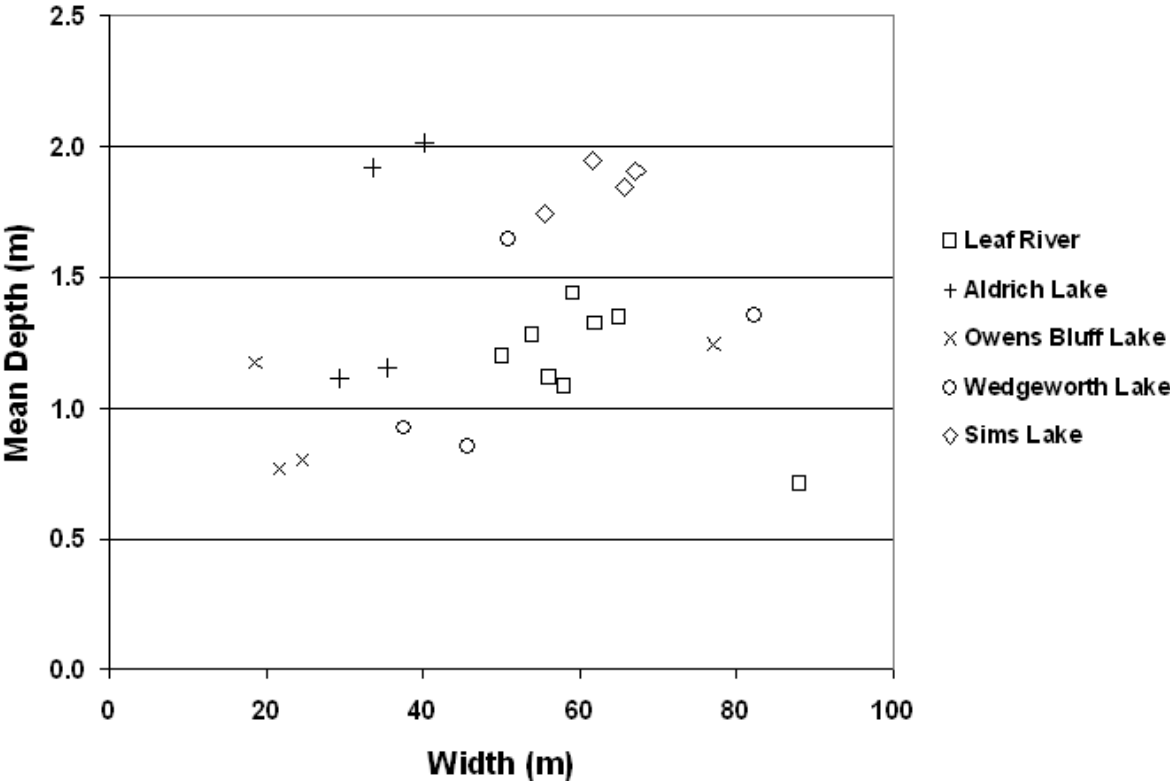


Figure 2-5. Bankfull width and mean depth comparison for Leaf River 2006, Sims Lake circa 1950, Aldrich Lake circa 1911, Wedgeworth Lake circa 1938, and Owens Bluff Lake circa 1927

Table 2-6. Results of the Wilcoxon rank sum statistical comparison for width, area, mean depth, and width:depth

Channel metric	z-Score	<i>p</i> -Value	<i>N</i>	<i>m</i>	<i>n</i>
Bankful width	1.71	0.043	24	16	8
Bankful mean depth	-0.92	0.179	24	16	8
Bankful channel area	0.43	0.334	24	16	8
Bankful width to depth	2.69	0.004	24	16	8

Bed Degradation from 1974 Average

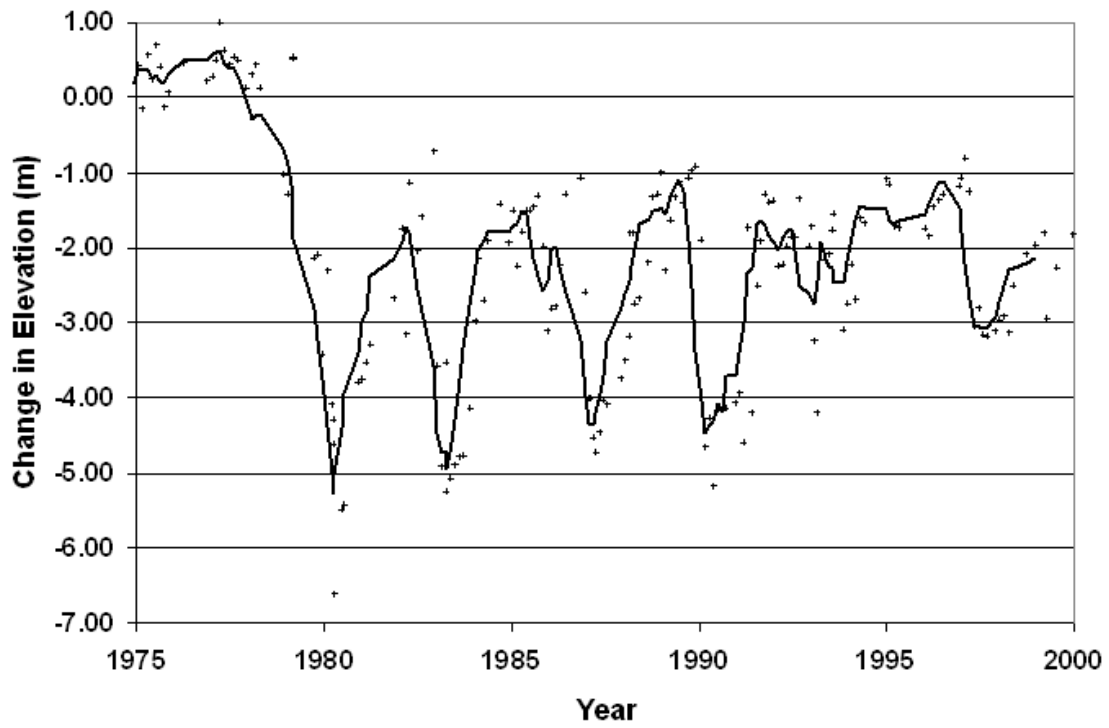


Figure 2-6. Thalweg elevation changes over the past 25 years at the USGS stream gauge, Hattiesburg, Mississippi. The heavy black line denotes the five-sample moving average

Leaf River Water Surface and Oxbow Lake Water Surface

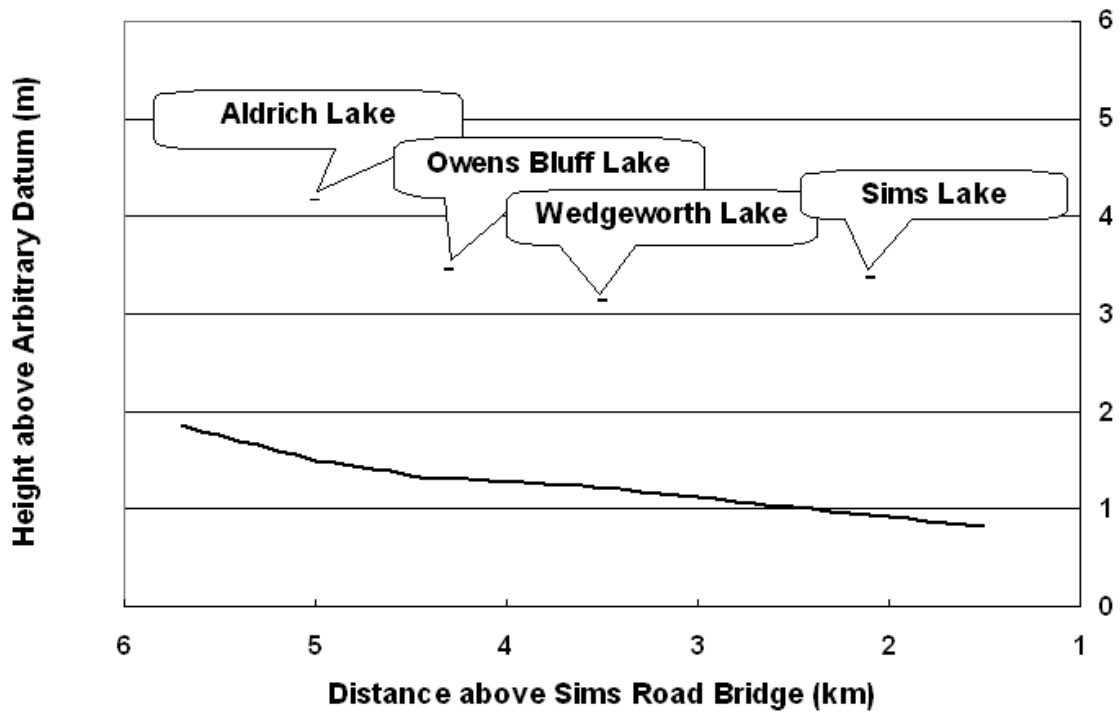


Figure 2-7. River and oxbow lake relative water surface elevations

CHAPTER 3 SINUOSITY AND THE CLUSTERING OF ALLUVIAL CUTOFFS

Introduction

The question driving this work asks if there is evidence of self organization and critical thresholds in the system governing river planform dynamics. Our specific research hypotheses ask if there is evidence of self organization through spatial clustering in the alluvial cutoffs of the Pascagoula River Basin of southeastern Mississippi. They also ask if there are critical thresholds in sinuosity where alluvial cutoffs form in the Pascagoula River and its tributaries. The questions are resolved through the use of multiple sets of aerial river planform imagery; charting changes in the river's planform and sinuosity over time and space.

Problems of Scale and Time in Study

River meandering induces alluvial cutoffs, which leave oxbow lakes on floodplains around the world. Active meandering rivers impact floodplains and human endeavors whenever humans intrude on the floodplain. Therefore it is necessary to better understand the dynamics of meandering rivers, cutoffs, and oxbow lakes, particularly over the human scale of time. While understanding is necessary for both applied and theoretical reasons, the study of many phenomena associated with streams is problematic over such short scales of time. Many meander processes, including meander extension and meander translation, occur with some regularity on the landscape over the human life span; however, meander cutoffs can occur only rarely or not at all over the same timescale.

Availability is a key aspect to the problem of time in geomorphic inquiry (Schumm, 1991). In most cases, there is simply not enough time to observe a reach or segment of

stream for alluvial cutoffs. This problem is further compounded by spatial-temporal scaling issues: cutoffs have been reported as occurring with some frequency in the upper reaches of a stream network (Hooke, 2003), but in most cases, these particular reaches of stream have been largely unobservable due to the length of the temporal record and spatial resolution limitations of remotely sensed imagery (Stolum, 1998). On the other hand, the lower reaches of river networks have large, easily observable streams, but they seem to operate at a much slower pace, creating alluvial cutoffs too slowly over the decades since air photo and satellite imagery have been available.

Past research on meander dynamics and alluvial cutoffs in planform geometry has focused either on extensive sections of the lower portions of the largest of rivers, like the lower Mississippi (Gagliano and Howard, 1984; Hooke, 2007b) or the Amazon River (Stolum, 1998), or on short stretches of smaller streams where alluvial cutoffs occurred (Hooke, 2003, 2004). In each case, the scale of the study is limited either by data availability or by the pace of the processes themselves. This study attempts to bridge those efforts by examining the streams of the Pascagoula River Basin of southeastern Mississippi over 50 years across a range of scales, from the smallest tributary streams recognizable in air photos to the Pascagoula River, which drains nearly 23,000 km².

Meandering and Alluvial Cutoffs in a Dynamic System

Meandering is the root cause of alluvial cutoffs. As rivers meander, they induce a progressive increase in channel sinuosity (Hooke, 1995). It is this tendency to increase in sinuosity that eventually prompts meanders to elongate and eventually to cut off.

Meandering has been associated with steady state equilibrium in largely unconfined alluvial rivers. The meandering process is viewed as one of the means by which a stream adjusts its grade via sinuosity so as to reach an equilibrium state in

response to external forces (Leopold and Bull, 1979; Schumm, 1993). Equilibrium has been a core concept in the study of streams over the past 50 years. The concept of geomorphic systems began with the work of Strahler and Chorley (Phillips, 1992). The systems approach to geomorphology unraveled many questions about how the landscape operates. Geomorphologists have long recognized that geomorphic systems often behave in unexpected ways. Often these unexpected forays by systems into complex behavior could reasonably be attributed to outside factors that intruded on the workings of an open system. But in many cases, there was an understanding that some of these systems operate with internal thresholds (Schumm, 1979) and that the very idea of steady state equilibrium entails a certain degree of self-regulation within the system.

As was alluded to previously, planform changes via meandering also alter the gradient of the stream in the longitudinal profile. A number of explanations related to external factors have been given for meandering behavior and associated cutoffs in rivers; some of these are summarized by Hooke (2004) and include climate- or human-induced land cover change. However, over time, there has been a move toward accepting the inherent instability of meander courses and the complexity of forms that develop in meanders over time (Hickin, 1974; Stolum, 1996). Conceptual models of bend evolution have been developed that show nonlinearity in rates of meander development. This nonlinearity has also been recognized directly from empirical evidence (Hickin and Nanson, 1975). Studies of nonlinearity in meander movement versus the radius of curvature in meanders have found that beyond a certain curvature relative to the channel width, meanders tend to grow more rapidly (Nanson and Hickin,

1983). Meander migration is nonlinear, with the tendency to migrate at low curvature; a tendency to grow or extend at higher curvature; and a tendency to develop further complexity in form near the limits of curvature, until the meander is cut off and removed from the river course (Hooke, 2007a).

Once again, this nonlinear behavior has been attributed to external factors (climate, land cover change) that have forced the system into a period of adjustment. This thinking is in alignment with the notion of an equilibrium system with a single average condition that differs only in response to external forces. However, recent work, influenced by developments in other fields, has introduced a nonlinear hue to the view on geomorphic systems in general and to river meanders and their evolution in particular. It is recognized that in a number of rivers, there is no equilibrium condition evident over historical timescales (Hooke, 2007a). Closer examination of meanders at recent timescales reveals that meanders behave in a nonequilibrium manner, with compound forms, varying rates of growth, and surprising complexity in their development.

This trend for unconfined alluvial streams to increase in sinuosity until alluvial cutoffs occur is well established. Schumm (1979) used the process as the very definition of an intrinsic threshold in river systems. Hooke (2004) reports a sustained increase in sinuosity for periods as long as 150 years in Britain, where the increase in sinuosity in specific reaches was followed abruptly by a period of alluvial cutoffs. The link between meandering as a mechanism to increase sinuosity and cutoffs as a mechanism to decrease sinuosity is well established. Sinuosity is the critical measure for understanding meander dynamics and alluvial cutoffs. Because meander

development is nonlinear and increases as each meander progresses, sinuosity in the system would technically operate with a positive feedback. The more sinuous the reach, the more developed the meanders, the faster the rate of growth or elongation in the meanders, and thus the greater the sinuosity. There is, however, a theoretical threshold to sinuosity. Stolum (1996) places this value at π (pi); once the upper bound is reached, the system theoretically encounters a threshold at which alluvial cutoffs begin to occur, reducing sinuosity and returning the system to a sinuosity below the threshold. Hooke (2007b) found, after analyzing 24 segments of the Mississippi River over 150 years that the highest values in sinuosity tend to be followed by a decline and that the upper bound for sinuosity is just over 3, after which cutoffs tend to occur.

Multiple forms of cutoff have been categorized and described. Lewis and Lewin (as cited in Hooke, 1995) found five types of cutoff in 14 streams in Wales. These were divided by the location on the meander as well as by morphological and sedimentological characteristics. Lewis and Lewin reported that the most common location for meander cutoffs was in the middle portion of the basin, where stream power was greatest, but they also noted that neck cutoffs had a tendency to occur in the lower portion of the basin, where lower gradients prevailed, whereas chute cutoffs seemed to occur in steeper areas. Other studies have also categorized meander cutoffs. Erskine et al. (1992) cited four types of meander cutoff in a paper on Australian rivers. They mentioned neck and chute cutoffs, as defined by Allen (1965); mobile bar cutoffs from Lewis and Lewin's work; and bend flattening from Matthes (1948).

Neck and chute cutoffs are the result of the river finding a more direct route down-valley. As meandering progresses, the distance traveled by the river around the bend

lowers the local gradient substantially, creating opportunities for more direct and steeper gradient pathways to capture the river and direct its flow along a new course. Neck cutoffs occur when a new channel is cut across the narrow neck of an elongated meander. Once this occurs, Erskine et al. (1992) describes a process in which the bed load sediments in the river channel plug the immediate ends of the abandoned channel, creating an isolated cutoff or oxbow lake. After this point, very little infill occurs from bed load sediments, and the bulk of sedimentation is via fine sediments delivered during episodes of overbank flooding. Chute cutoffs happen in a similar manner to neck cutoffs; however, the new, shorter path is typically in a swale or existing low point on the inside of a current meander bend. In these cases, bed load material is transported into the cutoff behind a point bar, and the material continues to accumulate, until the upper end of the cutoff is closed. After this, overbank fines tend to become the dominant sediment type, but frequent pulses of coarse material are often deposited, creating a diverse environment sedimentologically.

Hooke (1995) examined a reach of the River Bollin between Wilmslow and Macclesfield on the Cheshire Plain. The Bollin has a drainage area of 55 km and a mobile channel that has experienced a number of cutoffs in recent years. Two cutoffs occurred between 1980 and 1985; the first occurred in 1980 and was a neck cutoff with a 275 m loop with a 0.3 m drop in elevation. The second was a cutoff that occurred in December 1985, a few meanders downstream from the first cutoff. This is a commonly reported phenomenon, where the effects of one cutoff can be passed upstream and downstream, propagating outward and destabilizing adjacent reaches of stream, prompting further cutoffs. Hooke (1995) studied these cutoffs closely after their

occurrence, finding that it took from less than 1 year to 7 years for the cutoffs to be closed off from the rest of the river. Gagliano and Howard (1984) found, in their study of the lower Mississippi River oxbows, that cutoffs took 2–10 years to experience “blockage” from the main channel. Some cutoffs of the Leaf and Chickasawhay rivers of the Pascagoula Basin were closed on the upper end after 1 year, but not at the lower end. However, both ends appear to be completely closed off after 10 years (personal observation).

Hooke’s (1995) work on cutoffs of the River Bollin was on a reach that has been mapped in detail since the 1840s. Over that span, a 600 m reach (valley distance) increased its sinuosity from an initial low of 1.52 to 2.92 in 1979. Only four cutoffs occurred over that time span, so there was little to reduce the sinuosity in the system. Since that time, however, there have been multiple cutoffs: two in the 1980s, which were mentioned earlier, and then another six, which occurred between 1998 and 2002. All but one of these was a neck cutoff, and collectively, they reduced the sinuosity to 1.40 by 2002. Since that time, the reach appears to be stable and largely unchanged.

Cutoff clusters like the one mentioned earlier have been reported in the literature, but in many cases, they have been ascribed to urbanization upstream (Mosley, as cited in Hooke, 2004) or to climatic fluctuations (El Niño–Southern Oscillation–driven flood/drought regimes; Erskine et al., 1992). Hooke (2004) argues convincingly that the cutoffs in River Bollin are a result of internal processes, with the clustering as evidence of the natural instabilities associated with self-organized criticality.

Self-Organizing Systems, Thresholds, and Criticality

The 38th Binghamton Symposium was on “Complexity in Geomorphology.” In a white paper following the conference, Murray et al. (2009) named the examination of the

magnitudes and spatial and temporal patterns of self-organized processes as one of the great challenges in geomorphic inquiry today. Self-organization in natural systems is well established as the tendency for certain systems to develop certain reoccurring, regular forms. This tendency is attributed to inherent or autogenic drivers that are independent of external forces.

Landscapes are created by complex interactions between processes and forms in an open system. If an autogenic behavior causes systems to evolve toward a threshold state, then the system tends to move toward a critical state, experience an event or fallback at the threshold, and then resume its movement back toward the critical state (Phillips, 1999). This type of behavior in systems is known as self-organized criticality (SOC) and has been observed in a number of natural systems. The recognition and introduction of the concept of self-organization in natural systems began with the work of Bak et al. (1987). Bak's work was on sandpiles and supposes that many natural systems evolve toward an unstable or critical state, at which minor perturbations can set off large changes within the system. The incidence of an event or perturbation may or may not induce large changes, but the hallmark of SOC behavior is sensitivity within the system to minor changes.

Stolum's (1998) work on SOC in rivers used three large meandering rivers in the Amazon Basin as well as a model river to simulate and conceptualize a system that is unobservable at the human scale of time. For the details of this deterministic fluid mechanical model, Stolum (1998). Stolum's system exhibits a range of sinuosity from 1.00 to around 3.14 in an unconstrained environment. In the system, a sinuosity of 1.00 is not only a straight path down-valley, but also represents an "ordered" or subcritical

state (Hooke, 2004). However, the nature of meandering and its tendency to increase sinuosity over time creates an attractor within the system. Sinuosity is pulled toward increasing values, until a critical state is reached in the system and cutoffs may begin to ensue. If cutoffs do not occur, then the system continues to increase in sinuosity (and disorder), becoming supercritical, whereby multiple cutoffs or cutoff clusters (Hooke, 2004) occur. These differing processes for adjusting sinuosity within the system create a system that oscillates within a range of sinuosity, yet is self-organized, with an inherent tendency to move toward the attractor and criticality (Fig. 3-1).

Regional Setting

The setting for this study is the Pascagoula River Basin, which occupies southeastern Mississippi as well as a small portion of southwestern Alabama in the United States. The managing agency for this basin is the Pat Harrison Water Management District. The district encompasses 15 counties, while the Pascagoula drains nearly 23,000 km². Elevations in the basin range from over 200 m in the north to sea level in the south, where the river enters the Gulf of Mexico. Although the Pascagoula Basin lies completely within the Gulf Coastal Plain, the basin is 250 km long from north to south and comprises a number of local physiographic regions, including the North Central Hills, the Jackson Prairie Belt, the Longleaf Pine Belt, and the Coastal Pine Meadows (U.S. Army Corps of Engineers, Mobile District, 1968).

The tributaries of the Pascagoula vary in size, relief, and land cover; Table 3-1 summarizes the drainage areas for the streams within the sub basins that this study examines. Fig. 3-2 depicts the Pascagoula Basin and its tributaries. The Pascagoula's two major tributaries lie mostly in the Longleaf Pine Belt, with the Leaf River draining a substantial portion of that belt, while the Chickasawhay River drains the hilly uplands

and prairies of the Black Belt Region in the far north before flowing into the Pine Belt. The surface geology of the Longleaf Pine Belt includes Forest Hill Sand, Red Bluff Clay, Vicksburg Group, and Chickasawhay Limestone of the Oligocene. Also, there are the Catahoula Sandstone, Hattiesburg Formation, and Pascagoula Formation of the Miocene. Finally, there is the Citronelle Formation of Pliocene age. The geology of the Upper Chickasawhay River and the Prairie Belt to the north is predominately composed of the dark, rich soils for which the Black Belt is named; there is also the Jackson Group Clays of Eocene age. In general, the geology is more resistant to the river network in the northeastern portion of the basin, and the rivers flowing in those portions tend to be incised with narrow valleys relative to the relatively unconfined rivers flowing in the western and southern portions of the basin (Mossa and Coley, 2004a).

The land cover in the basin is predominately forest, with agriculture being slightly more prevalent in the northern portion of the basin and forest or silvaculture being more prevalent in the middle and lower portions of the basin. Sixty-one percent of Mississippi is categorized as forest, and the Pascagoula does not appear to differ substantially from that average (Mossa et al., 2006).

The climate in the study area is humid subtropical, with hot summers and cool winters. The mean temperature for 105 years of record is roughly 20°C, and annual rainfall is approximately 140 cm, with a fairly even spread throughout the year (U.S. Army Corps of Engineers, Mobile District, 1983). The main rainmaking mechanisms in the region are winter and spring fronts, summer thunderstorms, and tropical storms. As a result, fall is the driest season and spring is the wettest season. Of the rainmaking

mechanisms, only winter and spring fronts produce serious flooding, with the largest floods occurring predominately in April.

Materials and Methods

Data Description and Origin

This study uses multiple sources of planform or map data. The oldest source is a 1947 U.S. Geological Survey (USGS) 15 min, 1:62,500 scale topographic map series. The coverage of this series is predominately in the lower portion of the basin, on the lower reaches of the Leaf and Chickasawhay rivers, the Pascagoula River, and its lower tributaries along Black and Red creeks.

The next available source of data is the U.S. Department of Agriculture's Farm Service Agency (FSA) aerial photography program, which began in the 1950s. This area of Mississippi was photographed between 1955 and 1960, with the bulk of the photos captured in 1955. These photos are black and white and at a 1:20,000 scale. Coverage for this layer is very extensive, with only the smallest upper reaches of streams not visible because of forest canopy.

Following the 1950s photographs are a 1980s (specifically, 1982–1985) series of USGS 7.5 min, 1:24,000 topological maps that were scanned as digital raster graphics (DRGs). Coverage for this layer is as extensive as in the 1950s photos and, in some cases, extends farther up into the smaller tributaries than do the old black-and-white air photos.

The next source of data is the 1990s (specifically, 1992–1996) series of digital ortho quarter quadrangles (DOQQs). The DOQQs are at a scale of 1:12,000 and have the most extensive coverage of all the data sources in the study, covering all portions of stream that were covered by the 1950s and 1980s data.

The final source is the 2005 National Agriculture Imagery Program (NAIP). NAIP imagery is collected by aircraft in natural color (three bands, red-green-blue) and has a 1 m ground resolution and a specified accuracy of 5 m at 95% confidence.

Data Standards and Preparation

The DRGs from the 1980s and DOQQs from the 1990s were georeferenced to the Mississippi Transverse Mercator (MSTM) projection by Mississippi Automated Resource Information System staff. The metadata for these data indicate that both data sets possess horizontal accuracies that are compliant with National Map Accuracy Standards (NMAS). NMAS (U.S. Geological Survey, 1947 15-Minute Quadrangles) require that not more than 10% of semi-invariant features on a USGS topographic map are greater than 0.85 mm (1/30th of an inch) from their real-world map positions at scales larger than 1:20,000. This horizontal accuracy is maintained in USGS scanned topographic maps, or DRGs and DOQQs. This corresponds to ± 10.16 m at 1:20,000; ± 12.19 m at 1:24,000; and ± 31.75 m at 1:62,500 (Mossa and Coley, 2004b).

The accuracy of the different data layers is expressed as root mean square error (RMSE), which is the square root of a summation of sample point deviations from their actual positions. The allowable RMSE can be calculated from NMAS by dividing the standard by 1.96 for the 95% confidence interval. This yields an RMSE of 5.2 m at 95% confidence for the FSA air photos at 1:20,000 scale, an RMSE of 6.2 m at 95% confidence for the DRGs and DOQQs at 1:24,000 scale, and an RMSE of 16.2 m at 95% confidence for the 15 min series of maps at 1:62,500 scale. By the same token, the NAIP specifies that inspected locations match photo-identifiable ground control points with an accuracy of within 5 m at a 95% confidence level.

The base coordinate system for all layers was derived from the DOQQs; all data created for this project were defined to match the MSTM projection; and a custom Universal Transverse Mercator (UTM) projection was used because Mississippi sits astride the boundary between UTM zones 15 and 16. The MSTM uses the North American Datum of 1983 and has its central meridian at 89.75°W longitude.

In the case of the FSA photos, the source data were black-and-white film transparencies scanned so as to preserve a 1 m ground cell resolution. These scanned transparencies were then cropped to remove borders and fiducials and were georegistered to the 1990s DOQQs. Each photo had 16–25 ground control points, depending on the number of available identifiable features. A first-order polynomial was used to convert the image to real-world coordinates, with each of the polynomial parameters tested for significance at the 95% confidence level, ensuring an accurate transformation (Mossa and Coley, 2004b). Once each image was rectified, a visual edge-matching process was performed to ensure that each stream was aligned with its adjacent and overlapping air photos. If any stream channel segment was misaligned by greater than 8 m (recall that the NMAS standard at 1:20,000 scale is 12 m), a new set of ground control points was selected, and the registration was repeated until there was proper alignment within the specified standards (Mossa and Coley, 2004b).

After all data were prepared, they were placed in a Geographic Information System (GIS), where the imagery was used to create vector files of the banks of streams in the study area. The screen resolution for digitizing was fixed at 1:2000 scale. This resolution was selected to maximize the observer's ability to recognize and capture material observable at a 2 m² resolution on the base imagery (the resolution of the air

photos was 1 m²). The left and right banks of each stream segment were represented by lines with vertices that were greater than 5 m apart yet typically less than one channel width apart. These lines extended to the border of each quadrangle, where they were closed, creating a polygon for that quad. These data represented the channel position for that particular quad at that particular time step. The use of quads to define reach segments was arbitrary and was selected only to simplify data queries (Mossa and Coley, 2004b). Complex channels, channel bars, and meander islands created by neck cutoffs were captured in the data whenever they were present and were recorded as such in the database accompanying the vector data. This process was repeated for each quad and each time step, until all reaches in the study were captured in the GIS. The channel boundaries on each side of the streams were then used to create lines marking the channel centerline for each reach. These centerlines were used, along with similarly constructed valley lines, to calculate channel sinuosity at 1 km intervals on all streams in the study, except for the Leaf and Chickasawhay rivers. Because of the length of the Leaf and Chickasawhay rivers (over 160 km and 150 km, respectively), the Leaf and Chickasawhay intervals were set at 2 km in length.

As was stated earlier, the coverage of each layer across the entire basin is not equally complete, but the 1950s, 1980s, 1990s, and 2000s data layers provide a comprehensive coverage of the streams within the basin, both spatially and temporally. In all cases, the planform data were utilized to create maps of the channel boundary at the time of each particular set of imagery. The total channel distance for just the 1990s DOQQ imagery was over 1300 km of river length and nearly 1000 km of valley length. The 1980s DRG and 2000s NAIP imagery yielded slightly lower yet similar lengths of

digitized stream channels. FSA photos from the 1950s were roughly 10% shorter, but this was mainly because of the aforementioned difficulties in recognizing the upper reaches and smallest channels beneath the forest canopy. The 1940s period had the shortest length of digitized channel because the map coverage for the basin was limited to the southern portion.

Data Calculations

This study employs three different types of information to examine the phenomena associated with meandering rivers. The first type of information is the recognition and demarcation of alluvial cutoffs in the GIS. Not all cutoffs are easily recognizable features in the planform and can be confused with other meandering processes like translation. Each cutoff was identified by viewing two adjacent (in time) channel boundary vector layers in the GIS. These layers were placed atop the original base imagery for the most recent of the vector layers so that any channel change recorded between the two vector layers could be observed in the most recent layer. For example, the 1980s stream channel boundary vector layer from DRGs was opened as time step 1. The 1990s stream channel boundary vector layer from the DOQQs was opened as time step 2. Both vector layers were placed atop the DOQQ raster image that was used to create time step 2. When the channel moved appreciably between time step 1 and time step 2, the background image could be used to determine if a cutoff had occurred. When there was no evidence of a second channel or an abandoned channel, then it was likely that the planform change in the channel occurred gradually via translation. If there was evidence of the former channel, then the cutoff channel was marked along the channel centerline at the center of its length. This is generally near the apex of neck cutoffs and midway between the top and bottom of the cutoff in chute cutoffs. Neck cutoffs were

very easy to recognize, even in the smallest streams, but chute cutoffs were increasingly difficult to distinguish as the drainage area for the stream decreased. Whenever there was uncertainty involved in the process, the research erred on the side of caution by choosing not to demark a potential chute cutoff. This process was repeated for every segment of stream that had available vector layers and base imagery, with each cutoff being marked as a single point in the GIS, along with a temporal value in the database.

The second type of information involved creating a record of the temporal and spatial relationships between the cutoffs recognized in the data described previously. The temporal relationship was recorded as a discrete number that represented the time span in which the cutoff occurred. For example, if two cutoffs occurred in a reach of stream between the 1980s (DRG) layer and the 1990s (DOQQ) layer, then the cutoffs occurred in the same time step. If, however, one of the cutoffs instead occurred between the 1990s (DOQQ) layer and the 2000s (NAIP) layer of imagery, then the two cutoffs occurred in time steps that are once removed from one another. This temporal relationship works reasonably well for most of the time steps available in the study (1940s–1950s, 1980–1990s, 1990–2000s), but it is less than perfect as a measure between the 1950s and 1980s because of the length of time between images of the stream.

The spatial relationships between cutoffs were established by measuring the downstream distance (as opposed to the down-valley distance) from the point denoting one cutoff to the point denoting another cutoff. This distance was measured in the GIS on the stream centerline for the vector layer from the imagery immediately before the

time step where the cutoff occurred. This process was created for every single cutoff, meaning that the spatial distance between two cutoffs (cutoff A and cutoff B) was determined twice, and in the case of cutoffs that occurred in different time steps, the distance was measured on different vector layers, providing a slightly different spatial distance (so the distance from A to B in time step 1 does not equal the distance from B to A in time step 2). This process may seem cumbersome (measuring distance twice for each pair), but it was necessary for the inclusion of the spatial scaling factor detailed later.

Taken alone, the distance between two cutoffs in a single reach is a reasonable representation of their spatial relationship. But when taken across an entire basin, raw distance ignores the change in scale from a headwater tributary to the primary stream. To account for the effects of spatial scaling, the distance between cutoffs has been converted to channel widths via the following procedure: The channel width was measured on the vector layer of channel boundaries from the 2000s NAIP source imagery. The location of the single channel width measurement was somewhat arbitrary, but the observer attempted to measure at the closest point to the cutoff and to avoid areas of channel that were not indicative of the average condition in the reach (e.g., at locations with bar islands or bedrock constrictions).

The use of channel widths as a measure of distance has a strong physical rationale. It has long been recognized in research on rivers that channel width is a scaling factor in a variety of other stream measures, including meander wavelength. By converting the distances between cutoffs into channel widths, we are creating a measure that works across a variety of scales and, more important, has a well

established physical relationship with meanders. Knighton (1998, p. 215) notes that research in a variety of stream environments consistently reports a meander wavelength that is between 10 and 14 channel widths.

The channel width measures were obtained from the 2000s-era imagery (NAIP) because it was flown over a short time span relative to the other base data sources, ensuring a narrow range of stream stages across the entire basin. The imagery was specifically captured during July 2005. During this month, the discharge measured at USGS stream gauges around the basin was near the median recorded discharge for those gauges. For example, the USGS stream gauge on the Chickasawhay River at Enterprise, Mississippi, had a monthly average discharge of $39.44 \text{ m}^3 \text{ s}^{-1}$, which is in the 68th percentile for monthly average discharge over a 70-year record. The USGS stream gauge on the Leaf River at Hattiesburg, Mississippi, had a monthly average discharge of $35.62 \text{ m}^3 \text{ s}^{-1}$, which is in the 40th percentile for monthly discharge over a 70-year record.

With the channel width data, the spatial distance between cutoffs was converted into the number of channel widths between cutoffs. Because the established distance between meanders is 10–14 channel widths, it is a simple matter to transform distance measured in channel widths to the number of meanders upstream and downstream, thereby establishing a set of natural categories for assessing the spatial association between two cutoffs.

The final type of information utilized in this study is sinuosity measures for equal interval segments of each stream. As stated earlier, the segments were created at 1 km intervals on all streams, except for the Leaf and Chickasawhay rivers, which were set at

2 km intervals because of the length of each river in the study. Sinuosity was calculated for each segment and each time step by dividing the centerline stream distance for the segment by the centerline valley distance for the segment. The result is a dimensionless ratio of the river's path relative to its valley.

Results

Alluvial Cutoffs

If we refer to the map of the study area (Fig. 3-2), we note that streams were investigated across a range of spatial scales. Fig. 3-2 also shows the locations of the cutoffs that occurred over the past 50 years. Table 3-1 further defines the range of scales in the study by showing the length of each segment sampled, the drainage area for the segment, and the number of cutoffs observed for each time step.

There were 127 cutoffs found over the 1000 km of stream that were examined. When we look at the cutoffs, we can order them by their location in the basin, their time of formation, and their spatial relationship with the other cutoffs in the study.

Eighty-three percent of the cutoffs in the basin were located in stream segments under 3000 km² in drainage area. However, of the total length of stream examined, only 71% of the stream segments had under 3000 km² in drainage area. Other comparisons by cumulative percentage relative to drainage area support the notion that there are more alluvial cutoffs occurring in the lower drainage area portions of the basin. This notion is borne out in the information displayed in the map of the study area (Fig. 3-2) and the summary table introduced earlier (Table 3-1). It is further accentuated by Fig. 3-3, which displays the cumulative percentage of cutoffs and stream segment lengths relative to drainage area.

Even with the limited number of stream segments examined in the study, it is obvious that alluvial cutoffs displayed on Fig. 3-3 surge ahead relative to the length of segments examined. This suggests that cutoff density per length of stream is higher in the lower drainage area portions of the study. When we examine the number of cutoffs per kilometer of stream in the study, we find that the global average for all streams less than 20,000 km² in drainage area is 0.12 cutoffs km⁻¹, or one cutoff for every 8.2 km. If we look at similar figures for all streams under 3000 km² in drainage area, we find that the average is 0.15 cutoffs km⁻¹, or one cutoff for every 6.9 km. If we repeat the process for 2000 km² and 1000 km² drainage areas, we find the average cutoffs creeping upward to 0.20 cutoffs km⁻¹ at 2000 km² and 0.39 cutoffs km⁻¹ at 1000 km². In the uppermost stream segments with the lowest drainage areas, we find a cutoff for every 2.59 km examined. Fig. 3-4 shows a histogram of the frequency of alluvial cutoffs at different drainage areas. This particular histogram does not have data binned at equal intervals so as to provide a better look at the distribution of alluvial cutoffs across the basin. In comparison, Fig. 3-5 uses data binning at equal intervals and therefore shows less information about the distribution but does accentuate the point that cutoffs are predominately occurring in the smaller, lower-drainage-area streams.

When we look at when the cutoffs occurred over time, the coarse temporal resolution limits our ability to detect any trends. We do find that 10 cutoffs occurred in roughly 350 km of channel observed on the 1940s USGS 15 min series topographic maps and in the 1950s FSA aerial photographs. This translates into approximately one cutoff for every 35 km over the roughly 10-year span. A similar look at the span between the late 1950s FSA photos and the 1983 7.5 min series DRGs finds that 37 cutoffs

occurred, with approximately 1 cutoff for every 28 km over what is roughly a 30-year span. Moving forward in time, we find that 54 cutoffs occurred between the 1983 DRGs and the 1996 DOQQs. This translates into about one cutoff for every 19 km of stream examined. The rate of cutoffs occurring seems to slow between the 1996 DOQQs and the NAIP imagery from 2005. During that 9-year span, we find only 26 cutoffs, which converts into roughly 1 cutoff for every 40 km of stream.

The spatial relationships between alluvial cutoffs are expressed in channel widths. The rationale for this approach is covered in the methods, where the meander wavelength for streams in a variety of environs was stated to be 10–14 channel widths. If we take these values, we can make the claim that 12 channel widths upstream or downstream is theoretically equivalent to one meander wavelength and that 25 channel widths is equivalent to two meander wavelengths. It is this approach that provides the basis for the following series of paragraphs and figures.

When we define the spatial neighborhood between cutoffs as being within 100 channel widths, we find that 93 of the 127 cutoffs found in the study have a spatial neighbor. There are a total of 202 spatial associations within 100 channel widths, with only 34 cutoffs having no neighbor. The frequency of cutoffs with zero, one, or more neighbors is displayed in Fig. 3-6. It is important to note that 100 channel widths is an excessive definition of a spatial neighborhood, and it is unlikely that alluvial cutoffs that are eight meander wavelengths apart have an explicit physical connection.

When we halve our definition of the spatial neighborhood to cutoffs within 50 channel widths of one another; we find that 68 of 127 cutoffs found in the study have a spatial neighbor. There are a total of 123 spatial associations within 50 channel widths,

with 59 cutoffs having no neighbor. The frequency of cutoffs with zero, one, or more neighbors is displayed in Fig. 3-7. In this case, a 50-channel-width spatial neighborhood translates into roughly four meander wavelengths, so the likelihood of a physical connection between associated cutoffs is higher.

When we halve our definition of the spatial neighborhood again, to just cutoffs within 25 channel widths of one another, we find that only 49 of 127 cutoffs found in the study have a spatial neighbor. There are a total of 67 spatial associations within 25 channel widths, with 78 cutoffs having no neighbor. The frequency of cutoffs with zero, one, or more neighbors is displayed in Fig. 3-8. A 25-channel-width spatial neighborhood translates into just two meander wavelengths upstream or downstream, so it is likely that a physical connection between associated cutoffs exists.

This information is further summarized in Fig. 3-9, in which the total number of spatial associations between cutoffs is displayed in a histogram, with data binned at roughly one-meander-wavelength increments. It is again important to note that the 100-channel-width or eight-meander-wavelength limit to the chart is an arbitrary one. It is likely that the physical relationship between supposedly proximal cutoffs becomes spurious before 100 channel widths.

Channel Sinuosity

The channel sinuosity for each reach and each time step is summarized in Tables 3-2 and 3-3. Table 2-2 displays the drainage area for each segment as well as the down-valley distance (as opposed to the stream distance displayed in Table 3-1). Also displayed are the sample size or number of reaches per segment and the sample mean sinuosity and sample variance for each segment. Table 3-2 shows this information for the FSA aerials from the late 1950s and for the USGS 7.5 min DRGs from the 1980s.

Table 3-3 displays similar information for the 1990s DOQQs and the change between the 1950s and 1990s.

This information provides some insight into the patterns of sinuosity throughout the streams in the basin. Of particular interest is that the global average sinuosity for the entire Pascagoula Basin is consistent over the nearly 50-year span. Another item of interest is that there is almost no net change in average sinuosity between 1955 and 1996. Some segments, most notably West Tallahala Creek, experienced noticeable straightening, while others, most notably Thompson Creek, became more sinuous over that time span. However, on average, the streams in the Pascagoula Basin appear to maintain a consistent sinuosity of roughly between 1.66 and 1.67 over a 40-year span. We will explore this more fully in the following section.

Discussion

Alluvial Cutoffs and Clustering

When we examine the distribution of cutoffs within the basin, it is clear that a substantial portion of the activity is taking place in smaller streams with lower drainage areas (Fig. 3-3). However, we also seem to find that cutoffs occur regularly in some areas and not at all in other areas. This trend is particularly conspicuous in the eastern half of the basin, where local geology along the Chickasawhay River and Buckatunna Creek leaves a substantial portion of these streams incised and fairly stable over the time span of this study.

Ten cutoffs occurred on the Chickasawhay River above Buckatunna Creek over 50 years' time. Six of the 10 cutoffs occurred in a single reach, where the stream exits the fairly narrow confines of its valley and meanders freely for roughly 5 km. In the lower portion of the Chickasawhay River below Buckatunna Creek, 5 of the 12 cutoffs

recorded over the 50 years of the study occur in a single span of less than 9 km, a reach that is roughly 80 channel widths in length from the upper to lower cutoffs. Once again, this reach is located in an area where the river is free to meander and create cutoffs. It is important to note, however, that all of the Chickasaway from below Leakesville, Mississippi, to the confluence with the Pascagoula River is freely meandering. Yet in a distance of approximately 30 km, over half of the cutoffs occur in the single reach mentioned previously. Buckatunna Creek also exhibits a concentrated pattern in its distribution of cutoffs. All six of the Buckatunna Creek cutoffs are clustered in a reach of stream just 6 km long. From the uppermost cutoff to the lowest is a distance of over 140 channel widths, yet each cutoff is within 40 channel widths of the next. When the cutoffs in the Chickasaway portion of the Pascagoula are tallied, 17 of the 28 cutoffs found in the 329 km examined occur in just three clusters, with a combined length of slightly more than 20 km. To rephrase that information, 61% of the cutoffs occur in just 6% of the total length of stream examined.

The pattern in the western portion of the Pascagoula Basin is not as clear. However, there is strong evidence for clustering here, as well. It is important to note that in this study, the term cluster refers to a collection of three or more cutoffs within close proximity, as defined by the spatial neighbor definitions outlined earlier. The Leaf River and its tributaries are less confined geologically and different from the Chickasaway; also, there is a larger range of drainage areas examined in the Leaf Basin. However, there are multiple clusters of cutoffs, particularly in the upper portion of the Leaf and in some of its tributaries. The 12.2 km of the Leaf River above its confluence with West Tallahala Creek contain 7 of its 11 cutoffs in two clusters, each roughly a kilometer in

length. Both Bouie and Okatoma creeks display a similar pattern, with Bouie Creek having 4 of its 11 cutoffs over 35 km occurring in a single cluster approximately 1.6 km long. Okatoma Creek has 12 of 14 cutoffs over 43 km occurring in four clusters of three cutoffs each, with each cutoff cluster being less than 1.1 km long. When spread across a paragraph, this information is hardly breathtaking, but it is important to recognize that in this upper portion of the Leaf River, we find that 23 of the 42 cutoffs found in the 225 km of stream examined, occur in clusters of three or more and the combined length of the reaches containing those clusters is only 7.6 km. Put simply, 55% of all the cutoffs occurring in Leaf Basin with a drainage area under 3000 km² occur in close proximity to at least two other cutoffs and are concentrated in less than 7% of the total length of stream surveyed.

This phenomenon is in alignment with the behavior reported by Hooke's (2004) study on the River Bollin. Recall that the River Bollin is only 55 km² in total drainage area and a very small stream by Mississippi standards. In River Bollin, eight cutoffs occurred in the span of just a few years in a reach under 1 km in length, so the cutoff clustering in space and time is very evident in this small stream. The Leaf River is a much larger stream, and in its tributaries and lower reaches below its confluence with the Bowie River, there were only three cutoff clusters. The conditions in each case were similar to the conditions outlined earlier. Each of the clusters was located on smaller tributaries of the Leaf River: one occurring on Bogue Homo Creek in the uppermost portion of that tributary and the other two occurring on Thompson Creek. These combined leave a total of 14 of 22 cutoffs over 63 km of stream occurring in just three clusters of less than 4.5 km in combined length.

In the Pascagoula Basin, the pattern for clustering of cutoffs begins to break down as the drainage area increases. In all of the lower Leaf and the Pascagoula River, there is only one other cluster of cutoffs, and that occurs on the Pascagoula and requires the full span of 50 years to emerge, and is nearly 190 channel widths from top to bottom on a segment of stream with a very wide channel. The Pascagoula cluster fits the loosest definitions of a spatial neighbor as outlined in this study, but it is really just three cutoffs spread over 30 km of stream. If we choose to disregard its presence, we can claim that nine cutoffs occurred widely spread over 193 km of stream, suggesting that cutoff clusters are largely limited to smaller streams, at least over human scales of time.

Sinuosity and Cutoff Clusters

Stolum (1996) suggests that the maximum value for sinuosity in an unconstrained river is approximately 3.14. Under the hypothesis of SOC in river meanders, we would expect that as the sinuosity of a segment or reach of river approaches this value, the occurrence of multiple cutoffs becomes more likely. When the sinuosity is well below this value, multiple cutoffs in a reach are not impossible, but we would expect that single cutoffs are more likely. The basis for this hypothesis is in the work of Bak et al. (1987), where theoretical sandpiles grew while undergoing periodic avalanches, until their growth made them unstable, eventually prompting even a single avalanche to propagate throughout the system, spawning multiple avalanches in a large event that returned the sand pile to a more stable state, where smaller avalanches still occurred.

In the Pascagoula River Basin, we calculated the sinuosity for 443 segments of stream, so it is possible to compare the sinuosity of segments where cutoffs occurred with the sinuosity of segments without cutoffs. We do find a significantly higher sinuosity in reaches with cutoffs than in reaches without cutoffs, with a p -value of 0.01 in a

comparison using the large-sample version of the Mann-Whitney-Wilcoxon test on ranked data. But the raw differences in sinuosity are not as great as we would expect, and their significance can generally be assumed to be tied to a number of other potentially related factors such as geology and valley confinement.

There were 14 reaches of stream with three or more alluvial cutoffs. The average sinuosity of these reaches was 2.12, compared to a global average sinuosity of roughly 1.67. When we look at the sinuosity for the individual clusters and find their percentile ranks within the larger population of sinuosity measurements, we find that they do depart significantly from the rest of the population, with a p-value of 0.0001 in a comparison using the Mann-Whitney-Wilcoxon test, but the departure is nowhere near as great as Stolum's (1996) model suggests or as Hooke's (2004) report on the cutoff cluster on River Bollin shows, where the precutoff sinuosity was 2.92. Table 3-4 shows before and after sinuosity information for each of the cutoff clusters found in the study, along with the percentile rank of the cutoff cluster sinuosity when compared to the reach sinuosity measures for the entire basin. Two items from the table deserve explicit mention: the first is that each of the cutoff clusters occurs in an area where the sinuosity is well above the median sinuosity for the entire basin. A high sinuosity is a good indicator of a reach's potential for alluvial cutoff. The second is that there is a perceptible reduction in reach sinuosity after the cutoffs, even when the cluster takes as long as 50 years to occur. In all cases, the reduction in reach sinuosity is substantial, with a 26% average reduction in sinuosity. This suggests that there is empirical evidence that alluvial cutoffs do serve as the main mechanism to reduce sinuosity and

move the reach away from a potentially critical threshold, with the post cutoff sinuosity averaging in the 40th percentile.

When the data from the Pascagoula are compared to the benchmark study reach on River Bollin, the results are under-whelming and, at face value, could cast some doubt on Stolum's hypothesis of SOC in river planform dynamics. But it is important to recognize that Stolum's hypothesis was created from a model with minimal discharge fluctuations and completely unconstrained or freely meandering rivers. His critical threshold of 3.14 sinuosity is not readily apparent in our data, but the Pascagoula is a basin with a great deal of variability in its conditions. Much of the basin does not meet the 100-channel-width-wide valley specified by Stolum. An excellent example of the contradictions common to natural rivers is the most sinuous reach in the Pascagoula Basin: A 2 km reach of the Upper Chickasawhay River has a sinuosity of 3.88, yet it is one of the most stable reaches in the study and has maintained a nearly constant channel position over 50 years of observation. Obvious contradictions aside, SOC appears to offer a great deal of insight into how sinuosity may function as a driver of planform change.

Self-Organized Criticality and Sinuosity Changes over Time

Under the hypothesis of SOC in rivers, we can expect some basic trends to emerge from any set of stream sinuosity measures. At low sinuosity, we would expect that the stream would only increase in sinuosity over time as the system moves toward the hypothesized critical attractor. Once the sinuosity approaches the attractor, we would expect for sinuosity to decrease over time with alluvial cutoffs (Stolum, 1998). Recall the conceptual model for stream sinuosity (Fig. 3-1). If the data that created that model were placed in a scatter plot of t versus $t + 1$, we would expect that the data

points in the plot would hover around the 1:1 line, with most points resting either on or slightly above the line as the sinuosity gradually increases over time. The three sets of alluvial cutoffs in the conceptual model would be the only departure from this pattern, with each data point representing an episode of cutoffs sitting far below the 1:1 line as the sinuosity in the reach decreased abruptly over time. Fig. 3-10 displays this conceptual plot; note that under this simplified model, there are only three points from the 100-run model that rest below the 1:1 line, each representing one of the three cutoffs that occurred in the model.

When we observe a similar plot of the sinuosity data from the Pascagoula Basin, the results are not so clear (Fig. 3-11). However, we do note that the data rarely deviate greatly from the 1:1 line and that when they do, there is a tendency for reaches without cutoffs to rest slightly above the line, signifying that in many locations in the basin, sinuosity is either unchanging or increasing slightly over time. The instances where the points in the scatter plot lie well below the 1:1 line represent the cutoffs that occurred in the Pascagoula. None of the reaches with cutoffs are as glaring in their departure as the points in the conceptual model, and many of them occur at a sinuosity far below Stolum's specified 3.14, but it is reassuring to note that even in a basin with a wide variety of conditions and human impacts, reductions in reach sinuosity are largely accomplished by alluvial cutoffs.

Hooke (2007b) looked at self-organization in meandering rivers in a similar fashion by examining sinuosity changes in 24 reaches of the lower Mississippi River. The data in this analysis of sinuosity are from Schumm et al. (1994) and come from before the Mississippi was shortened substantially. In the analysis, Hooke found that the most

dynamic reaches over a roughly 150-year span were also the reaches with the highest sinuosity. A nonlinear ordinary least squares regression of the maximum sinuosity against the range in sinuosity for the 24 reaches found that a power function fit the data very well, with an R^2 of 0.54.

The Pascagoula Basin provides data from 443 segments of stream over 50 years of observation, yielding 1154 observations of sinuosity change. If we regress these data via ordinary least squares, we find that it also fits to a power function with an R^2 of 0.17. It is important to note that these data are not normal and are markedly heteroscedastic, which is really the point of the regression in the first place: to point out that as reach sinuosity increases, the range of sinuosity, and hence the variance, also increases. One other item of note is that nearly all of the reaches with alluvial cutoffs can be considered outliers in such a regression, and if the sample size were any smaller, each of them would exercise an unseemly amount of leverage. Statistically speaking, reaches with alluvial cutoffs are clearly from a different population with respect to the “ordinary” dynamics of sinuosity.

Despite the impropriety of applying least squares regression to the data set, a regression-based approach can illustrate the nonlinear tendencies of sinuosity in alluvial rivers. Fig. 3-12 displays a regression of sinuosity versus change in sinuosity for all of the reaches of the Pascagoula. The figure also shows the regression equation, which happens to have a statistically significant beta coefficient. The slope of the equation is negative, despite the fact that over 56% of the observations had a positive change in sinuosity over time. This is predominately because of the leverage of the points representing the alluvial cutoffs. One basin-wide comparison of the Pascagoula reaches

is insightful but largely inappropriate for a system that is reputed to be nonlinear. A more useful approach is outlined in the following paragraphs.

Hooke (2007b) divided the sinuosity data from the Mississippi River into two samples, one with an initial sinuosity value of less than 2 and one with an initial sinuosity value of greater than 2. The two t versus $t + 1$ plots were markedly different, with the lower sinuosity values tending to register an increase in sinuosity over the next time step and the higher sinuosity values tending to register a decrease over the next time step. The division at 2 sinuosity was not arbitrary, but the following approach to dividing the population provides a more in-depth method for choosing the value for the break.

When the sinuosity values for all the reaches measured in the study are ordered from least to greatest, we can take the change in sinuosity values for each reach and create a function that displays the overall pattern of sinuosity change given the initial sinuosity in a reach. This function is a simple cumulative sum of deviations from zero or no change. If a given range of reach sinuosity values tends to average an increase in sinuosity over time, then the function will be positive and increasing. However, once the cumulative sum begins to include a range of reach sinuosity values that are, on average, negative, then the cumulative sum of the function will begin to decrease. If enough reaches reduce their sinuosity over time, then the cumulative sum of the function will return to zero and eventually become negative as the global average becomes negative.

Fig. 3-13 displays this cumulative sum of deviations for all sinuosity values measured in the Pascagoula Basin in a lightweight gray line and a 50-sample moving

average for the function with a heavy black line. Fig. 3-14 shows the first derivative of this function, which clearly defines where the function is increasing, at its maximum, and decreasing. It turns out that the function maximum occurs at a sinuosity of 1.89, which is in the 75th percentile of the entire data set. The slope of the rising limb of the function is greatest at 1.69 sinuosity, and it can be argued that the function is consistently positive until it reaches about 1.87. All of these are evidence of an overall trend in the basin toward increasing sinuosity over time as the initial channel sinuosity increases up to roughly 1.89. This behavior is consistent with Stolum's (1996) hypothesis of an attractor in the system pulling the river toward higher sinuosities.

When the sinuosity is greater than 1.89, we find that the basin-wide trend is toward a reduction in sinuosity over time. This is consistent with the hypothesis of SOC, whereby the stream system increases toward a critical point and begins to reduce its sinuosity via cutoffs. Hooke (2004, 2007b) states that these reductions in sinuosity will at first occur via chute cutoffs and single-neck cutoffs while the system is in a subcritical state that is theoretically bounded by π on its upper end. As the channel sinuosity increases, the likelihood of clusters of cutoffs occurring increases as the system approaches criticality and, eventually, a supercritical state. The Pascagoula data set does provide evidence for a reduction in sinuosity over time for reaches that are at higher initial sinuosity, but it is important to note that these reaches with alluvial cutoffs are a very small part of the larger data set and that each represents change at a magnitude that is far greater than the processes that initiate increases in sinuosity. The presence of only 127 identifiable chute and neck cutoffs is more than enough to turn the

net trend for the basin downward and nearly enough to offset the net increase in sinuosity over a large portion of 1154 observations in 602 reaches over 50 years.

This is a study on the issue of scale, both in space and in time. Stolum (1998) alludes to the spatiotemporal scaling of self-organized processes in his article on meander dynamics, in which he uses the limitations of the sizes of rivers available for study via remotely sensed data and the rate at which these rivers change as the impetus for studying such dynamics via river models. He argues that because changes on large rivers occur slowly, we need to observe them over longer periods of time to find evidence of cutoff clusters.

It is this critical lack of availability in time that prompts us to look far and wide in this study, substituting space for time in the search for the spatiotemporal clustering of the alluvial cutoffs indicative of a reach of stream that is in a supercritical condition. Although this study found clusters of cutoffs in only a few reaches in smaller tributary streams, it does establish a framework whereby the possibility for similar instances can occur in the larger streams, albeit with a temporal spacing over such intervals as to be nearly unrecognizable as clusters over short spans of observation.

Conclusions

This study has attempted to use empirical data to examine hypotheses on the complexity of meandering rivers. We find that there is an obvious spatial clustering of alluvial cutoffs in the Pascagoula Basin, which implies some measure of self-organization within the system. We also find that sinuosity is a clear driver of planform river channel change, particularly as inherent thresholds within the system are reached and cutoffs develop.

These findings are in alignment with those by Hooke (2007) and Stolum (1996) on self-organization and criticality in rivers. The results of the study are far from the hypothesized ideal of Stolum (1996). However, the earthy messiness of the Pascagoula data does much to better define the role of sinuosity as the driver of the self-organization and criticality in real meandering rivers.

In no way do these empirical results detract from the theory of an intrinsic or autogenic factor at the heart of meandering processes. The results provide a glimpse of two differing processes; slow progressive meander extension and rapid yet punctuated channel shortening via cutoff. Each are each mechanisms for adjusting the sinuosity within the system, thereby creating a system that oscillates within a specified range, yet is self-organized, with an inherent tendency to move toward an attractor and criticality.

Conceptual Model of Sinuosity

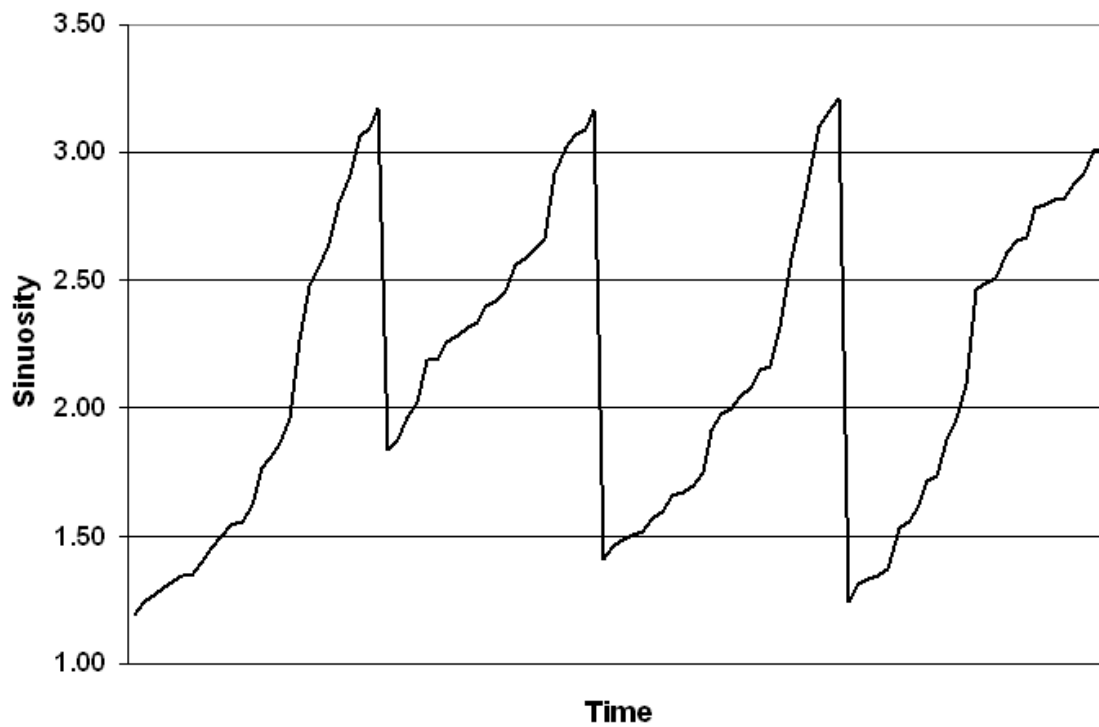


Figure 3-1. A conceptual model of sinuosity changes for one reach over time; the sharp declines represent channel avulsion and cutoffs, whereas the long periods of increase represent channel extension via meander elongation

Table 3-1. Summary of cutoff information for reach segment used in the study

Stream segment	Drainage area (km ²)	Length (km)	Cutoffs				Total	Avg./km
			1947–1955	1959–1982	1983–1994	1996–2005		
West Tallahala Creek	250 ^d	7.1	na	1	1	0	2	0.28
Thompson Creek ^a	610	17.8	3	1	7	2	13	0.73
Bouie Creek	780	35.4	na	1	9	1	11	0.31
Okatoma Creek	940	43.2	na	6	7	1	14	0.32
Bogue Homo Creek	1090	45.6	na	5	4	0	9	0.20
Red Creek	1240	68.1	3	2	3	2	10	0.15
Buckatunna Creek	1530	57.9	na	2	4	0	6	0.10
East Tallahala Creek	1680	79.5	na	0	2	9	11	0.14
Bowie River ^b	1720	16.0	na	0	0	0	0	0.00
Leaf above W. Tallahala Creek	1950 ^e	12.2	na	3	4	4	11	0.90
Black Creek	1980	76.0	2	1	2	0	5	0.07
Chickasawhay River above Buckatunna	2400 ^e	158.8	na	5	3	2	10	0.06
Leaf above Bowie River	2800 ^d	111.9	na	3	0	1	4	0.04
Big Black Creek	3220 ^d	8.9	0	0	0	0	0	0.00
Leaf above E. Tallahala Creek	4800 ^d	42.2	0	1	0	0	1	0.02
Leaf above Bogue Homo Creek	6590 ^e	14.4	1	0	0	0	1	0.07
Chickasawhay River	7690	112.3	na	4	6	2	12	0.11
Leaf above Thompson Creek	7700 ^d	15.8	1	0	0	0	1	0.06
Leaf River	9270	46.8	0	0	1	1	2	0.04
Pascagoula above Big Black Creek	18,020	73.8	0	2	1	1	4	0.05
Total		1043.7	10	37	54	26	127	0.12

^a Did not use the bottom 10 km of Thompson Creek because of floodplain gravel mining.

^b Did not use the bottom 8.8 km of the Bowie River because of floodplain gravel mining.

^c Did not extend study past Big Black Creek because Pascagoula stage is at sea level 5 km downstream at Graham's Ferry.

^d Drainage area estimated from values from other segments.

^e Drainage area estimated from nearby U.S. Geological Survey stream gauge.

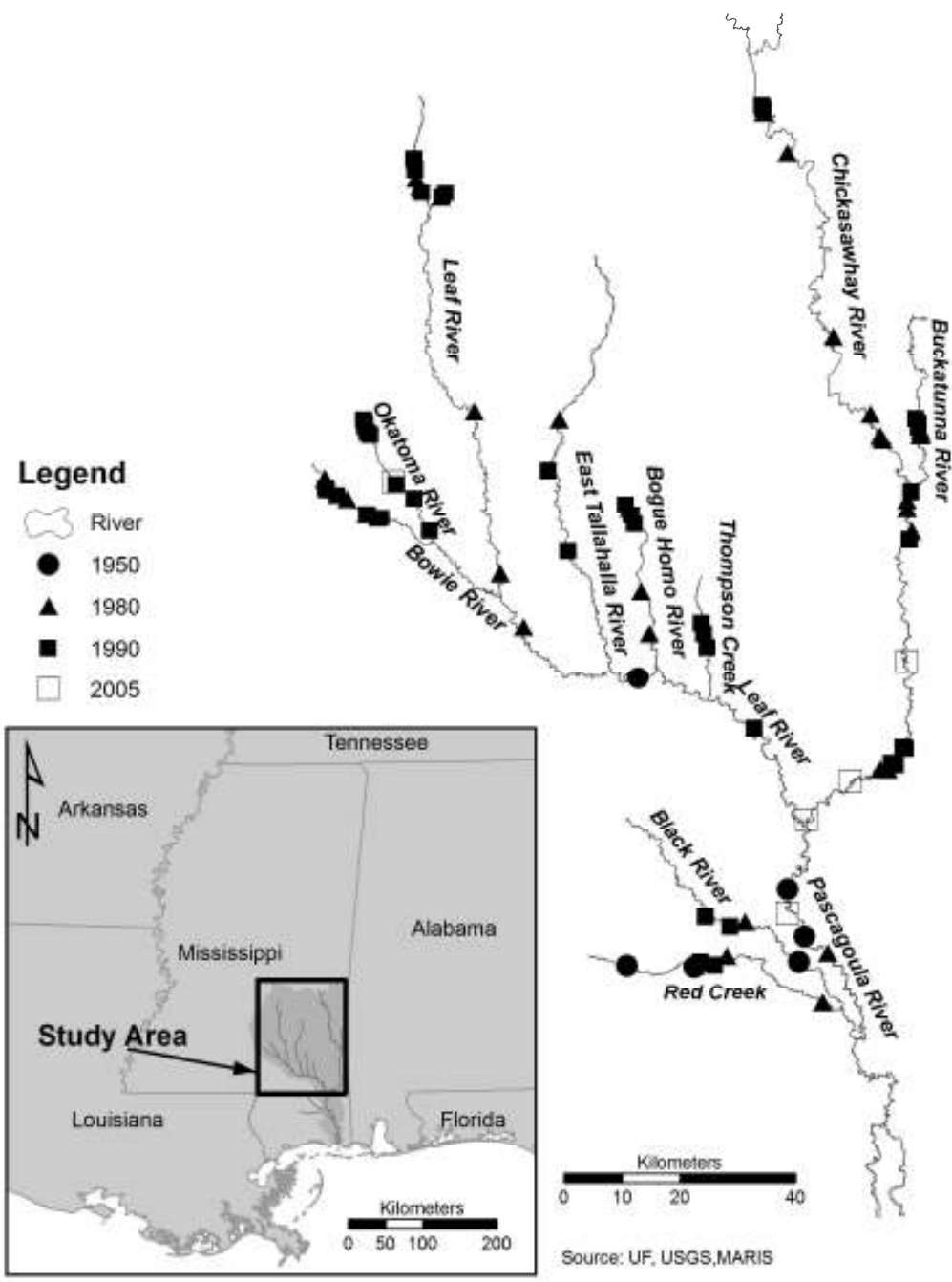


Figure 3-2. Map of study area, with study streams and alluvial cutoffs displayed

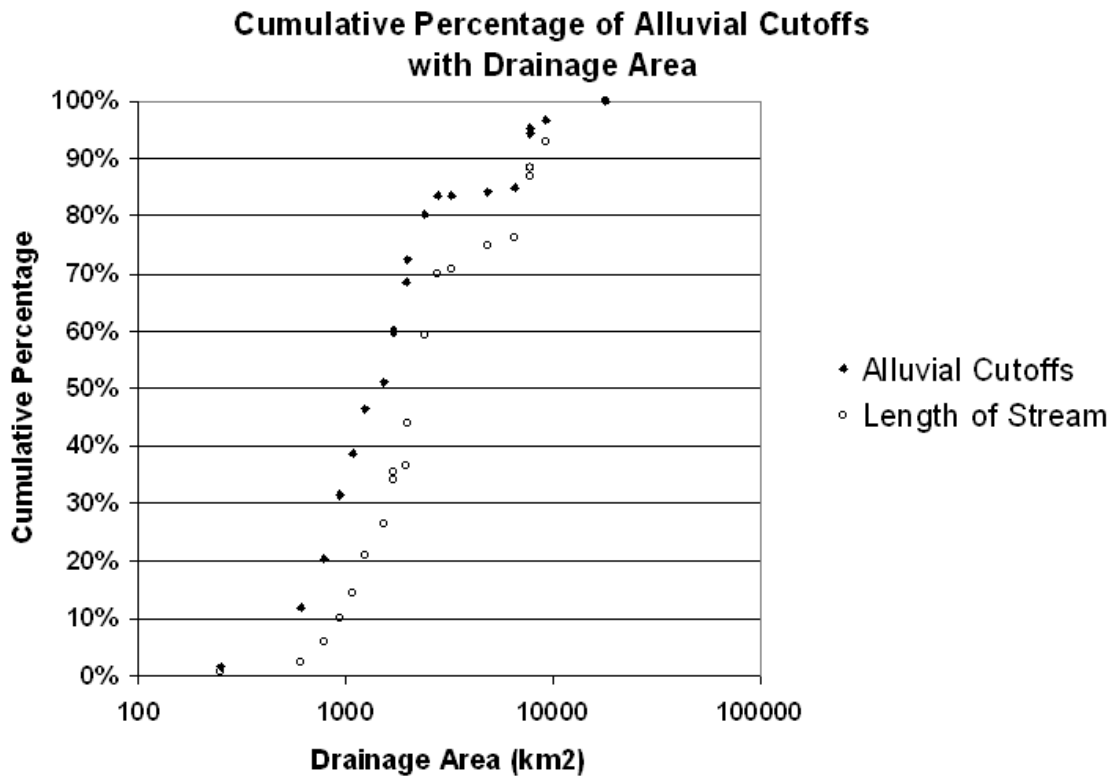


Figure 3-3. A graphical comparison of the cumulative percentage of alluvial cutoffs and drainage area for the stream segments in the study

Histogram of Alluvial Cutoffs

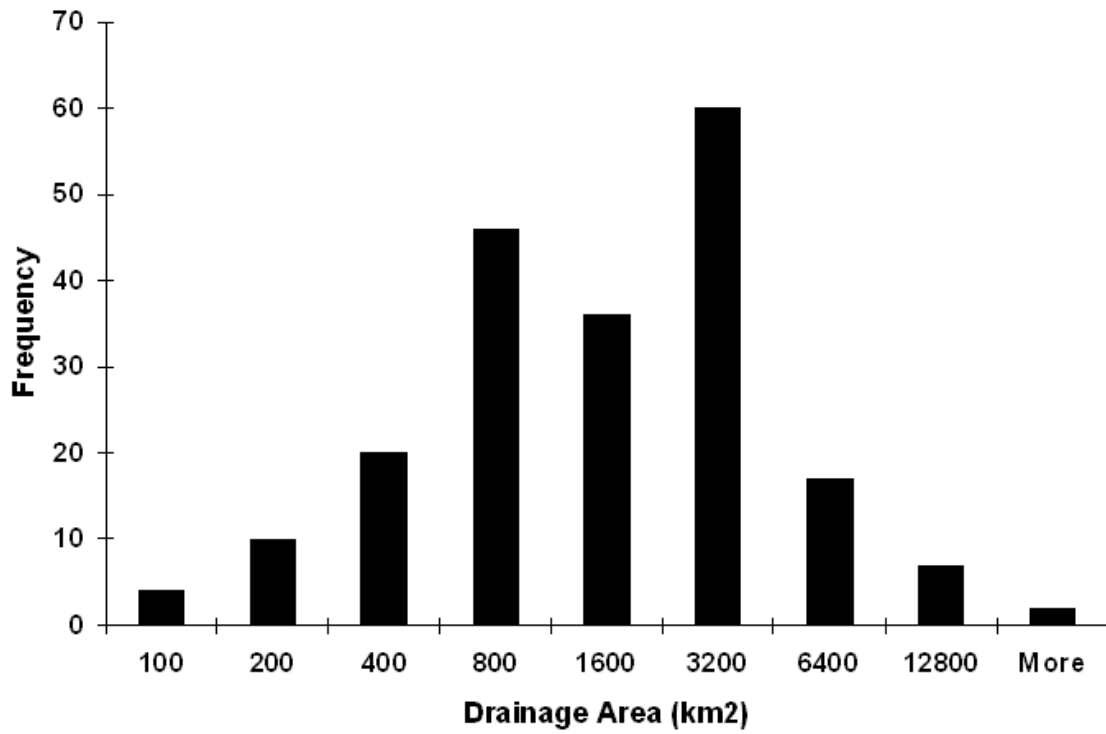
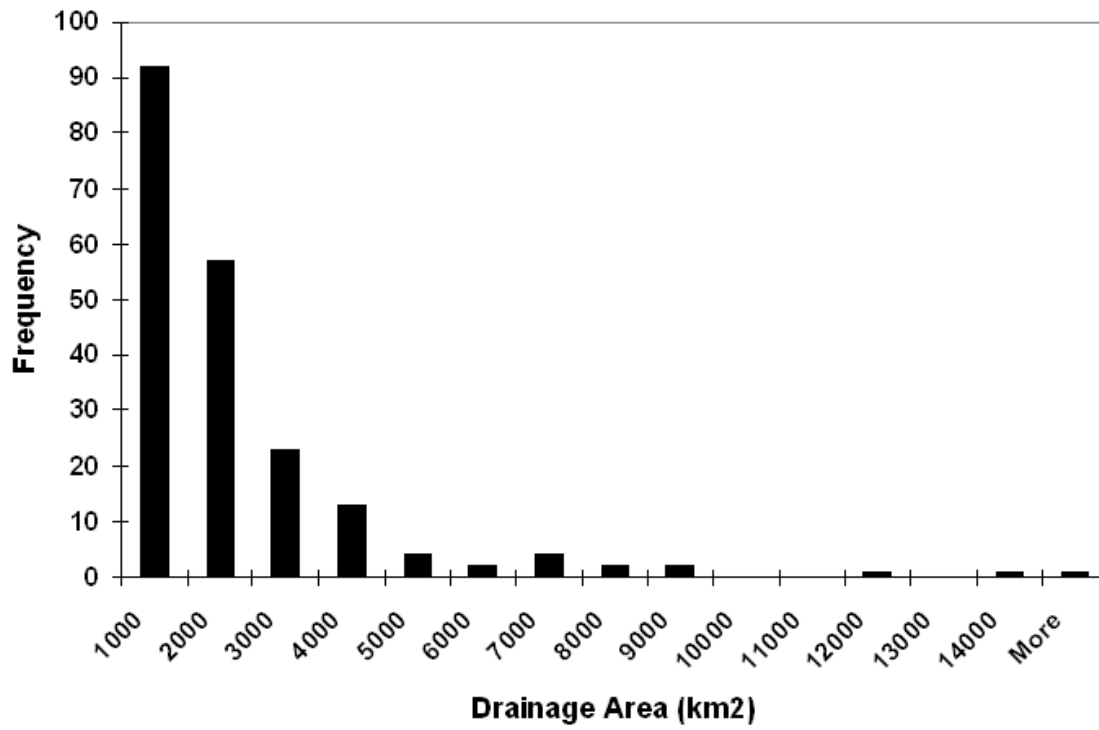


Figure 3-4. A histogram of the frequency of alluvial cutoffs across the range of drainage areas in the study; note that the data are not binned at equal intervals

Histogram of Alluvial Cutoffs



Spatial Association at 100 Channel Widths

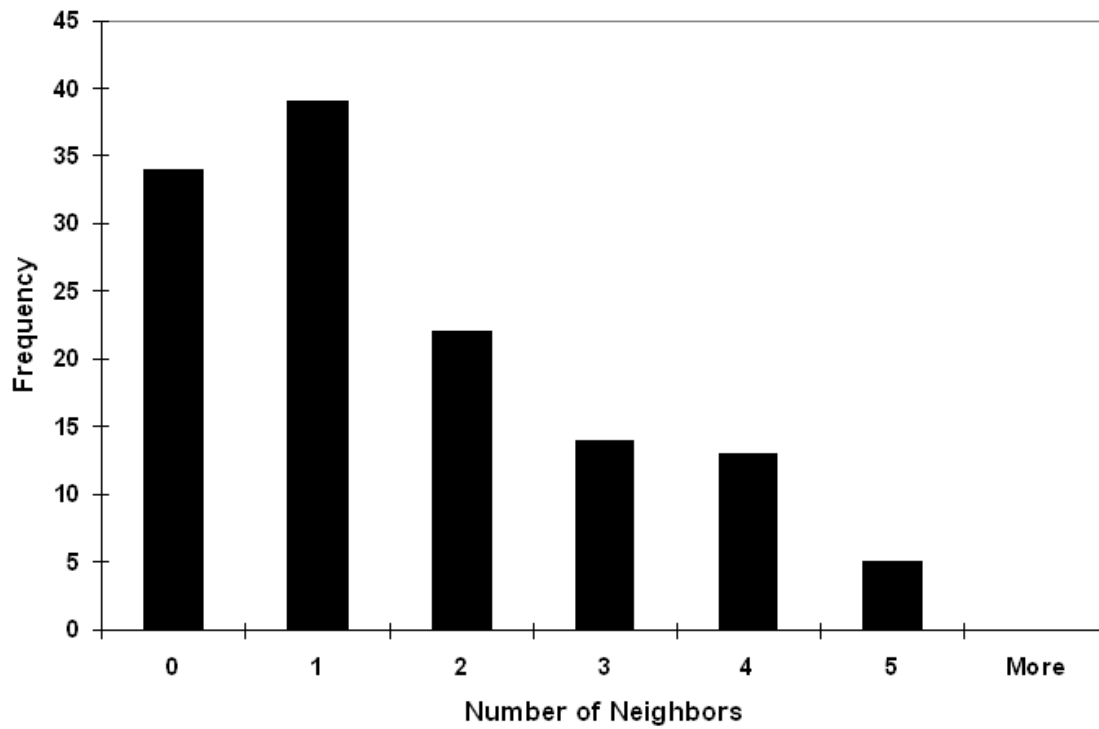


Figure 3-6. A histogram of spatial associations between alluvial cutoffs at 100 channel widths

Spatial Association at 50 Channel Widths

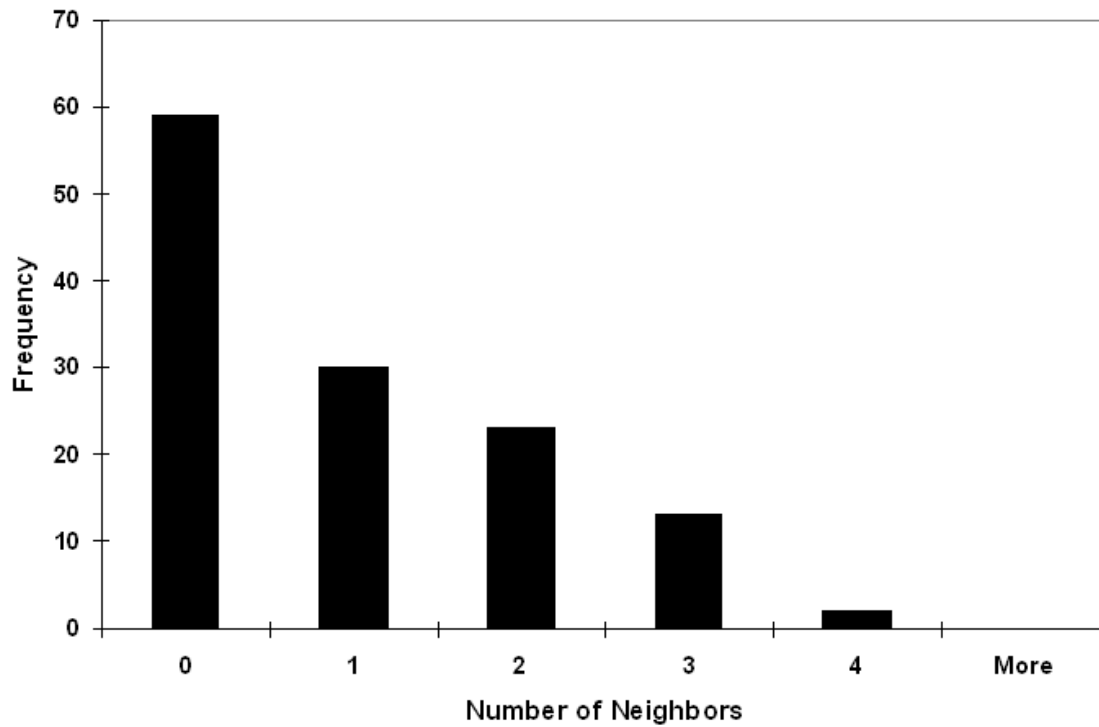


Figure 3-7. A histogram of spatial associations between alluvial cutoffs at 50 channel widths

Spatial Association at 25 Channel Widths

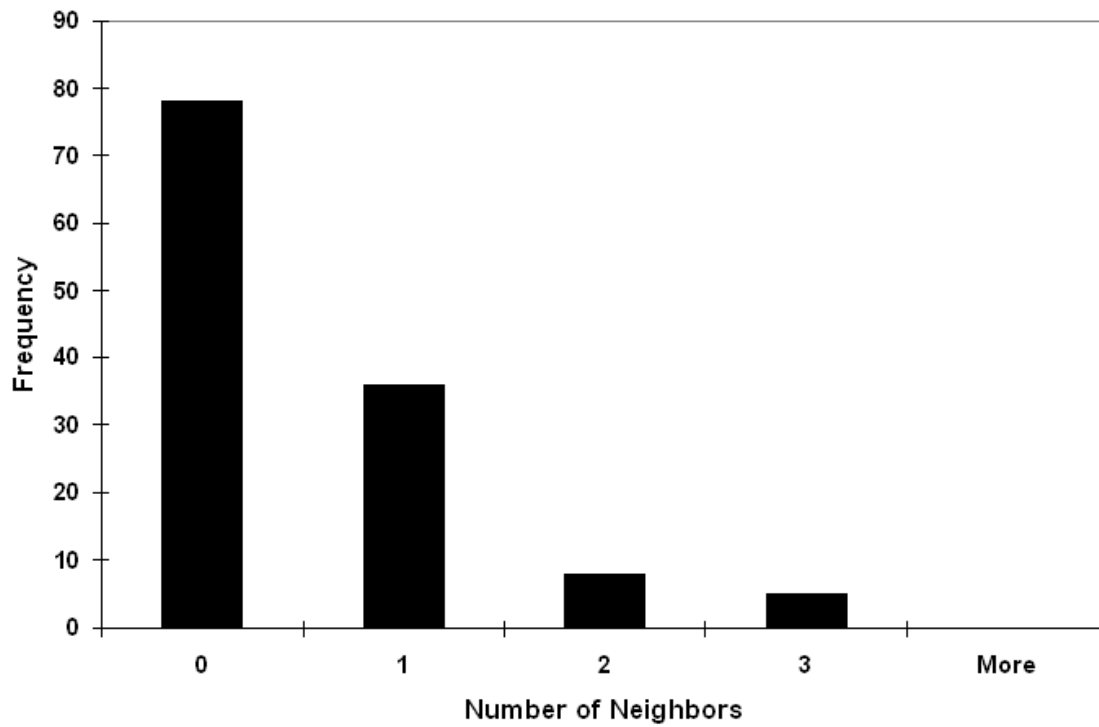


Figure 3-8. A histogram of spatial associations between alluvial cutoffs at 25 channel widths

Histogram of Alluvial Cutoff Associations

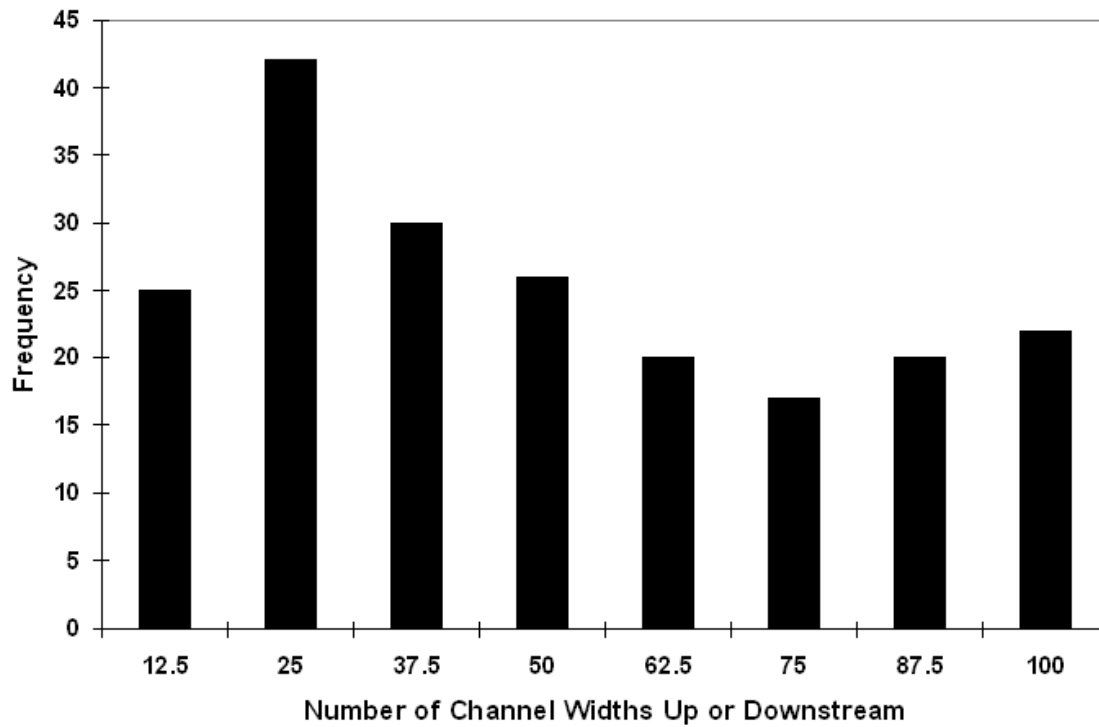


Figure 3-9. A histogram of the spatial associations between alluvial cutoffs at 12.5 channel widths or one meander wavelength increments

Table 3-2. Summary of sinuosity information for reach segments

Stream segment	Drainage area (km ²)	Valley distance (km)	Number of segments	Mean sinuosity	Variance
1955–1958					
W. Tallahala Creek	250	6	5	1.97	0.15
Thompson Creek	610	9	9	1.79	0.03
Bouie Creek	780	26	23	1.85	0.22
Okatoma Creek	940	26	26	1.53	0.06
Bogue Homo Creek	1090	31	30	1.58	0.19
Buckatunna Creek	1530	34	34	1.82	0.24
E. Tallahalla Creek	1680	64	45	1.59	0.13
Bowie River	1720	2	11	1.54	0.19
Leaf above W. Tallahala	1950	20	4	1.55	0.12
Black Creek	1980	58	44	1.78	0.18
Chickasawhay above Buckatunna	2400	84	42	1.80	0.41
Leaf River above Bowie River	2800	72	36	1.54	0.09
Leaf River above E. Tallahala	4800	26	13	1.48	0.23
Chickasawhay River	7690	78	34	1.66	0.14
Leaf River above Thompson	7700	18	9	1.58	0.19
Leaf River	9270	28	14	1.60	0.16
Pascagoula River above Black	18,020	42	21	1.59	0.16
Total and Average (Avg.)		624	400	1.66	Avg.
1983					
W. Tallahala Creek	250	6	6	1.84	0.12
Thompson Creek	610	9	9	1.72	0.02
Bouie Creek	780	26	26	1.74	0.17
Okatoma Creek	940	26	26	1.48	0.05
Bogue Homo Creek	1090	31	31	1.48	0.14
Buckatunna Creek	1530	34	34	1.76	0.24
E. Tallahalla Creek	1680	64	63	1.58	0.09
Bowie River	1720	2	11	1.53	0.19
Leaf above W. Tallahala	1950	20	10	1.67	0.08
Black Creek	1980	58	58	1.72	0.16
Chickasawhay above Buckatunna	2400	84	42	1.77	0.38
Leaf River above Bowie River	2800	72	36	1.50	0.08
Leaf River above E. Tallahala	4800	26	13	1.47	0.21
Chickasawhay River	7690	78	34	1.62	0.14
Leaf River above Thompson	7700	18	9	1.59	0.19
Leaf River	9270	28	14	1.63	0.16
Pascagoula River above Black	18,020	42	21	1.55	0.14
Total and Average (Avg.)		624	443	1.63	Avg.

Table 3-3. Summary of sinuosity information for reach segments

Stream segment	Drainage area (km ²)	Valley distance of (km)	Number of segments	Mean sinuosity	Variance
1996					
W. Tallahala Creek	250	6	6	1.83	0.09
Thompson Creek	610	9	9	1.91	0.03
Bouie Creek	780	26	26	1.80	0.18
Okatoma Creek	940	26	26	1.55	0.09
Bogue Homo Creek	1090	31	31	1.54	0.16
Buckatunna Creek	1530	34	34	1.82	0.25
E. Tallahalla Creek	1680	64	63	1.66	0.10
Bowie River	1720	2	11	1.56	0.20
Leaf above W. Tallahala	1950	20	10	1.77	0.09
Black Creek	1980	58	58	1.74	0.17
Chickasawhay above Buckatunna	2400	84	42	1.79	0.40
Leaf River above Bowie River	2800	72	36	1.57	0.09
Leaf River above E. Tallahala	4800	26	13	1.51	0.24
Chickasawhay River	7690	78	34	1.61	0.15
Leaf River above Thompson	7700	18	9	1.59	0.19
Leaf River	9270	28	14	1.64	0.18
Pascagoula River above Black	18,020	42	21	1.55	0.15
Total and Average		624	443	1.67 Avg.	
1955–1996					
W. Tallahala Creek	250	6	5	-0.13	0.03
Thompson Creek	610	9	9	0.12	0.02
Bouie Creek	780	26	23	-0.03	0.05
Okatoma Creek	940	26	26	0.02	0.03
Bogue Homo Creek	1090	31	30	-0.04	0.02
Buckatunna Creek	1530	34	34	0.01	0.01
E. Tallahalla Creek	1680	64	45	0.04	0.03
Bowie River	1720	2	11	0.02	0.00
Leaf above W. Tallahala	1950	20	4	0.02	0.08
Black Creek	1980	58	44	0.00	0.02
Chickasawhay above Buckatunna	2400	84	42	-0.01	0.01
Leaf River above Bowie River	2800	72	36	0.03	0.01
Leaf River above E. Tallahala	4800	26	13	0.02	0.03
Chickasawhay below Buckatunna	7690	78	34	-0.05	0.05
Leaf River above Thompson	7700	18	9	0.01	0.00
Leaf River	9270	28	14	0.05	0.01
Pascagoula River above Black	18,020	42	21	-0.04	0.03
Total and Average		624	400	0.00 Avg.	

Table 3-4. Alluvial cutoff clusters and sinuosity changes

Cutoff cluster location	Drainage area (km ²)	Time span (years)	Number of cutoffs	Sinuosity before (percentile rank)	Sinuosity after (percentile rank)	Total change
Thompson Creek	400	10–20	3	1.752 (64)	1.410 (32)	–0.342
Okatoma Creek	450	<10	3	3.198 (99)	1.907 (75)	–1.291
Bouie Creek	550	<10	4	1.631 (52)	1.494 (39)	–0.137
Okatoma Creek	600	10–20	3	1.814 (69)	1.186 (11)	–0.629
Thompson Creek	600	<10	4	2.558 (96)	1.212 (14)	–1.346
Bogue Homo	650	20–30	4	1.832 (70)	1.659 (54)	–0.173
Okatoma Creek	750	30–40	3	2.571 (96)	1.257 (17)	–1.314
Okatoma Creek	800	40–50	3	1.658 (54)	1.375 (28)	–0.283
Red Creek	1000	40–50	3	2.368 (93)	1.887 (74)	–0.481
Leaf above W. Tallahala	1400	20–30	3	1.723 (61)	1.181 (11)	–0.543
Buckatunna Creek	1500	30–40	6	2.157 (89)	1.651 (53)	–0.506
Leaf above W. Tallahala	1800	<10	4	2.082 (86)	1.425 (32)	–0.658
Chickasawhay above Buckatunna	2100	10–20	6	1.892 (75)	1.566 (47)	–0.325
Chickasawhay River	6900	30–40	5	1.842 (70)	1.351 (26)	–0.490
Pascagoula River	18,000	40–50	3	2.356 (92)	1.974 (81)	–0.382
Average				2.096 (78)	1.502 (40)	

Conceptual Model of Sinuosity

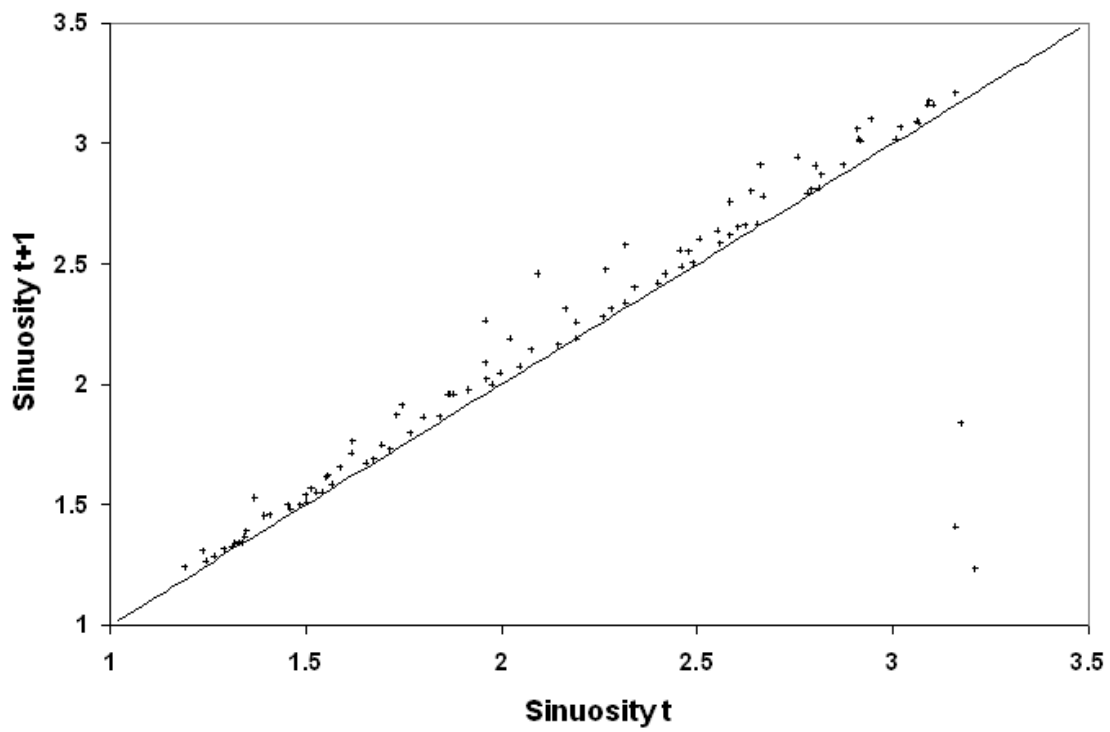


Figure 3-10. A plot of time versus time + one step from the conceptual model of river sinuosity introduced in Fig. 3-1

Reach Sinuosity in the Pascagoula Basin

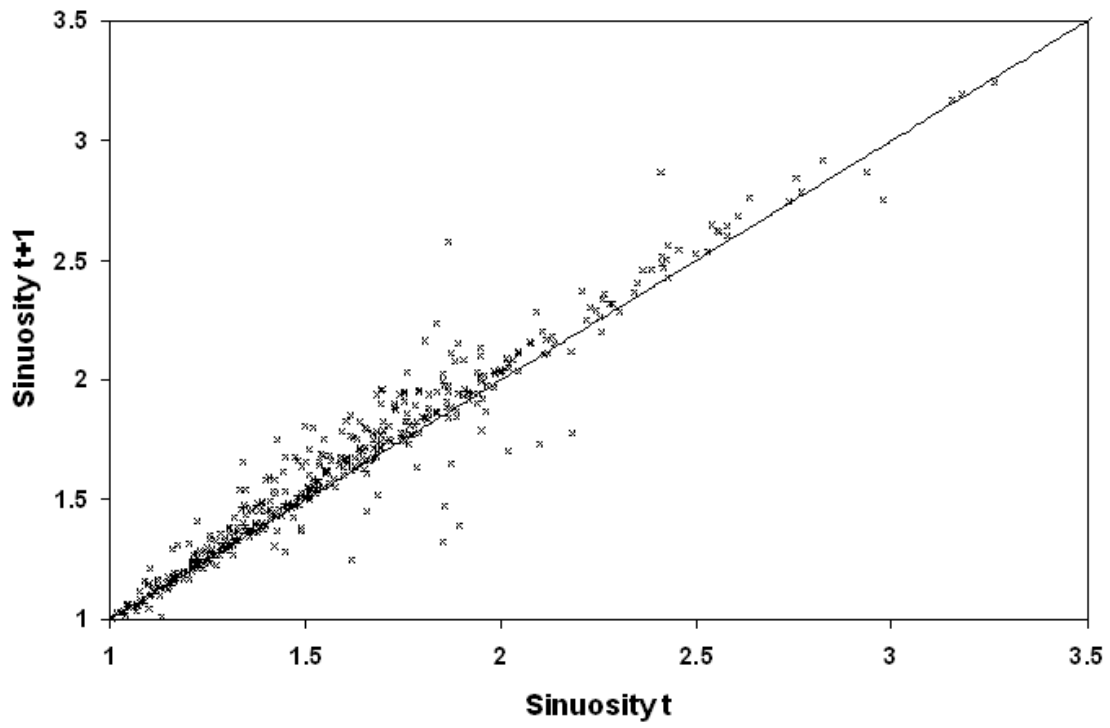


Figure 3-11. Reach sinuosity scatter plot of time versus time + one step in the Pascagoula River Basin

Stream Reach Sinuosity Change versus Reach Initial Sinuosity

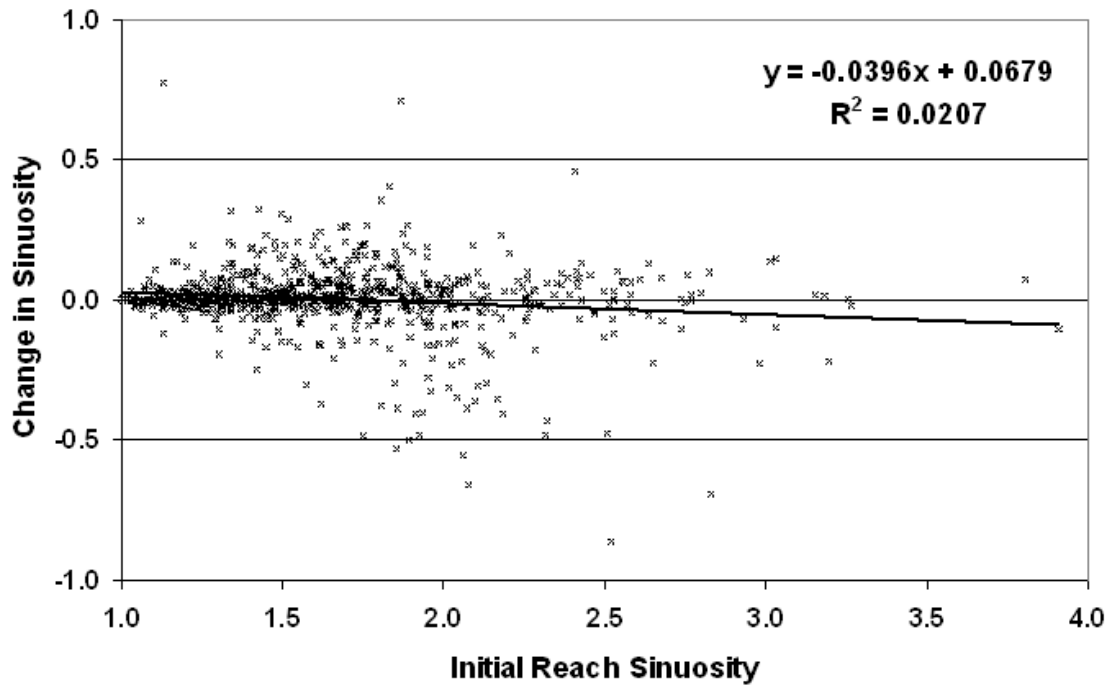


Figure 3-12. Scatter plot of reach sinuosity change versus initial reach sinuosity

Cumulative Reach Sinuosity Change

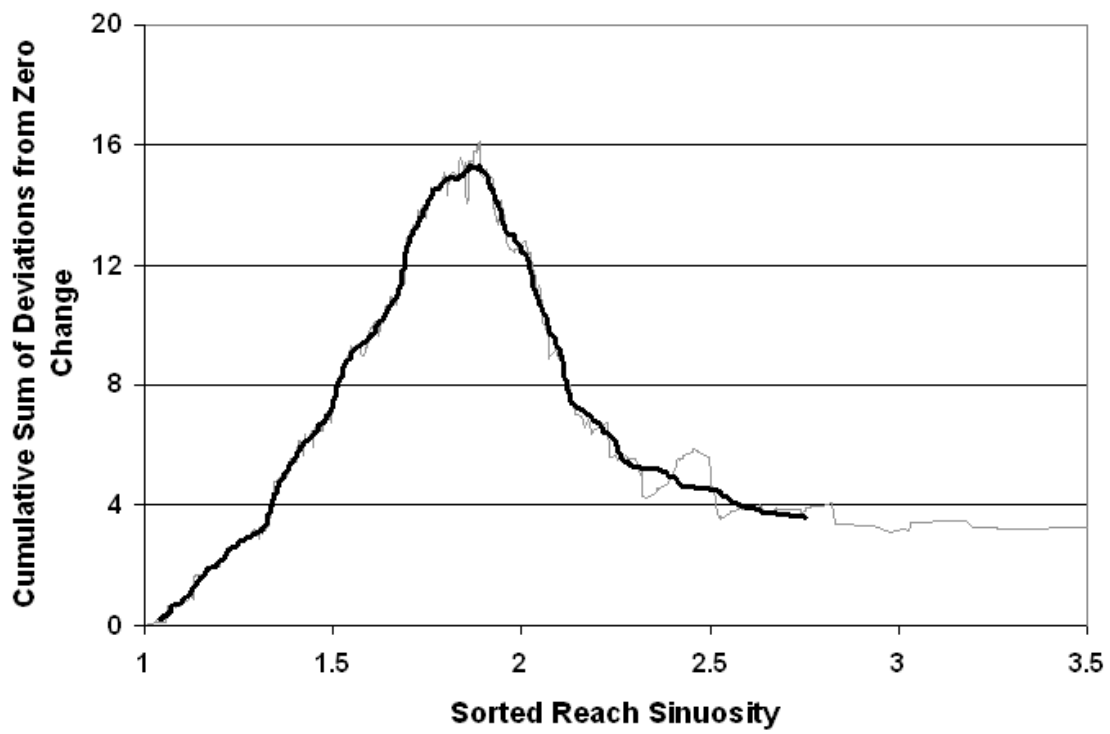


Figure 3-13. Sum of deviations from zero change plotted with sorted initial reach sinuosity

Cumulative Reach Sinuosity Change

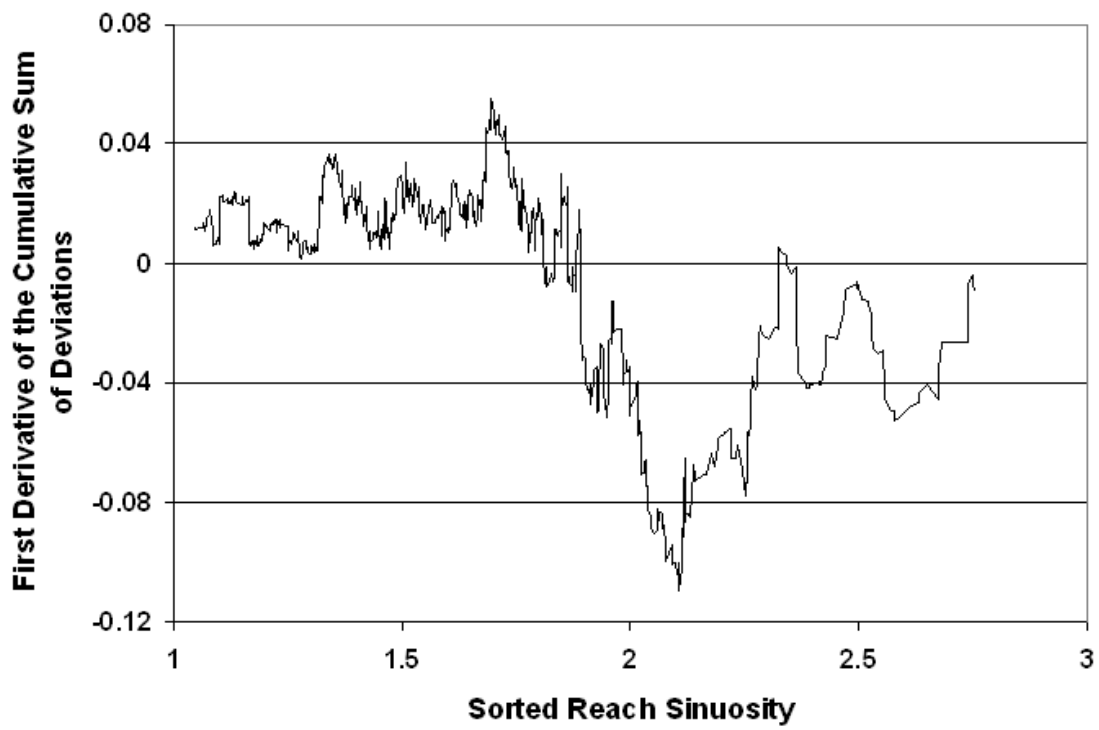


Figure 3-14. First derivative of the sum of deviations from zero change plotted with initial reach sinuosity

CHAPTER 4 THE INFILLING OF OXBOW LAKES

Introduction

This work began with the question of how floodplain lakes fill in, but its focus is also on a related question: how long does it take for them to fill in? It is important to note that all lakes are for the most part transitory features on the landscape. From their inception, they begin to fill in with sediments. As such, the vast majority of lakes found in the world today are geologically young and date from the end of the Pleistocene. This basic premise does not apply to lakes in areas that are tectonically active. Lakes in basins of tectonic origin generally have continued subsidence that offsets the steady deposition of sediments, thereby extending their geologic lifetime considerably (Einsele and Hinderer, 1997).

In the case of the lakes on the floodplains of the rivers worldwide, the lifetime of these landforms is far shorter than tectonic lakes or even lakes of glacial origin. Their time on the landscape is the equivalent of a geologic eyeblink. They begin as alluvial cutoffs and lose much of their original volume in the first decade after their formation. Few but the largest oxbow lakes last more than a century or two, but their complete removal from the landscape is contingent on a number of factors. This chapter explores those factors by examining the alluvial cutoffs and oxbow lakes of the Leaf and Chickasawhay rivers of southeastern Mississippi, United States.

Alluvial Cutoffs

River meandering induces alluvial cutoffs, which leave oxbow lakes on floodplains around the world. As rivers meander, they induce a progressive increase in channel sinuosity (Hooke, 1995). It is this tendency to increase in sinuosity that eventually

prompts meanders to elongate and eventually to cut off. This tendency for unconfined alluvial streams to increase in sinuosity until alluvial cutoffs occur is well established.

Multiple forms of cutoffs have been categorized and described. Lewis and Lewin (as cited in Hooke, 1995) found five types of cutoffs in 14 streams in Wales. These were divided by the location on the meander as well as morphological and sedimentological characteristics. Other studies have also categorized meander cutoffs. Erskine et al. (1992) cited four types of meander cutoffs in an article on Australian rivers. They mentioned neck and chute cutoffs as defined by Allen (1965), mobile bar cutoffs from Lewis and Lewin's work, and bend flattening from Matthes (1947).

Neck and chute cutoffs are the result of the river finding a more direct route down valley. As meandering progresses, the distance traveled by the river around the bend lowers the local gradient substantially, creating opportunities for more direct and steeper gradient pathways to capture the river and direct its flow along a new course. Neck cutoffs occur when a new channel is cut across the narrow neck of an elongated meander.

Erskine et al. (1992) describes when a cutoff occurs. Bed load sediments in the river channel plug the immediate ends of the abandoned channel, creating an isolated cutoff or oxbow lake. Once this occurs, very little infill occurs from bed load sediments, and the bulk of sedimentation is via fine sediments delivered during episodes of overbank flooding.

Allen (1965) also describes the processes that operate after a stream avulsion. When the stream abandons a section of its channel, the former channel is eventually separated from the new channel by the deposition of bed load materials at the ends of

the cutoff in contact with the river. When this occurs, the newly formed lake becomes a zone of quiet water and begins to fill with sediments that are in suspension during overbank flows. The end result is the filling of the cutoff with material that differs sedimentologically from the material in the bed of the original river channel.

Cutoffs have been reported as occurring with some frequency in the upper reaches of stream networks (Hooke, 2003). Lewis and Lewin (as cited in Hooke, 1995) reported that the most common location for meander cutoffs was in the middle portion of the basin where stream power was greatest, but they also noted that neck cutoffs have a tendency to occur in the lower portion of the basin where lower gradients prevailed, whereas chute cutoffs seemed to occur in steeper areas. Chute cutoffs happen in a similar manner to neck cutoffs; however, the new shorter path is typically in a swale or existing low point on the inside of a current meander bend. In these cases, bed load material is transported into the cutoff behind a point bar, and the material continues to accumulate until the upper end of the cutoff is closed. After this, overbank fines tend to become the dominant sediment type, but frequent pulses of coarse material are often deposited, creating a diverse environment.

On the other hand, Stolum (1998) reported that although the lower reaches of river networks have large, easily observable streams with alluvial cutoffs, the processes creating cutoffs seem to operate at a much slower pace, creating the cutoffs too slowly to be easily observed in the decades since air photo and satellite imagery have been available.

Hooke (1995) studied two cutoffs closely after their occurrence, finding that it took from less than 1 year to 7 years for the cutoffs to be closed off from the rest of the river.

Gagliano and Howard (1984) found in their study of the lower Mississippi River oxbows that cutoffs took 2–10 years to experience “blockage” from the main channel. Some cutoffs of the Leaf and Chickasawhay rivers of the Pascagoula Basin were closed on the upper end after 1 year but not at the lower end. However, both ends appear to be completely closed off after 10 years (personal observation).

Hooke’s work on cutoffs of the River Bollin was on a reach that has been mapped in detail since the 1840s. The 600-m reach (valley distance) had four cutoffs occur over that span, so there was little to reduce the sinuosity in the system. Since that time, however, there have been multiple cutoffs, two in the 1980s and then another six that occurred between 1998 and 2002. All but one of these was a neck cutoff, and collectively, they reduced the sinuosity to 1.40 by 2002, leaving a substantial length of abandoned channel. Since that time, the reach appears to be stable and largely unchanged, but the cutoffs have filled in and are not oxbow lakes.

Lake Sedimentation

The overwhelming majority of the research done on lake sedimentation has been by paleolimnologists working on nonfloodplain lakes. Whether the nature of the work is climatic, ecological, or geomorphic, paleolimnology is the science of using sediments to reveal past environmental conditions (Smol, 1990). Despite its sedimentological basis, it is important to recognize that paleolimnology has myriad applications because so much can be interpreted from so little that is preserved (Frey, 1988).

The rationale for paleolimnology comes from a lake’s tendency to accumulate sediments from its surrounding basins (Frey, 1969). Because water-filled basins will accumulate sediments chronologically, different layers represent accumulation under different environmental conditions (Frey, 1988). One caveat to this basic assumption is

that once deposited, the sediments must remain relatively undisturbed by bioturbation and other mixing processes (Smol, 1990). This tends to restrict fine paleolimnological analysis to quiet lake environments. Most deep-lake sediments are derived via a process called focusing, where sediments from the shore's littoral zone reach deep water via resuspension. As a result, the center of a lake is somewhat buffered from a rapidly changing surface environment (Binford et al., 1983). But even so, the differing rates of change between the lakes connected to rivers in a "fast" terrestrial environment and the "slower" deep-lake environments can be accounted for so long as we recognize that we are looking at a lacustrine system that is fluvially dominated and as such operates at a rate that is far faster than would be expected of even a small kettle or sinkhole lake. This fast pace of sedimentation, however, does not preclude the use of these lake sediments for interpreting change over shorter time spans up to 10^2 years. In this case, the application of paleolimnological techniques to oxbow lakes allows us to access the information of a previously untapped resource.

The analysis of floodplain sediments for the purpose of understanding past conditions is well established, but these studies tend to focus on lateral deposits. Pizzuto (1987) reports that there are two types of river sediments: channel deposits formed via lateral migration and overbank deposits formed by vertical accretion. He also points out a number of studies that incorporate lateral deposits and then points out the need for the relatively understudied overbank deposits. Allen (as cited in Lecce and Pavlowsky, 2004) also expresses this sentiment by asking for a better understanding of overbank deposition. Although Allen was speaking of deposition on the floodplain, a

study of sedimentation in oxbow lakes is largely a study of the infilling of the lake by fine overbank sediments.

Works by Erskine et al. (1992) and Owens and Walling (2002) makes use of floodplain cores and techniques developed in the field of paleolimnology to reconstruct changes in sediment sources and the rate of overbank flood deposition. Owens and Walling used specific isotopes of lead (^{210}Pb) and cesium (^{137}Cs) to establish a chronology in their sediment cores. These cores were up to 80 cm in depth with samples at 2-cm increments. They were composed of fine sediments on the floodplain between 45 and 100 m from the channel in a depositional environment not at all unlike the oxbow lakes in this study.

There has also been some work done on the channels that often connect rivers to oxbow lakes. These channels are referred to by a number of names, including tie channel and batture. A batture is a channel that is elevated above the river. It is often occupied during higher flows, and in its role as a connector to surrounding oxbow lakes, it is often the primary source of sediment to the lake. The pattern of sedimentation in these channels can be problematic because flow can be into or away from the river, depending on the water elevation. Despite the messy pattern of sedimentation, Rowland et al. (2005) makes good use of sediments delivered to oxbow lakes by batture in Louisiana, United States, and Papua New Guinea. Rowland utilizes optically stimulated luminescence to determine the depositional ages of prograding deltas at the batture inflow to oxbow lakes. By determining the rate of advance of these batture into the lake, it is possible to estimate how long it will take for these channels to deliver enough sediment to completely fill the lakes.

Landform Longevity

The notion of completely filling the volume of lake with sediment sparks some interesting questions about the longevity of these landforms on the landscape. Because the floodplain environment is potentially a sediment-rich environment, we can expect that a floodplain lake will expire long before an upland lake of similar volume. There are obviously mitigating circumstances to this assumption, and this study will address a few. The literature has a few examples of this perspective on lakes and more specifically reservoirs. Einsele and Hinderer (1997) examined the sediment yield in streams and the resulting life span of connected reservoirs and lakes. They view the matter via sediment budgets, with a particular eye toward the work of engineers in determining the life span of reservoirs. Most notably, they describe the potential life span of lakes as a function of storage capacity versus sediment inputs. Owens and Slaymaker (1994) conducted a similar study on the filling of a lake in British Columbia. Much in the way of the work by Rowland, they based their estimates of time required to fill the lake on measurements of a prograding delta. Another point of interest is that in all cases, one must consider not only the input and volume, but also subsidence and how and when the sediments are delivered.

Hinderer and Einsele (2001) also did research on lake sedimentation rates as a function of denudation rates over an entire basin. Their analysis is geomorphic in its focus being the erosion rate in the basin. It was also global in its scope, examining lakes in a variety of settings, including perialpine lakes in Europe and British Columbia, Canada, savanna lakes in East Africa, and past lakes in the arid basins of Nevada and Utah, United States. In all cases, they recognize the persistence of the landforms as a function of initial volume and surrounding conditions. Sources of sediments can include

both human activities and natural processes, with the lakes functioning almost as a closed system with substantial inflows of sediment yet minor to nonexistent avenues for outflow or export. Given this factor, it is again readily apparent that all basins are sediment sinks and that lakes are from their inception a dying landform.

Regional Setting

The Leaf and Chickasawhay Rivers of the Pascagoula Basin

This study examines two floodplains of the Pascagoula River Basin of southeastern Mississippi in the United States (Fig. 4-1). The westernmost floodplain is occupied by the Leaf River, a stream that flows from central Mississippi just east of Jackson to Merrill, Mississippi, where it joins with the Chickasawhay River to form the Pascagoula River. The Leaf River drains 9,272 km² as it flows nearly 200 km from over 150 m in elevation in the uplands of the Jackson Prairie Belt to 8 m in elevation where it enters the Pascagoula. The Leaf lies mostly in the Longleaf Pine Belt, where the surface geology includes the Forest Hill Sand, Red Bluff Clay, Vicksburg Group of the Oligocene along with the Catahoula Sandstone, Hattiesburg Formation and Pascagoula Formation of the Miocene, and the Citronelle Formation of Pliocene age. The local geology impacts the river in some reaches, but the vast majority of its length is freely meandering with a well-developed floodplain.

The Chickasawhay River occupies the easternmost floodplain in the study. The Chickasawhay drains 7,692 km² from an elevation of roughly 120 m where the river is formed at the junction of Okatibbee and Chunky creeks above Enterprise, Mississippi, to its confluence with the Leaf River at Merrill. As the Chickasawhay flows southward for roughly 160 km, it leaves the Black Belt, where the geology is predominately the Jackson Group Clays of Eocene age, before entering the Chickasawhay Limestone. In

general, the geology beneath the Chickasawhay is far more resistant, leaving a substantial portion of the upper Chickasawhay incised into narrow valleys relative to the Leaf River. However, the lower 40 km of the Chickasawhay below Leakesville, Mississippi, is unconfined and meanders across a large floodplain.

The land cover in the basin is predominately forest, with agriculture being slightly more prevalent in the northern portion of the basin and forest or silvaculture being more prevalent in the middle and lower portions of the basin. Both river floodplains are forested with bottomland hardwoods including sweet gum, *Liquidambar styraciflua*, sweet bay, *Laurus nobilis*, red maple, *Acer rubrum*, black willow, *Salix nigra*, and bald cypress, *Taxodium distichum*.

The climate in the study area is humid subtropical, with hot summers and cool winters. The mean temperature for 105 years of record is roughly 20°C, and annual rainfall is approximately 140 cm, with a fairly even spread throughout the year (U.S. Army Corps of Engineers, 1983). The main rainfall-making mechanisms in the region are winter and spring fronts, summer thunderstorms, and tropical storms. Of these mechanisms, only winter and spring fronts produce serious flooding, with the largest floods occurring predominately in April.

Detailed Field Study: Four Lakes

The detailed field portion of this study occurred on one specific reach of stream less than 5 km south of Hattiesburg, Mississippi. This reach of the Leaf River is approximately 5 km long with a dynamic channel on an active floodplain. In the study reach, four meander cutoffs have occurred, each resulting in an oxbow lake. This cluster of alluvial cutoffs was created over roughly 50 years, with the first occurring in

the early 1900s and the last occurring between 1955 and 1960. The four lakes vary in age and in their exposure to a number of local land uses in the area.

The uppermost of the four lakes is Aldrich Lake. Its formation predates air photos and available maps for the area, but botanical evidence from bald cypress *Taxodium distichum* tree cores suggests that the inception of the lake was 1911 ± 10 years. The lake is located on private land in an area set aside for hunting and fishing. Aldrich Lake is the least impacted by local gravel operations over the past 40 years; to this day, it remains surrounded by deciduous forest.

Immediately downstream of Aldrich Lake and on the opposite bank of the river is Owens Bluff Lake. This lake is so named because it rests against the valley wall or bluff created by the Leaf River. This lake also predates air photos but is estimated through botanical evidence to have formed in 1927 ± 10 years. The lake also rests on privately owned land. However, the landowner began extracting gravel roughly 30 years ago and continued for the next two decades before curtailing operations in the immediate vicinity of the lake. The mining in the area has had a noticeable effect on the lake in that the gravel was removed from the point bar of the cutoff meander, and afterward this area was used to store the sand spoils from the surrounding area.

Farther downstream and on the opposite bank is Wedgeworth Lake. This lake is estimated to have formed between 1926 and 1942, but it is certain that it formed after Owens Bluff Lake. The lake is privately owned at the moment but used to be a popular fishing area for the local community. It is unique among the four lakes in the study in that it has a small creek flowing into it. Over the past 70 years, sediment from this creek created a bar that is now forested and completely separates the oxbow into two.

Wedgeworth Lake now suffers badly from a handful of invasive exotic water plants, including one of the first recorded outbreaks of giant salvinia, *Salvinia molesta*, in Mississippi.

The final lake in the study is Sims Lake. This lake is located farthest downstream and formed last of the four lakes in the study. It was formed between the 1942 and 1955 sets of aerial photographs, most likely in the earlier portion of this time period. The lake is completely contained in a privately owned plot of land with surrounding forest being largely undisturbed. The lake is used for recreation, and the landowner has made some modifications, partially dredging the shallow, point bar side of the lake in the 1980s and constructing a concrete sill at the outflow of the lake, raising the lake surface nearly a meter.

Materials and Methods

Lake Area and Perimeter Changes

This study uses two sources of planform imagery to assess changes in the lakes on the floodplain over the span of 50 years. The first set of imagery is the U.S. Department of Agriculture's Farm Service Agency (FSA) aerial photography program. These were photographed between 1955 and 1958, with the photos for the Leaf River being captured in 1955 and the photos of the Chickasawhay River being captured in 1958. These photos are black and white and at a 1:20,000 scale. The second source of planform imagery is the 2005 National Agriculture Imagery Program (NAIP). NAIP images are natural color with bands of red, green, and blue. Aircraft collected these images in July 2005 with a 1-m ground resolution per pixel.

The FSA photos were digitally scanned so as to preserve a 1-m ground cell resolution. The scanned photos were cropped to remove borders and then

georegistered to a base layer mosaic of digital ortho quarter quads (DOQQs) at a 1:24,000 scale. The base layer quadrangles have a National Map Accuracy Standard (NMAS) that requires that not more than 10% of semi-invariant features on the original U.S. Geological Survey (USGS) topographic map be greater than 0.85 mm (1/30th of an inch) from its real-world map position at scales larger than 1:20,000. This horizontal accuracy is maintained in the DOQQs, so the expected accuracy of the scanned FSA photos is ± 12.19 m at 1:24,000. Each scanned photo used 16–25 ground control points depending on the number of available identifiable features. A first-order polynomial was used to convert the image to real-world coordinates with each of the polynomial parameters being tested for significance via a *t* test at the 95% confidence level (Mossa and Coley, 2004b). This yields a root mean square error of 6.2 m at 95% confidence for the FSA air photos. Once each image was registered, a visual edge-matching process was performed to ensure that each stream was aligned with adjacent and overlapping air photos. If any stream channel segment was misaligned by greater than 8 m, a new set of ground control points was selected and the registration was repeated until there was proper alignment within the specified standards (Mossa and Coley, 2004b).

The NAIP imagery is automatically referenced directly to the DOQQs before it is made available to the public. The spatial resolution of the imagery is listed as 1 m, and the government contract specifies that the horizontal accuracy for photoidentifiable ground control points is 6 m at a 95% confidence level. Both the FSA aerials and NAIP imagery are referenced to a DOQQ layer that utilizes the base coordinate system from the Mississippi State transverse mercator (MSTM) projection. The MSTM is a custom UTM projection used because Mississippi sits astride the boundary between UTM

zones 15 and 16. The MSTM uses the North American Datum of 1983 (NAD 83) and has its central meridian at 89.75°W longitude.

Once the two sets of planform imagery were prepared for the Leaf and Chickasawhay rivers, they were placed in a Geographic Information System (GIS) so that the oxbow lakes on the floodplain could be digitized. The screen resolution for digitizing was fixed at a 1:2000 scale, and each lake shoreline was digitized as a single polygon to create a vector layer of lake locations on the floodplain in 1955 or 1958 and 2005. Each polygon was given a unique identifier, but polygons of lakes in the 1950s were whenever possible linked to the polygons of the same lake in 2005, allowing the area and perimeter of each lake to be compared over the span of approximately 50 years.

Field Data Collection and Analysis

The field data for this study take multiple forms. While in the field, both bathymetry and depth of sediment were collected at a number of locations within each of the four oxbow lakes that comprised the detailed portion of this study. The study also collected two complete sediment cores from each of the oxbow lakes. The methods employed to collect these forms of data are outlined below.

The bathymetry data for each of the four lakes were collected using a portable inflatable kayak with a collapsible probe with 5-cm graduations to measure depth and a handheld Garmin GPS unit to pinpoint the location of the probe. At each location, the probe was slowly lowered until it encountered the resistance of the lake sediment layer. This depth was recorded as the depth of water in the GPS unit. Afterward, the probe was pushed through the relatively fine lake sediments until it encountered the sand and gravel riverbed sediments below. The depth to the former riverbed was then recorded in

the GPS as the depth to bottom. The locations for the measurements in each lake were arranged in transects or cross sections across the former river channel. Each transect typically contained five data points, but in some cases the width of the lake would dictate that anywhere from one to seven data points be collected. After each transect was completed, the next transect was located roughly one to two channel widths upstream or downstream from the last transect.

Obtaining the lake bathymetry prior to sediment coring is crucial so that you can determine where the lake is deepest and therefore sediment is usually the thickest (Wright, 1991). Sites in deep water make use of a process called focusing. Focusing refers to the tendency for deeper water to have faster rates of sediment accumulation because of resuspension of shallow water sediments. These middle or deeper portions of the lake are also generally going to have less sensitivity with respect to shore disturbances that affect sediments in the near-shore environment.

The sediment cores were collected using a vacuum piston corer mounted on a portable platform and A-frame that was constructed on shore and then fixed atop two inflatable kayaks. The vacuum piston corer was constructed according to the specifications set down by Fisher et al. (1992). This study opted to make a number of changes to the original design. We used 2-inch (5.08-cm)-outside-diameter polycarbonate tubing instead of the larger core tubes specified and substituted schedule 80 PVC coring rods for the heavier rods used in large lake coring. This was done to make the device more portable and easier to pack into largely inaccessible bottomland swamps of the Leaf River floodplain.

The platform utilized a pontoon-style construction with a central opening in the platform to allow for coring. The platform also had four cleats, one on each corner, as well as three sets of lines and anchors to fix it in place over the location selected for coring. Wright (1991) suggests that great care be taken when anchoring the coring platform so that it maintains a consistent position over its bottom. He also details the construction of field expedient anchors made out of sandbags and suggests that the anchor lines be well dispersed to spread the stresses from wind, the movement of the corer, and other disturbances. In our research, each of the anchors was constructed from a trio of concrete blocks tied together.

The locations for the sediment cores in each lake were selected from the bathymetry data collected for that lake. The core location was selected so that it was on the downstream limb of the oxbow lake and located at the deepest location to the river bottom beneath the lake. The downstream limb was selected because in the Pascagoula Basin, the upstream limbs of the oxbow lakes are often separated from the river first and tend to fill in more rapidly. The goal in site selection was to obtain a sediment core with the longest possible record of sedimentation in the lake. Two cores were taken from each site, with the second core being located 1 m upstream of the second core.

The bathymetry data also made it clear that the depth of sediments in the lakes was shallow enough to allow us to take all of the cores in a single push or drive, and as such, we did not require casing. This study utilized 8-foot (2.4-m)-long core tubes and collected each core in a single straight push through the lake sediments to the gravel bottom, where the resistance to the penetrating core tube increased markedly. Our

drives captured complete cores with sand and gravel riverbed sediments marking the bottom of each core and representing the beginnings of lake sediment deposition. There were air gaps in the tube on some of the longer cores, but these gaps were not a disturbance to the integrity of the core because we immediately took the captured core to the shore for extrusion, and all gaps were reconnected during the extruding process.

The longest core was 1.4 m in length, and all eight cores were over 1 m long. Once a complete core was collected, it was brought to the surface, the bottom was capped, and the vacuum was released on the piston so that it could be removed and prepared for the second core. Each core was stored upright on the A-frame of the pontoon while it was brought to shore, and a site was prepared for extruding.

The sediment cores were extruded vertically in the field into a tray so as to maintain the integrity of the soft horizontal layers at the mud-water interface. This was accomplished by inserting an extruding rod and stopper into the bottom of the core tube. When extruding a core, the rod is pushed upward at controlled increments until the sediment core exits the top of the core tube and falls into an extruding tray. Each core was collected at 4-cm increments and placed into labeled plastic sample bottles that were placed in a cooler until they could be refrigerated on return from the field.

At the end of the field season, the cores were transported from Mississippi to Florida, where they were moved from sample bottles to aluminum trays and weighed while wet. They were then dried in a drying oven for 6 hours at 90°C. After cooling, the samples were weighed dry and then placed in a muffle furnace where they were cooked at 550°C for 6 hours. After cooling, they were weighed again to calculate the loss on

ignition (LOI) for each sample. Finally, each sample was ground in a mortar with a pestle before being placed in a brass sieve set.

The sieve set comprised a #10 (U.S. size) sieve and a #230 sieve. Intermediate (#18, #35, #60, and #120) sized sieves were used to protect the #230 sieve, but all intermediate sieve material was combined as the sand component of the sample after sieving. Each sample was placed in a ROTAP sieve shaker for 10 min. Afterward, the sieves were weighed and the tare weight of each sieve was removed to provide the weight of the portion of the sample in each sieve. These sieve weights were then compiled into gravel, sand, and fine components.

We also collected botanical evidence to aid in the dating of the four lakes. The chief botanical evidence is in the form of bald cypress *Taxodium distichum* tree cores. Harper (1912) used trees to determine the age of oxbow lakes in a study also located on the southeastern coastal plain. He used tree cores from the oldest bald cypress *Taxodium distichum* tree growing on the bar deposits between the river and the oxbow lake. His study was tested more recently and was found to give decadal-scale precision on the age of oxbow lakes (Shankman, 1991). Shankman found that after a meander cutoff, the bar deposits in the southeastern coastal plain are colonized by black willow *Salix nigra* first but are rapidly replaced after about 60–80 years by bald cypress.

We searched each of the forested areas occupying the bars that formed at the ends of each oxbow lake for bald cypress trees and then collected tree cores at breast height from 10 trees in each stand. The age of the oldest tree in each stand plus 70 years provides an estimate of the closing of the lake to continuous river flow ± 10 years. Both Owens Bluff and Aldrich have established stands of bald cypress on the bar

deposits that separate each lake from the river. The oldest bald cypress found on the deposits at Owens Bluff Lake was 9 years old, and the mean of the stand was 6.8 years old. These data suggest that that Owens Bluff was separated from the river around 1927 ± 10 years. The oldest bald cypress on the deposits at Aldrich Lake was 25 years old and the mean of the stand was 21.6 years, yielding a date of origin of 1911 ± 10 years.

Neither Wedgeworth Lake nor Sims Lake had bald cypress trees on its bars; however, we were able to use the absence of bald cypress and supporting aerial photography to deduce that Sims Lake occurred after 1942 but before 1955. The river in the 1942 photos occupied the meander that is now Sims Lake. By 1955 the cutoff had occurred and the lake was completely detached from the river with vegetation covering the scars of the old river channel. This suggests that the cutoff forming Sims Lake occurred very early in the period between 1942 and 1955.

Wedgeworth Lake predates both the 1942 and 1955 photos, but in the 1942 photos, the cutoff that formed the lake was still connected to the river, suggesting that it occurred only a few years before the photograph. This argument for an origin in the late 1930s is supported by the absence of bald cypress seedlings in the area. At the time of the study, only 64 years had elapsed since the photo showing the cutoff joined with the Leaf River.

Lake Bathymetry Analysis

The lake bathymetry data that were stored in a GPS unit were later uploaded into a GIS as point data vector files in the MSTM projection. From there, the GPS locations were compared to a polygon vector file with lake shorelines.

The point data in the vector file were recorded with the location, the depth to sediment in centimeters, and the depth to the river bottom in centimeters. These depth values were converted to negative values so that they represented the elevation relative to the surface of the lake. Each point was connected to nearby points with vertices, creating a series of triangles in a coarsely triangulated irregular network (TIN). Ideally, the number of points collected in the field would be sufficient to capture all the variability on the bottom of the oxbow lake. But with limited time in the field, the lakes were sampled systematically and in a rough fashion, leaving the resulting coarse TINs without sufficient detail and with some areas without sufficient data. As such, the surrounding shoreline was used as a zero-elevation boundary while the existing bathymetry points were augmented via the following process.

Each sample point was used as a node in a series of connecting arcs that followed the original flow path of the river. These arcs were then cut into 5-m segments with intermediate nodes at the end points of each segment. Then the depth values for each node were interpolated at equal intervals directly from the existing depth values for the bathymetry data nodes. In some cases, there were few or no original data points available for a portion of a lake, so in lieu of fabricating data to fill the gaps, those portions were not included in the study. Both Wedgeworth and Owens Bluff lakes have substantial portions that are completely filled in with sediments, so we did not collect depth data from these areas.

Once the number of data points was augmented, the entire set of points was again placed in a TIN that contained enough information to create a fine representation of the bathymetry and sediment surface within the lake. This fine TIN was then converted from

a vector file into a raster file with a matrix of 1-m cells with values for each cell. This raster file, or GRID, is a rectangular array with all cells located outside the lake with a value of no data. The cells within the lake boundary or shoreline contain a value based on the information in the fine TIN that was ultimately derived from the original field data.

The conversion to a GRID file allows a number of mathematical computations. The field data for depth to river bottom and depth to the lake sediment can be used to calculate the depth of sediment at each location. From this, a summation of all the cells in the lake can be used to calculate the volume of lake to river bottom, the volume of lake to current bottom, and the volume of the sediments contained within the lake currently. These volume measures can be applied to the area values for the GRID to create a mean depth, mean depth of sediments, and mean depth to river bottom in each lake.

Results and Discussion

Alluvial Cutoffs and Oxbow Lakes

Each oxbow lake begins with an alluvial cutoff. These cutoffs leave marks on the floodplain and can either be terrestrial or lacustrine. This study examined the lacustrine remnants of alluvial cutoffs on two rivers of the Pascagoula Basin of southeastern Mississippi. Each of the two rivers can be further subdivided by drainage area into an upper and lower division (Table 4-1).

What we find is that the total number of lakes since the 1950s has increased. In the 1955 air photos, the two rivers that were examined had 109 identifiable open-water oxbow lakes over a channel length of 502.2 km. This equates to roughly 0.22 cutoffs km^{-1} or approximately 1 cutoff every 4.5 km. In 2005, the number of cutoffs had increased to 134, which equates to 0.27 cutoffs km^{-1} or approximately 1 cutoff for every

3.6 km of stream. Given these values, we can state that the rate of oxbow lake creation over the past 50 years exceeds the rate of lake removal or destruction.

However, the trend that is evident when looking at the entirety of the study area is not present in all the subdivisions. The Upper Chickasawhay is 158.8 km long beginning at the junction of Okatibbee Creek and Chunky Creek above Enterprise, Mississippi, and flowing southward to its junction with Buckatunna Creek. At this point, the drainage area nearly doubles and the Chickasawhay increases substantially in size, creating a natural break point in the study. The Upper Chickasawhay River is the longest of the divisions or study reaches, but for the majority of its length, the local geology, notably the Chickasawhay Limestone, constrains the river, leaving only about 20% of its length freely meandering across a floodplain wide enough to accommodate cutoffs and their resulting oxbow lakes. Despite the limited length of freely meandering stream, the Upper Chickasawhay had 12 oxbow lakes that were identifiable on the 1955 air photos of its floodplain. Over the 50-year span since those photos, two of those lakes were destroyed, both being reoccupied by the river. However, 12 new lakes were created since 1955 and identifiable on the 2005 imagery. Of the 12 new lakes in the Upper Chickasawhay, half occurred on a single reach only 5 km long. So although the activity on the Upper Chickasawhay is minor in terms of raw numbers, the intensity of the activity with respect to length of the meandering channel is impressive.

The Lower Chickasawhay River begins below its confluence with Buckatunna Creek and flows southward for 112.3 km to its confluence with the Leaf River at the head of the Pascagoula River. For the upper two-thirds of the 112.3 km, the Chickasawhay River is incised into and constrained by the Chickasawhay Limestone

and Catahoula Formation. It is, however, freely meandering over its lower third, where it flows over the Pascagoula and Hattiesburg Formation. It is here that the floodplain is marked repeatedly with oxbow lakes. In this southern portion of the basin, the air photos, which date from February 1958, reveal 54 identifiable floodplain lakes. In the nearly 50 years that have elapsed since then, this section of the Chickasawhay had 16 lakes created by new cutoffs and 11 lakes destroyed, either by sedimentation or by the movements of the river. The activity on the Lower Chickasawhay is, in terms of number of cutoffs, higher than any of the other river reaches in the study.

The Leaf River, on the other hand, has been relatively subdued with respect to creating lakes. The Upper Leaf River created eight lakes over the 50-year span while destroying eight lakes over the same span. The length of this reach is 124.1 km, from Taylorsville, Mississippi, to where the Leaf River joins the Bowie River at Hattiesburg, Mississippi. The density of lakes per length of stream in the Upper Leaf is higher than in the Upper Chickasawhay River. That being said, the Upper Leaf is largely unconfined by its geology and meanders far more freely than the Upper Chickasawhay, so the intensity of the activity is lower.

The Lower Leaf River begins where the Bowie River joins the Leaf. The Bowie River provides nearly 35% of the discharge for the Lower Leaf River, so the size of the Leaf River below its confluence with the Bowie River is substantially larger than the Leaf River above the confluence. This creates an obvious natural break for the study. The Lower Leaf has an extensive floodplain for nearly all of its 119.2 km. The effect of the underlying Citronelle Formation on this portion of the river is negligible and as such the stream meanders freely across its floodplain. The floodplain had 25 identifiable lakes in

the February 1958 air photos. Since that time, 11 more lakes have been created and only a single lake removed from the landscape when the river reoccupied the former cutoff.

Stream Stage and Discharge

Any comparison of floodplain features over time will be influenced by the stage or water height in the river at the time the imagery was flown. In this study, there are two sets of imagery: FSA aerials and NAIP images. The FSA aerials were flown mostly during February 1958, with the lower portion of the study area and nearly 70% of all the oxbow lakes in the study being photographed between February 16 and February 21, 1958. In a similar fashion, the NAIP images for the entire basin were all collected in July 2005. Given these facts, comparisons across the lower basin are relatively straightforward. However, the FSA aerials for the upper basin were flown by county and over a series of dates as much as 5 years apart. The Upper Chickasawhay photos were taken on March 29, 1955, while the Upper Leaf photos were collected on either May 2, 1955, December 21, 1959, or October 23, 1960.

Table 4-2 summarizes the discharge and stage of the Leaf and Chickasawhay rivers during the times at which the images were collected. The two USGS stream gauges used to compile these data are located at Hattiesburg, Mississippi, on the Leaf River and Leakesville, Mississippi, on the Chickasawhay River. The Hattiesburg gauge is located at the division between the Upper Leaf and Lower Leaf study areas and sits at a drainage area of roughly 4500 km². The Leakesville gauge is located about 50 river kilometers below the Upper Chickasawhay and Lower Chickasawhay division at Buckatunna Creek. Its drainage area is approximately 6970 km², and it is located in the lower quarter of Chickasawhay River. Although it is not ideally located, it is better

situated than any of the other stream gauges on the Chickasawhay River. Each gauge enjoys a lengthy record of stream monitoring, with each entering its eighth decade of continuous sampling of river stage or water height and calculated discharge.

As we can see from the data in Table 4-2, the imagery was captured under a variety of flow regimes. The March 1955 aeriels were flown during a very dry spring when the Chickasawhay was at only $50.5 \text{ m}^3 \text{ s}^{-1}$. This makes comparisons to the July 2005 imagery when the Chickasawhay was at a discharge of $123.7 \text{ m}^3 \text{ s}^{-1}$ less than optimal. At Leakesville, the stage difference between these two periods is roughly 1.1 m. In contrast, Leakesville's stage for February 1958 was approximately 5 m at the gauge to 4.4 m in July 2005, which is an easier comparison. It should be noted, however, that the Leakesville stage data are collected from a gauge located beneath a bridge that further confines the flow of an already confined river, creating a very deep channel where stage changes rapidly with discharge.

At Hattiesburg, the stage of the river for May 2, 1955, was 0.6 m. This is quite close to the stage for October 23, 1960, and for the NAIP imagery recorded during the traditionally dry and low-flow month of July. In July 2005, the Hattiesburg gauge recorded a stage of 0.8 m, making comparisons in most of the Upper Leaf River quite close in terms of stage. However, the FSA air photos from February 1958 and December 1959 were flown under markedly different hydrological conditions. Winter is traditionally a wet season in the Pascagoula Basin, so rivers are generally much higher than in July. At Hattiesburg, the average stage for February 21, 1958, was 1.3 m, and it was at 1.1 m in December 1959. Neither is over bankful stage, but the data suggest that

floodplain lakes will potentially be holding more water than in the summer 2005 images, causing them to have a larger surface area.

Given the preceding information and that in Table 4-2, we can make a couple assumptions about the comparison of the oxbow lakes on the different sets of images. In the Lower Leaf River, comparisons between 1958 and 2005 are potentially at different stages. Other comparisons on the Leaf should be close with respect to stage. In the Chickasawhay River, July 2005 was surprisingly wet, so comparisons between February 1958 and July 2005 on the Lower Chickasawhay are close with respect to stage. In contrast, comparisons of March 1955 to July 2005 involve images of the Upper Chickasawhay River at different levels.

It is important to recognize that in spite of these assumptions, 50 years is a lengthy period, and any comparison will be less than ideal because of imprecision introduced by a host of factors. Even with stage and discharge information for the two gauge sites, these locations may not be entirely representative of the larger study area. Furthermore, land use changes and their geomorphic impacts may exercise a strong influence over the floodplain and its oxbow lakes. Chapter 2 of this dissertation is focused exclusively on a large reach of stream that has undergone channel degradation since the 1950s, leaving its oxbow lakes on a floodplain that requires higher and higher stages before inundation.

Lake Surface Area Loss Over Time

Even with these difficulties in comparing oxbow lakes over such a lengthy time span, we can recognize a number of prevalent trends. The first is that oxbow lakes have on average lost surface area over time (Table 4-3). The average lake surface area loss for both the Leaf and Chickasawhay rivers was 12%. The lakes in the upper portion of

the Pascagoula Basin had higher rates of loss than the lakes downstream, and the 10 lakes of the Upper Leaf River lost nearly a quarter of their total surface area since 1955. This value of 25% includes a lake that grew by 500% when it was excavated as a gravel pit. In fact, we find that four of the five lakes on the Leaf River that gained substantial surface area did so as a result of directly observable human impact. Removing these lakes from the totals for the Leaf River boosts the average loss in area to over 20%.

The results for the Chickasawhay River are similar, but we cannot easily ascribe gains in lake surface area on the Chickasawhay to human impacts. Although the net surface area loss was 12% for the entire Chickasawhay, there are eight apparently undisturbed floodplain lakes that were markedly larger than in 1955. This move against the trend cannot be explained by discharge or stage, and there are 27 lakes in the same area that became substantially smaller over the same period. It is likely that there are other individual local factors involved, and we will explore some of those factors more fully in subsequent sections of this chapter that focus specifically on the bathymetry and history of sedimentation of four oxbow lakes.

Before we move on, it is important to make some observations about the results of this comparison of lake surface areas. The data for this examination were collected from the lake polygons digitized from the 1950s-era FSA aerials and 2000s-era NAIP images. We included only the lakes that lost surface area over the 50-year span in the correlation calculations, providing us with 39 observations from along the Chickasawhay River and 25 observations from along the Leaf River. Each of the two samples was used to test the percentage lake surface area loss over time for dependence with a trio

of potentially influential variables. Table 4-4 provides a summary of the correlation between percentage lake surface area lost and these variables.

The first of the three working hypotheses for these comparisons was that the percentage lake area loss is inversely proportional to the drainage area of the river where the oxbow lake is located. The rationale for this hypothesis is that an increase in drainage area is also an increase in river cross-sectional area, which is an increase in the volume of any resulting alluvial cutoffs. Lakes in the lower portion of the basin will be larger and deeper and will therefore take longer to fill in and lose surface area. The second hypothesis is based on the same premise but looks at the initial lake size and surface area instead of the lake's location in the basin, stating that the percentage lake area loss is inversely proportional to the initial surface area of the lake. The third hypothesis uses a completely different basis and states that percentage lake area loss is inversely proportional to the isoperimetric quotient of the lake in the 1950s. The isoperimetric quotient is a measure of compactness of shape and compares the area of a polygon, or in this case, a lake, to the area of a circle with the same perimeter as the polygon. If a lake were completely circular, its isoperimetric quotient would be 1.00. As the shape becomes more irregular, or in the case of oxbow lakes, elongated, its perimeter increases relative to its area, the isoperimetric quotient approaches zero. The rationale for this hypothesis comes from some basic assumptions in limnology, namely, that the greater the length of the paralimnion or littoral zone of the lake, the larger the potential source area for organic and inorganic sediments and the higher the sedimentation and lake filling rates.

The results of these comparisons reveal some surprises. In the Chickasawhay River, all three factors are closely correlated with one another and with percentage lake surface area loss. In both river systems, drainage area has the strongest correlation with percentage lake surface area loss, and in the Leaf River, it is the only significantly correlated variable. The results affirm that percentage lake area loss is inversely proportional to the drainage area of the river where the oxbow lake is located. In the Chickasawhay, all the independent variables are closely related; however, the effects of the variables on lake surface area loss varied from what was expected. The more compact oxbow lakes of the Chickasawhay had a significant tendency to lose a larger percentage of their surface area than the more elongate and less compact lakes. This is contrary to what was expected from the isoperimetric quotient. The initial lake surface area had a weak negative correlation with percentage lake surface area loss, but given its significant relationship with drainage area, the correlation could be a result of the indirect influence of that variable.

In the interest of being thorough, we performed all the same correlation tests on absolute lake surface area loss and found similar but weaker relationships. In the Chickasawhay River, the Spearman's rho between oxbow lake surface area loss and drainage area was -0.21 , which yields a p -value of 0.10 . In the Leaf River, the Spearman's rho for the same variables was -0.15 , which carries a p -value of 0.24 for a sample of $n = 25$ observations. Even with the reduced strength of correlation, it is reassuring to find that in both comparisons, the location of an oxbow lake in the watershed is a factor in the change in oxbow lake surface area.

Oxbow Lake Sedimentation: Core Results

Now our focus shifts from the large portion of the Pascagoula River Basin to a 5-km reach of floodplain along the Leaf River. In this 5 km are the remains of four alluvial cutoffs from the first half of the 20th century. Each cutoff is presently occupied by an oxbow lake, and each lake provides some insight into the question of how floodplain lakes fill in.

Section 2 gives a description of the study area, and section 2.2 describes the age and character of the four lakes examined in this study. The sediment cores for each lake are over a meter in length and sampled at 4-cm increments. Fig. 4-2 shows the percentage by mass of the organic (estimated from loss on ignition), inorganic, and water components of the Aldrich Lake sediment core. Fig. 4-3 displays the percentage by mass of gravel, sand, and silt/clay in the inorganic component of the same core. Fig. 4-4 shows the organic, inorganic, and water components of the core from Owens Bluff Lake, while Fig. 4-5 shows the gravel, sand, and silt/clay. Figs. 4-6 and 4-7 show the same information for the core from Wedgeworth Lake, and Figs. 4-8 and 4-9 display the information for the core from Sims Lake.

All the cores display similar trends in their patterns of deposition and composition. Table 4-5 displays a summary of the information from the 116 samples from four sediment cores. Regardless of the lake, the core tends to become more saturated as we move upward. The average water content for all samples is 38% but the top 20 cm of each core are nearly 60% water by mass, and this figure probably underestimates the water content at the sediment-water interface. At the same time, the organic component remains fairly consistent in each of the cores with an average of 4.1% by mass, with only occasional peaks to as high as 9.3%. This regular organic component to all parts of

the core makes sense when given the fact that much of the bottom of each lake is covered with submerged vegetation that has rooted throughout almost the entire length of the core.

The inorganic component of the core is further summarized in Table 4-6. The overall trend of each core was for sediment particle size to fine upward. The only part of the core with gravel was the bottom portion that marks the end of the lake sediments and the beginning of the original riverbed sediments. There is an interesting peak in coarse material in a portion of the core, but our inability to determine a specific date for this layer of sediment hinders the development of anything more than a relative based interpretation of the cores. However, if we place all the cores next to one another along with the discharge data from the nearby stream gauge on the Leaf River, we can make some interesting observations (Fig. 4-10). The first is that the oldest three lake cores have a pronounced spike in percentage sand that occurs in the first third of the core. This may represent relatively coarse sediment delivered during the 1943 flood. All four cores have another smaller peak slightly later in the core. This peak may represent the 1961 flood. Later in the core, the percentage sand drops off appreciably in the cores. This occurs even with human-derived inputs into Owens Bluff Lake and Sims Lake. It was argued convincingly in Chapter 2 of this dissertation that the 1974 flood on the Leaf River drastically altered the sediment load in this reach of the stream and prompted three decades of incision that left each of the four lakes increasingly high and dry with respect to the river and its sediment. Other features in the individual cores appear to be supported by the discharge record. It is likely that only Aldrich Lake was around for the back-to-back floods of 1919 and 1920, which explains the peak in percentage sand in

an early segment of the core. Both Wedgeworth and Sims lakes were reported by local sources and early maps as remaining connected to the river for a lengthy period of time. Wedgeworth Lake is remembered by local fishermen as being accessible by boat directly from the river for over a decade after its initial cutoff. Many of these observations are speculative without absolute dating, but there is enough information in the relative sense to suggest that this approach is a viable one for unraveling past sedimentation patterns and even hydrology and flow conditions in streams that are not gauged.

Oxbow Lake Sedimentation: Lake Bathymetry

The sediment core information in the previous section examines each lake's sedimentation over time. The following information examines the lake sedimentation over space. We can utilize water depth and sediment depth at the bottom of the oxbow lake to construct a map of lake bathymetry and lake sediment storage. This information can then be used to estimate the current lake volume, sediment volume, and the lake volume when the cutoff occurred. Table 4-7 summarizes this information for all four lakes. Each of the lakes is discussed in detail in the following paragraphs.

Aldrich Lake has no channel inputs, it has no feeder streams, and its tie channels have grown increasingly longer and smaller over time. As such it is almost completely detached from the river. Add in the substantial degradation in the Leaf River and it is essentially an isolated lake. Of the four lakes examined in this study, it has one of the highest percentages of organic material, and it has the highest percentage of fine materials, with over 70% of the core being silt sized or smaller. It also has the lowest rate of sedimentation, with only 27% of its measurable cutoff volume filled with sediments. Given that this lake is the oldest of the four, at just under 100 years, its low

rate of sedimentation is a testament to its relative isolation from both the river and local disturbance (Fig. 4-11).

Owens Bluff Lake is in direct contrast to the relatively quiet atmosphere in Aldrich Lake. Owens Bluff Lake is much closer to the Leaf River; its lower limb is the closest to the river of the lakes in the study. Furthermore, it has maintained this proximity to the river over the 5 decades during which we have been able to observe it. Its tie channel is well defined and observable in the field even through the densely vegetated floodplain during summer months. The lake itself is nestled up against the bluff that gives it its name, so there is some input off the hillside. There are no perennial feeder streams present, but the gravel mining in the area extends to less than 30 m from the lake. The plentiful spoil piles of sand located on the inside perimeter of the lake provide continual inputs of sediment to the inner margin of the lake. It is clear that this lake is in its last stages and will be filled in completely much sooner than the others. A local landowner was very clear in implicating the gravel mining that began in the 1980s as the factor that destroyed “a great little fishing hole.” This anecdotal evidence is supported by the imagery used in the study and by the observation that nearly 60% of its measurable volume is filled with sediments (Fig. 4-12).

Wedgeworth Lake has the most complex history of the four lakes. It resides in a fairly sheltered location on land that was up until recently owned by a hunting and fishing club. The lake is infested with a number of invasive species, and its entire surface has been covered with giant salvinia. This might explain why the lake has the highest percentage organic in its sediment core. This, however, is minor in comparison to the presence of a tributary stream that has drastically affected the pattern of

sedimentation within the lake. This stream is the only perennial stream flowing into any of the four lakes in this portion of the study. However, the stream is a recent addition to Wedgeworth Lake; USGS digital raster graphics from the mid-1980s show that the stream feeding into Wedgeworth was originally demarked as an ephemeral stream. It is barely noticeable in the 1958 FSA photos and had not created any sort of delta form in the lake over its first 20–30 years of existence. In the early 1980s the flow of a perennial stream that was originally flowing into nearby Sims Lake was diverted into the ephemeral stream feeding into Wedgeworth. This diversion created a large wetland and turned the stream feeding Wedgeworth into a permanent creek that immediately began to create a delta at its inflow into the middle third of the oxbow. Since that time, the delta has grown to the point where it cut Wedgeworth Lake into two. The bar currently supports trees that are 12–13 years in age and creates a 30-m-wide land bridge across the lake that is submerged only during floods. This tributary has provided Wedgeworth Lake with the highest rates of sediment input of any of the lakes examined. Fifty-seven percent of the measurable cutoff volume is occupied by sediment, leaving slightly less than half of the original lake volume to store water (Fig. 4-13).

Sims Lake has the most disturbed history of the four lakes. It remained connected to the Leaf River for some time after its formation, and during its early years, it drained the now truncated basin of the formerly perennial stream that is now diverted into Wedgeworth Lake. The gully marking the former stream was dry during all four seasons that we visited the lake. Its former inflow is marked by a now submerged delta, so at one time the sediment flow from the creek must have been greater. Sims has also been the subject of owner “improvements.” A concrete weir was constructed on the formerly

well-developed batture or tie channel to the downstream limb of the lake. This weir maintains far higher lake levels than in any of the other lakes in the study and is one cause of the increase in surface area of Sims Lake. The other cause is a result of a dredging operation by the owner where the point bar was removed from the lake and piled into a levee on the inside curve of the oxbow. Only 38% of the current lake volume is occupied by sediment. However, when we estimate the volume of the levee material and include it with the volume of sediment still in Sims Lake, we find that 82% of the measurable volume of the cutoff is filled with sediment (Fig. 4-14).

We began with the question, how do these floodplain lakes fill in? Although the processes involved in all lake sedimentation are relatively straightforward in that lakes capture and retain sediments from their surrounding basins over time (Hinderer and Einsele, 2001), our study shows that the rates at which these processes work vary drastically from lake to lake. When we look at the four lakes in this study, each has a decidedly different history and character, and all of this despite the fact that the lakes are adjacent to one another on the same floodplain and of relatively similar age.

So the question of how these lakes fill in is far less interesting than the question, given all the processes of sedimentation operating on these floodplain lakes over their history, how long does it take for them to fill in? The work of Einsele and Hinderer (1997) focuses nicely on the concept of residence time for a lake, reservoir, or any basin on the landscape over time and lays out the conceptual framework of sedimentation. But nowhere in their efforts is the massive variability in local and initial conditions between lakes brought into as sharp a contrast as in the history of sedimentation in our four lakes (Table 4-8). It is this variability that potentially sheds light

on how important the apparently minor local processes are in delivering the sediment that affects the volume of a cutoff and its lake over time. We will discuss three of these factors in the following sections.

The Effect of Connecting Channels between the River and Lake

The first factor is the presence and condition of the tie channel or batture that connects the river to its former cutoff. This factor is the best studied in the literature on floodplain lakes and is summarized by Rowland and Dietrich (2006), who examined a tie channel or batture connecting the Mississippi River to the Raccourci Old River where a cutoff occurred in 1851. Since 1851, the channel in question has extended itself 9 km into the lake, reducing the lake surface area by 24%. However, the authors found that the rate of advance has decreased by 80% since the late 1880s. They attribute this to changes in agricultural practices in the Mississippi Basin and structural controls in the Mississippi floodplain. Their results also find that these channels were likely to be significant in the past, with tie channels carrying up to 4% of the total suspended load of the river into oxbow lakes. Although their results stem from a very large system, there are many similarities to our system with respect to geomorphic processes and form.

The tie channels in the Raccourci Old River, and in another study on the Fly River of Papua, New Guinea, are universally located on the downstream limb of the oxbow lakes. Irrespective of scale, this trend carries over into nearly all the hundreds of lakes examined in the Pascagoula Basin. In all cases, the upstream limb of the cutoff is closed quickly by an alluvial bar, leaving the lower limb as the main source of sediment over the early years of the oxbow lake. Even after complete closure, it is the lower limb that receives the greatest accumulation of overbank sediments from the river during flooding. This mechanism is still at work in all four lakes, although it is severely impeded

by isolation in Aldrich Lake and by the construction of a concrete sill in Sims Lake. Even so, we speculate with some confidence that it was this mechanism that was responsible for much of the early sedimentation in our four lakes. Fig. 4-15 provides a simplified interpretation of how the processes of sedimentation will work to fill in the oxbow lake's volume over time. Once the cutoff is created, its output of sediment is severely reduced while input remains relatively high. As the cutoff is plugged and the oxbow lake is formed, each flood by the river delivers overbank fines that steadily reduce the volume of the lake until its open water is removed, returning the area to forested floodplain.

Before we transition to the next factor, it is important to restate that the importance of this mechanism is reduced, both in this case and in all cases where rivers undergo channel degradation. The degradation in the Leaf River after these cutoffs occurred will increase the elevation differences between river and lake and drastically reduce the rate of sedimentation from flooding. Add in the substantial widening of the river channel in this reach and we have a situation where the storage area of the channel is greatly increased, leaving only the largest floods with the potential to reoccupy the former floodplain. We can be confident that if this were the only factor involved, it would prolong each lake's time on the landscape, resulting in a similar situation as the one described by Rowland and Dietrich (2006).

The Effect of Tributary Streams

The second factor is only evident in two of the lakes over their histories, but its presence has substantially altered the morphology of one lake and left an obvious landform in the other lake. In our simplified conceptual model (Fig. 4-15), we assume that the river is the only source of sediment to the oxbow lake. But each river has a plethora of tributary streams, and although it is unlikely, it is probable that some alluvial

cutoffs will contain the inflow of these smaller creeks. Up until that point, the delivery of sediment from the tributary is often completely offset by the transport capacity of the larger river. However, once the cutoff occurs, the transport capacity is severely reduced, and when the cutoff is plugged, any transport will stop altogether. This means that there will be deposition at the inflow of the creek to the lake, no matter how insignificant the sediment load of this small stream. In the case of Sims Lake, this left a submerged but substantial delta at the end of the now dry gully. It is likely that if this input were not diverted, Sims Lake would be significantly reduced in volume.

The best example for this special case in oxbow lake sedimentation is Wedgeworth Lake. Although we have a sample size of only one, it is clear that the effect of the flow diversion from Sims Lake to Wedgeworth Lake has prompted serious changes in the Wedgeworth's form over the last 30 years. Wedgeworth Lake is cut into two parts by the sediment bar that formed at the creek's inflow. Currently all the sediment and water from the tributary is being delivered to the upper portion, prompting a slightly higher lake level (5–10 cm) in the upper lake and the development of a connecting channel across the now forested bar.

When we ponder this example, it is easy to scale its effects up or down by changing the size of the tributary. If a creek that is less than 2 m across and less than 50 cm deep can fill a portion of an oxbow lake that is more than an order of magnitude larger, it is obvious what a much larger tributary could do. If we consider the ratio between the cross-sectional area of the tributary and the main stream that creates the cutoff, it is clear that as the ratio approaches 1, this measure will have a larger and larger effect on the residence time of an oxbow lake formed. In the case of Wedgeworth

Lake, this effect is obvious and should see the lake filled in far faster than surrounding lakes that are free of this mechanism for sediment delivery.

The Effect of Local Sources of Sediment

Our last factor deserving special attention is the effect of surrounding land use. In this case, the contrast between Aldrich Lake and neighboring Owens Bluff Lake exemplifies how important the surroundings of a lake are to its longevity. The estimates of sedimentation over time in Table 4-8 show that Aldrich Lake has another 250 years on the floodplain of the Leaf River, while Owens Bluff Lake has one-fifth that time. We suspect that this disparity is far greater than our estimates suggest. This is striking because these two cutoffs began with roughly the same surface area and formed within 500 m and 15 years of one another.

What is particularly noteworthy is that Aldrich Lake is by far the oldest of the four lakes in this study yet has the lowest rates of sedimentation and the longest potential time remaining on the landscape. Aldrich Lake is nearly unchanged in its surface area since the 1958 FSA aerials. Its volume is decreasing very slowly because its only source of sediment at the moment is via overbank flooding. Given the Leaf River's incision, Aldrich Lake's bed sits nearly 2 m above the current riverbed, suggesting that under current conditions, it could last far longer than its estimated 250 years.

Owens Bluff Lake rests at a slightly lower elevation than Aldrich Lake but is still nearly 1.5 m above the current Leaf River. Despite the decreasing input of sediments from the Leaf River over the past 2 decades, Owens Bluff Lake is now separated into four segments, with active alluvial fans intruding on the lake in a number of other areas. The message here is clear: anthropogenic effects can trump all other factors and fill a lake in well before its time under natural conditions. Gravel mining near Owens Bluff

Lake has taken a cutoff and reduced its area by two-thirds since 1958 and by over one-half since 1983.

The dredging on Sims Lake can reinforce the importance of human effects. It is unfortunate that this lake has such a disturbed character. The work by the landowner to improve his lake has rendered it nearly useless in our study. This is echoed by the fate of a fifth oxbow lake that is not mentioned in any other place in this study. We selected this reach for detailed study because it contained a cluster of five cutoffs, the fifth cutoff formed during the 1960s and destroyed by gravel mining by 1996. It is impossible to overstate the effects of human land use on floodplains and the oxbow lakes that occupy them.

Final Thoughts on Oxbow Lake Sedimentation

We return to the question of how lakes fill in with the answer that sedimentation rates vary greatly from one locale to the next. For every lake that follows our conceptual model (Fig. 4-15), there are many others that take a very different route. Models of slow, steady sedimentation do not adequately describe the conditions in floodplain lakes. Sediment is delivered in pulses, and the magnitude and frequency of these pulses are subject to surrounding disturbance and changes in the sources of sedimentation. Floodplain lakes are a study in variability, and even our estimates of how long our four lakes have remaining on the landscape do nothing to account for stream avulsions and other factors that may see the lake reoccupied by the river channel or destroyed by human activity. Adjacent lakes can have decidedly different processes of sedimentation acting on them. Because of this, they tend to fill in differently and as such have drastically different residence times on the landscape.

Conclusions

When we observe the phenomenon of oxbow lake creation and destruction at the basin scale, we find that differing stage differences in the river for the times that imagery was available create less than ideal circumstances for comparison. Even differences in geology between the two rivers confound the results of this study.

However, when we observe the creation of cutoffs and lakes in the Pascagoula Basin, we find that there are trends revealed. Processes differ with location in the basin. The creation and destruction of lakes seems to occur at a faster rate in the upper smaller streams than in the lower, larger streams. Given the evidence on the landscape, we can hypothesize that lake creation in the upper basin does not exceed the lake destruction, meaning that over time, the number of oxbow lakes on the landscape remains low as the landforms are filled in and destroyed before they have time to build up in number. Essentially, they arrive and are destroyed in short order.

In the lower basin, however, the reverse is true. Lake creation seems to occur at a slow rate; however, lake destruction occurs at an even slower rate. Therefore the net balance of lakes on the landscape ends up being positive, with more lakes created before the existing lakes can be destroyed, leaving the floodplains in the lower portion of the basin scarred with the remains of partially filled-in oxbow lakes.

When we look at the percentage area loss with shape compactness, drainage area, and by basin geology, again, there are some key trends observed. Lakes lost 12% of their surface area on average in both the Leaf and Chickasawhay rivers. We find that the amount of lake surface area loss seems to occur at a faster rate in the upper, smaller streams than in the lower, larger streams. Certainly our ability to detect how much these processes differ is reduced by shortcomings in the data with respect to

discharge differences in imagery. But the discharge differences are not critical and perhaps only skew the results slightly. The correlation between drainage area and lake surface area loss is highly significant in both rivers, again reinforcing that processes differ with location in the basin.

The geomorphic character of the floodplain appears to be an ideal predictor of the incidence of alluvial cutoffs and oxbow lakes. These are clustered into areas with wide floodplains. This occurs regardless of the difference in sediment loads; however, we do find that from a theoretical standpoint, the Chickasawhay has a decidedly lower potential to fill in or remove its oxbow lakes by the virtue of its lower bed load relative to the Leaf River. The higher bed load component of the total sediment load in the Leaf increases its potential to fill in cutoffs; however, we can argue that this incision on the lower Leaf, as evidenced by Chapter 2 of this dissertation, leaves the river less likely to attain stages where overbank deposition can occur, thereby decreasing its ability to fill in or remove lakes.

When we address the question of floodplain lake sedimentation at the level of the individual lake, we again find that there are limitations in our data. The bathymetries of the four lakes measured in the study were calculated from a limited number of field data points. However the estimates of sedimentation are precise enough to recognize the large variability between lakes. We find that the variability defies description via a simple conceptual model, with the presence of tributary streams, the length of tie channels, and differences in bed elevation as well as the impact of local conditions creating many exceptions to the rule. But even so, we find that our understanding of the processes involved in filling these lakes is vastly improved.

Finally, there is the limited use of the lake sediment cores collected in this study. The situation in the sediments of these lakes is such that the translocation of material via biological processes is extremely high. This negates the application of many of the traditional techniques for dating layers in sediment cores. This study would benefit greatly from the use of optically stimulated luminescence (OSL) dating techniques. OSL has been shown as a method for estimating the date of burial on single grains of sediment as young as 25 ± 10 years (Rowland et al., 2005). Even without the use of OSL or other methods to fix specific dates within the lake sediment cores, we find that the lacustrine sediments in the oxbow lakes differ appreciably from the alluvial sediments that underlie them. We can make meaningful statements about how the cores tend to fine upward yet display enough variability for us to attribute changes in the percentage sand to hydrologic conditions.

Despite the shortcomings in this work, in all cases, its value is that it addresses a previously understudied landform in a dynamic environment. This work is one of the first forays into the lakes on the floodplain, and although the application of paleolimnological techniques in this area is problematic, it is nonetheless worthwhile. The floodplains of rivers are great ecological indicators, and in all environments, lakes provide great insight into how conditions change over time. The coupling of paleolimnology and fluvial geomorphology can be of great benefit to society's study of our changing environment.

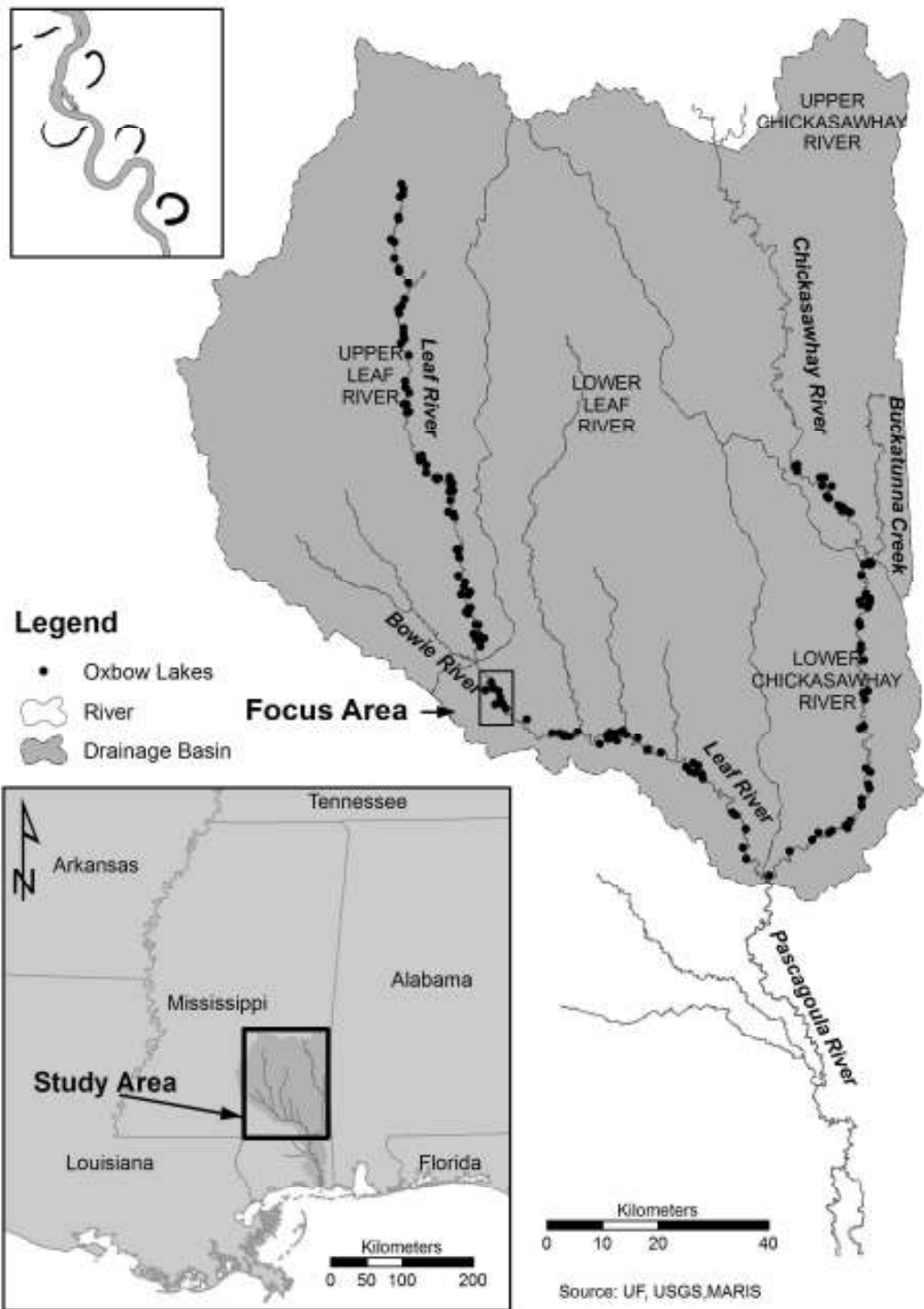


Figure 4-1. Map of the study area, including four subdivisions and focus area

Table 4-1. Summary of oxbow lake information for four divisions of the study area

Watershed division	Drainage area (km ²)	Total number of oxbow lakes	Number of lakes in 1955	Number of lakes in 2005	Lakes created	Lakes destroyed
<i>Leaf River</i>						
Upper Leaf	2800	26	18	18	8	8
Lower Leaf	9270	36	25	35	11	1
Leaf total		62	43	53	19	9
<i>Chickasawhay River</i>						
Upper Chickasawhay	2400	24	12	22	12	2
Lower Chickasawhay	7960	70	54	59	16	11
Chickasawhay total		94	66	81	28	13
Watershed total		156	109	134	47	22

Table 4-2. Average monthly stream discharge for dates when imagery was collected

Date	Leaf River discharge ($\text{m}^3 \text{s}^{-1}$) and stage (m) at Hattiesburg, MS	Chickasawhay River discharge ($\text{m}^3 \text{s}^{-1}$) and stage (m) at Leakesville, MS
March 29, 1955	Not applicable	50.5/3.3
May 2, 1955	24.0/0.6	Not applicable
February 21, 1958	69.9/1.3	183.5/5.0
December 21, 1959	50.9/1.1	Not applicable
October 23, 1960	15.2/0.5	Not applicable
Monthly average, July 2005	35.6/0.8	123.7/4.4

Table 4-3. Summary of oxbow lake surface area change over time

Watershed division	Total oxbow lakes present in both 1955 and 2005	Lakes losing (>10%) surface area	Lakes gaining (>10%) surface area	Total lake area in 1955 (m)	Total lake area in 2005 (m)	Percentage area change
<i>Leaf River</i>						
Upper Leaf	10	8	1	141,687	106,560	0.25
Lower Leaf	24	13	4	558,261	512,133	0.08
Leaf total	34	21	5	699,948	618,693	0.12
<i>Chickasawhay River</i>						
Upper Chickasawhay	10	7	1	133,999	112,750	0.16
Lower Chickasawhay	43	27	8	681,620	607,816	0.11
Chickasawhay total	53	34	9	815,619	720,566	0.12
Watershed total	87	55	14	1,515,567	1,339,259	0.12

Table 4-4. Spearman rank correlations of percentage lake surface area loss and river drainage area, initial lake surface area, and lake compactness via the isoperimetric quotient

	Spearman's rho with percent surface area loss, 1955–2005	
	Leaf River oxbow lakes (<i>p</i> -value)	Chickasawhay River oxbow lakes (<i>p</i> -value)
River drainage area	-0.55 (≤ 0.01)	-0.38 (0.01)
Initial lake surface area	-0.00 (0.50)	-0.23 (0.09)
Isoperimetric quotient	0.04 (0.43)	0.43 (0.01)
Sample size (<i>n</i>)	25	39

Aldrich Lake Sediment Core

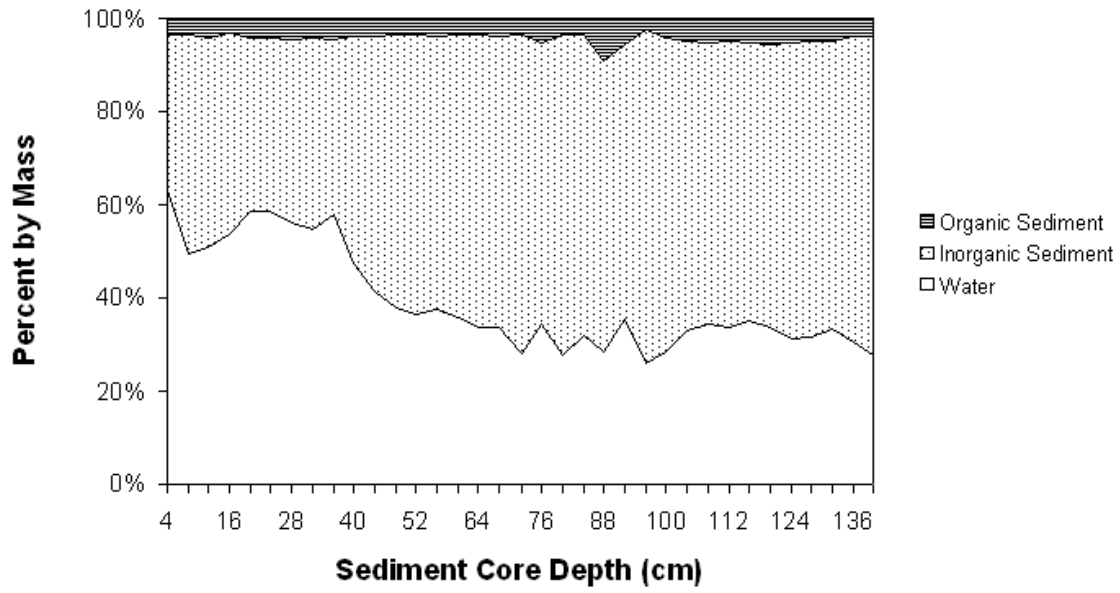


Figure 4-2. Organic, inorganic, and water percentage by mass for the Aldrich Lake sediment core

Aldrich Lake Sediment Core

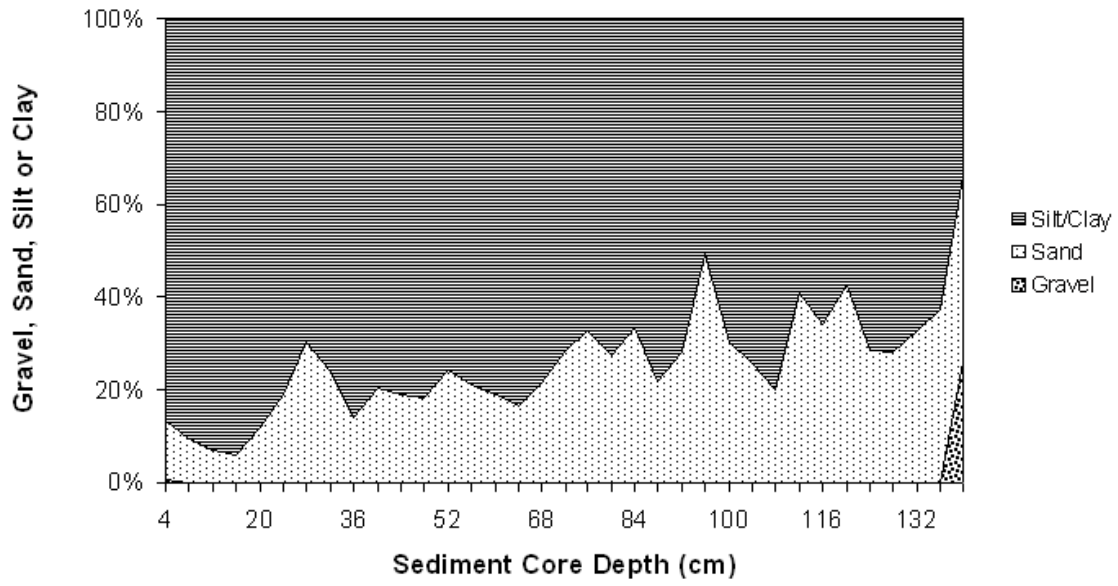


Figure 4-3. Particle size distribution for inorganic component of the Aldrich Lake sediment core

Owens Bluff Lake Sediment Core

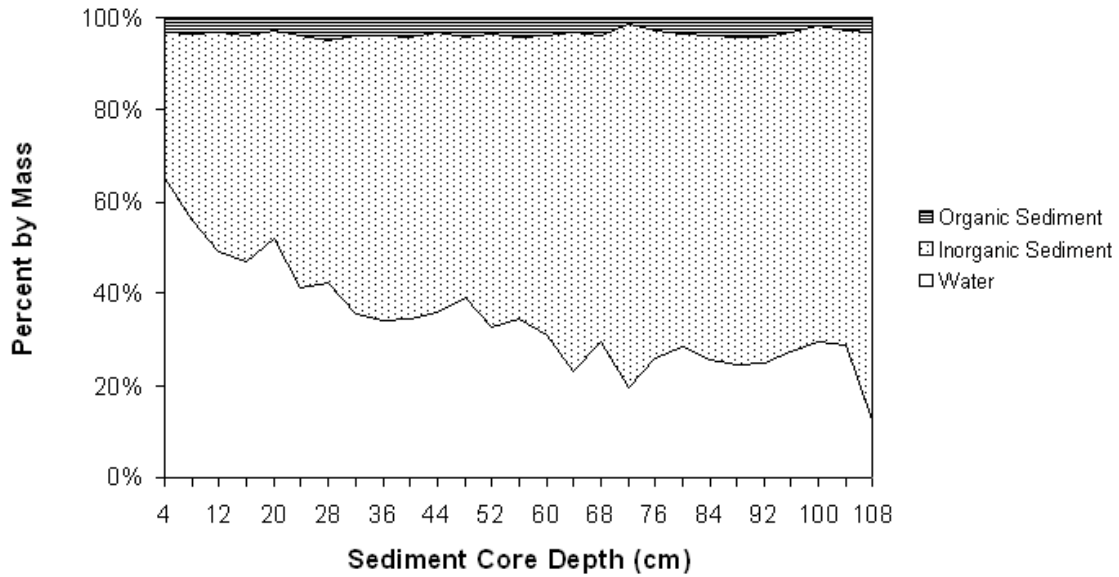


Figure 4-4. Organic, inorganic, and water percentage by mass for the Owens Bluff Lake sediment core

Owens Bluff Lake Sediment Core

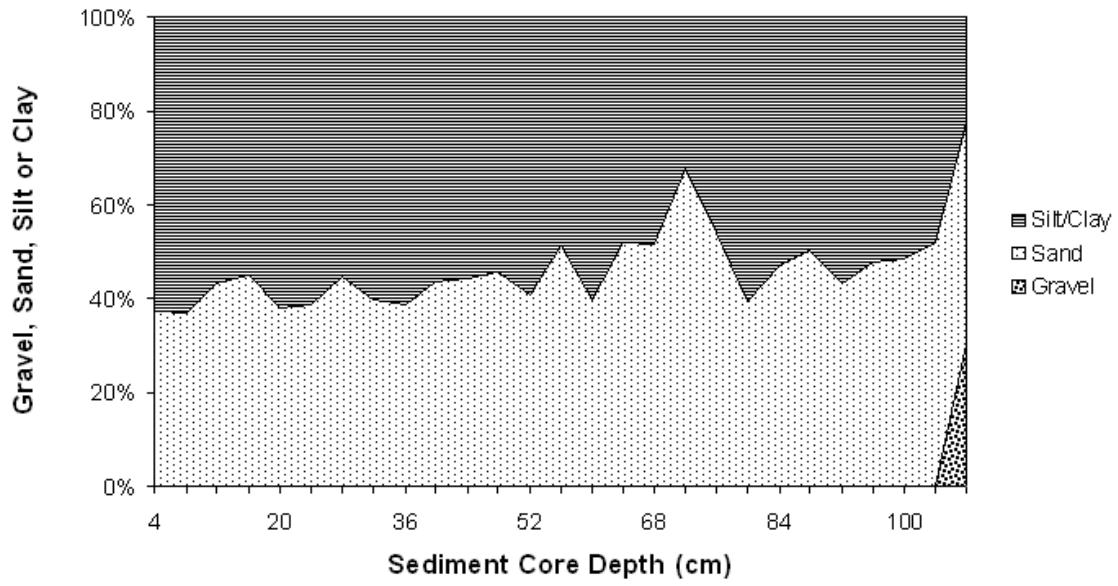


Figure 4-5. Particle size distribution for inorganic component of the Owens Bluff Lake sediment core

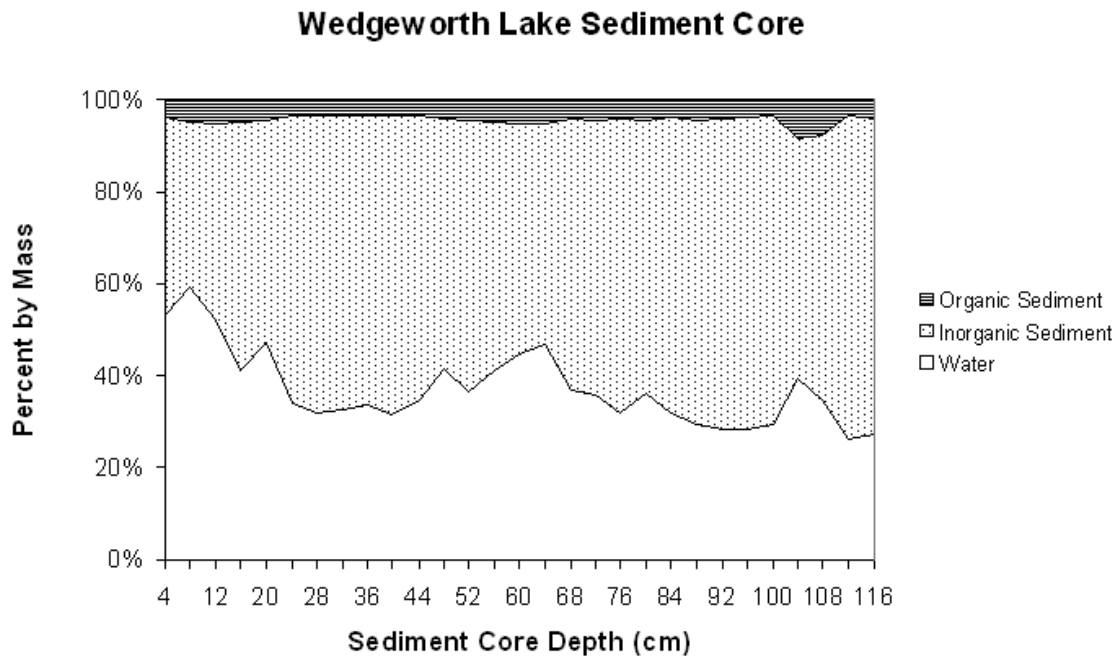


Figure 4-6. Organic, inorganic, and water percentage by mass for the Wedgeworth Lake sediment core

Wedgeworth Lake Sediment Core

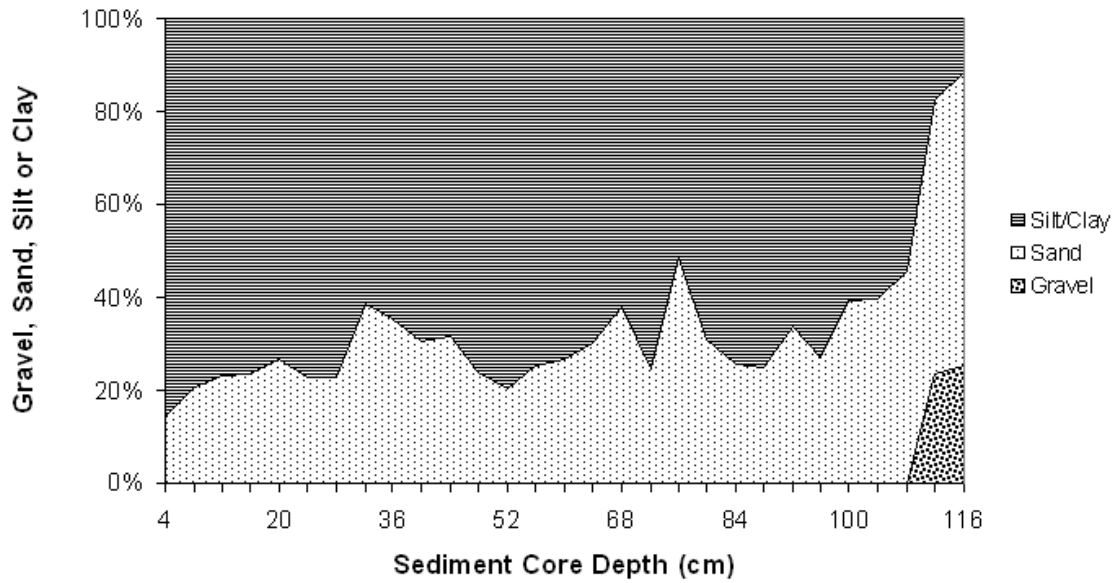


Figure 4-7. Particle size distribution for inorganic component of the Wedgeworth Lake sediment core

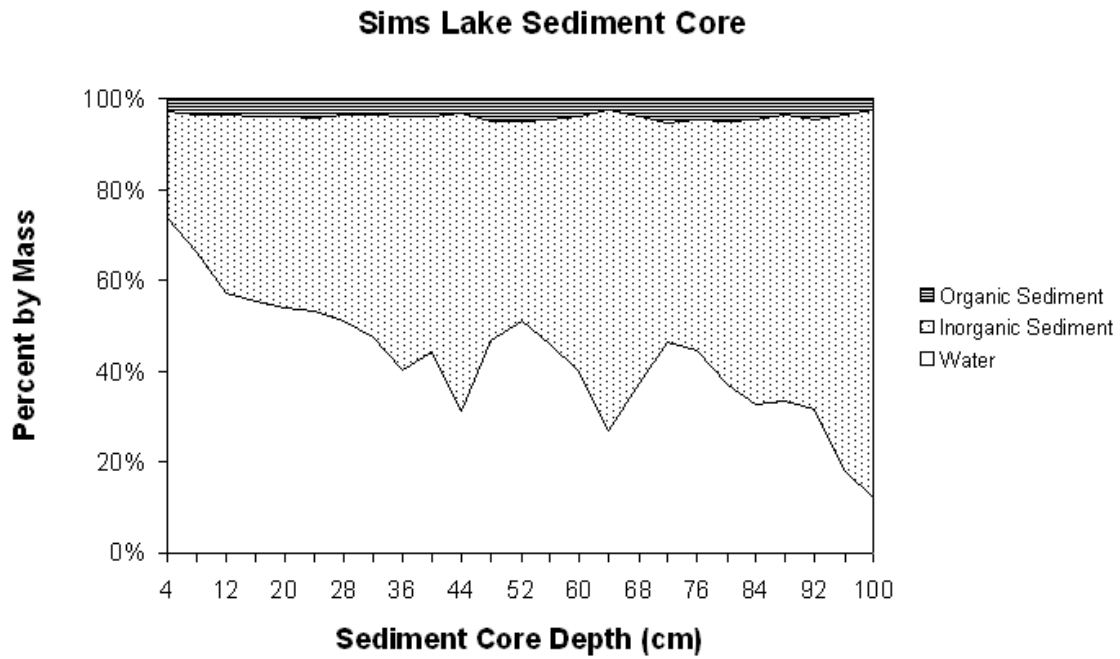


Figure 4-8. Organic, inorganic, and water percentage by mass for the Sims Lake sediment core

Sims Lake Sediment Core

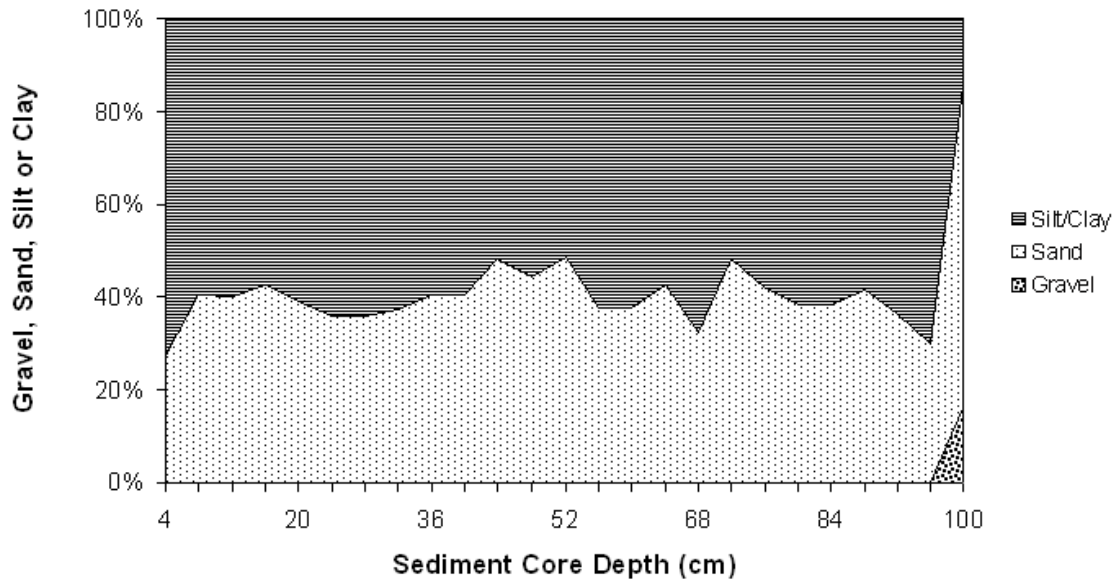


Figure 4-9. Particle size distribution for inorganic component of the Sims Lake sediment core

Table 4-5. Summary of sediment core components for Aldrich, Owens Bluff, Wedgeworth, and Sims lakes

Lake	% Water	% Inorganic	% Organic	
		<i>Average</i>		
Aldrich		39.2	56.5	4.3
Owens Bluff		34.4	62.1	3.5
Wedgeworth		37.2	58.4	4.5
Sims		43.1	53.0	3.9
		<i>Standard deviation</i>		
Aldrich		11.0	10.8	1.1
Owens Bluff		11.7	11.8	0.8
Wedgeworth		8.3	8.8	1.2
Sims		13.9	14.0	0.7

Table 4-6. Summary of sediment sizes for Aldrich, Owens Bluff, Wedgeworth, and Sims lakes

Lake	% Gravel	% Sand	% Silt/clay	<i>n</i>
<i>Average</i>				
Aldrich	0.8	25.0	74.3	35
Owens Bluff	1.1	45.6	53.3	27
Wedgeworth	0.8	30.5	68.7	28
Sims	0.6	40.6	58.7	25
<i>Standard deviation</i>				
Aldrich	4.4	10.3	12.2	
Owens Bluff	5.8	6.8	9.2	
Wedgeworth	4.4	9.8	12.8	
Sims	3.2	7.9	10.6	

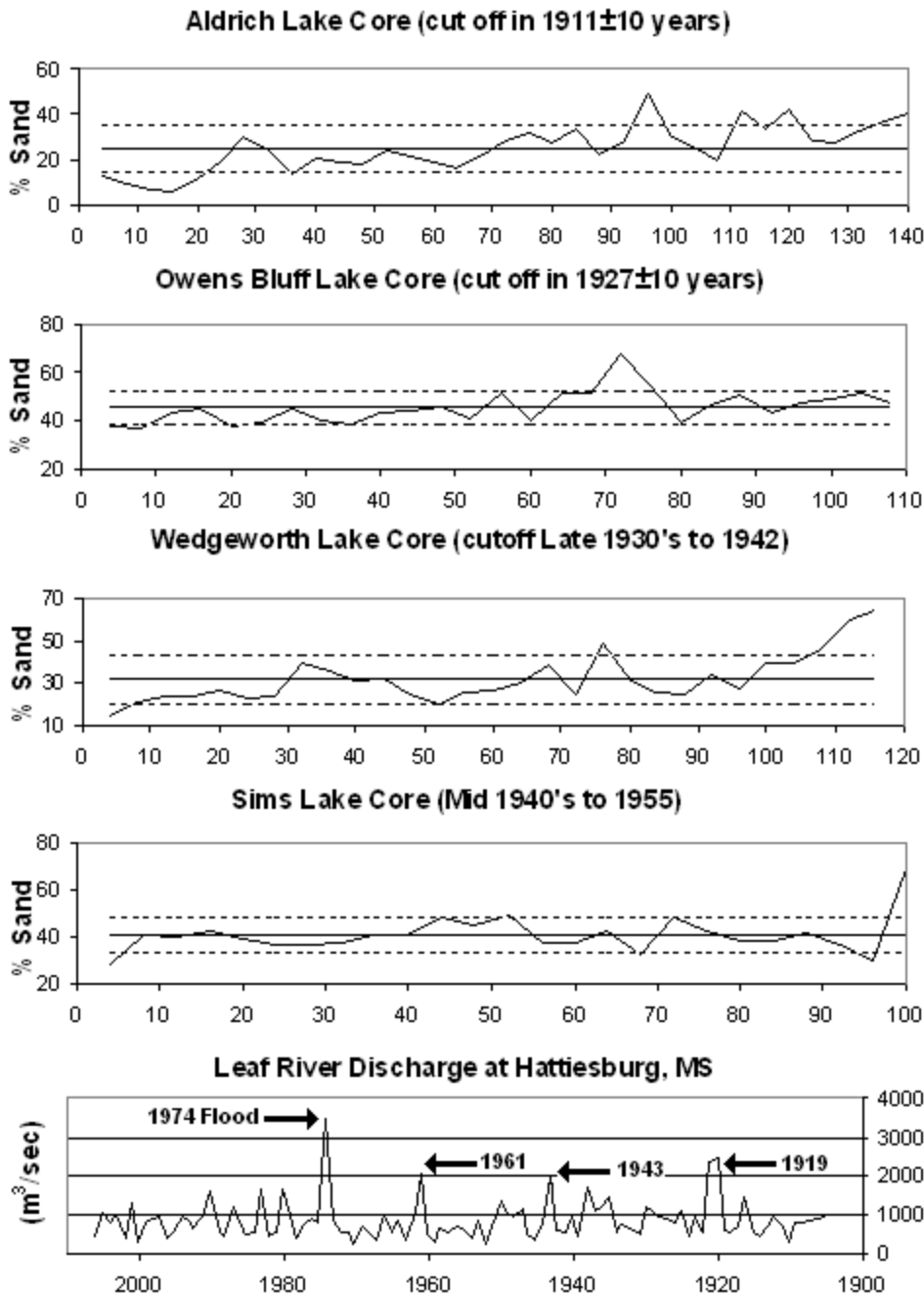


Figure 4-10. Percentage sand for each lake sediment core. The sampling interval is 4 cm, the solid horizontal line represents the mean percentage sand for the entire core, and the dashed horizontal lines represent ± 1 standard deviation. (bottom) Peak discharge and some noteworthy floods measured by the stream gauge at Hattiesburg, Mississippi.

Table 4-7. Summary of lake information and bathymetry-based estimates of lake, sediment, and cutoff volumes

Lake	Lake area (m ²)	Lake mean depth (m)	Current lake volume (m ³)	Lake sediment volume (m ³)	No. of bathymetry points
Aldrich	27312	1.07	29152	11042	81
Owens Bluff	20360	0.80	16380	8313	45
Wedgeworth	20882	0.55	11499	17524	77
Sims	66469	0.51	34140	45509	65
Lake	Cutoff area (m ²)	Cutoff mean depth (m)	Total cutoff volume (m ³)	Cutoff sediment volume (m ³)	Percentage volume filled with sediment
Aldrich	27271	1.47	40133	10982	27
Owens Bluff	33705	1.21	40878	24498	60
Wedgeworth	43581	1.39	60570	34273	57
Sims	46248	1.20	55418	45509 ^a	82 ^a

^aSims Lake has only 38% of its current volume filled with sediment.

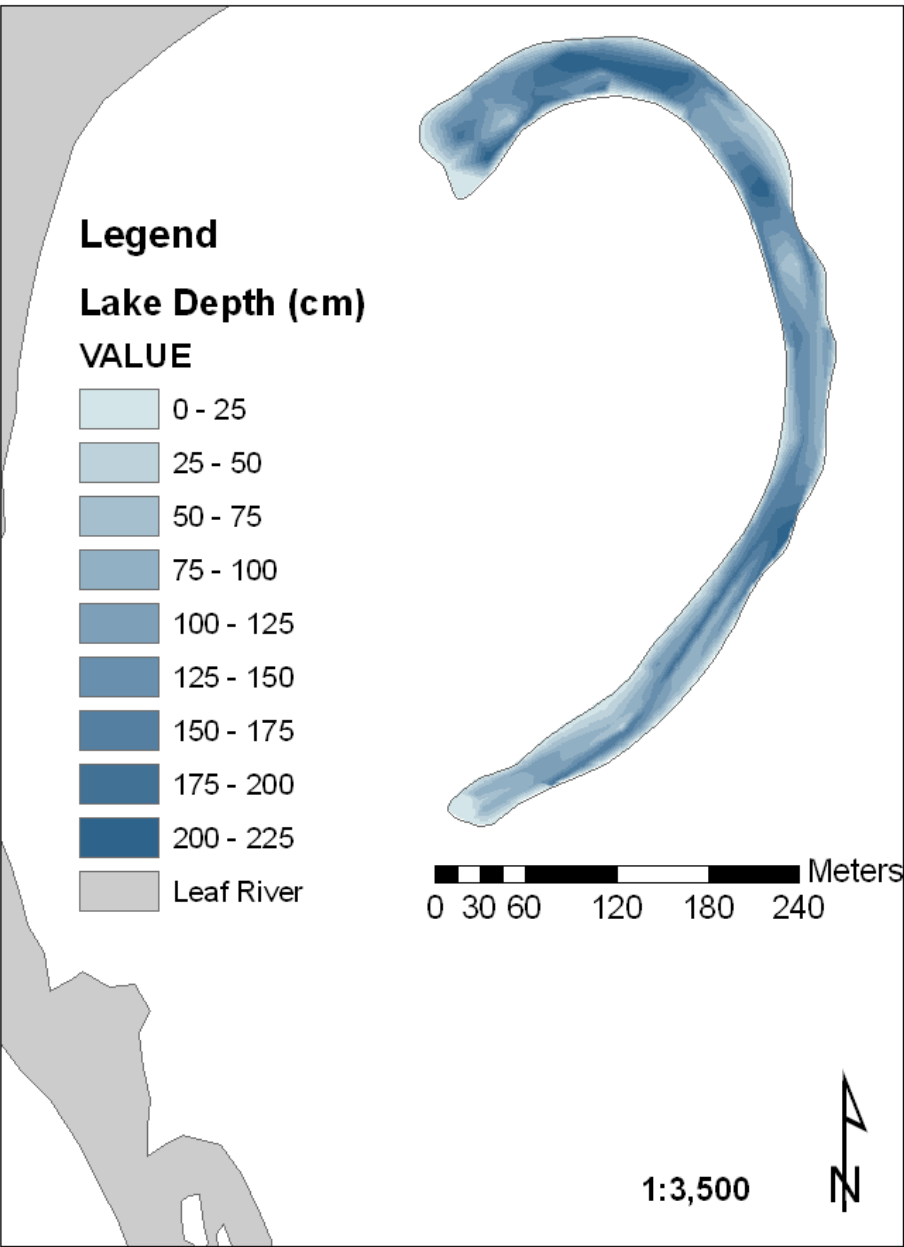


Figure 4-11. Bathymetry map for Aldrich Lake

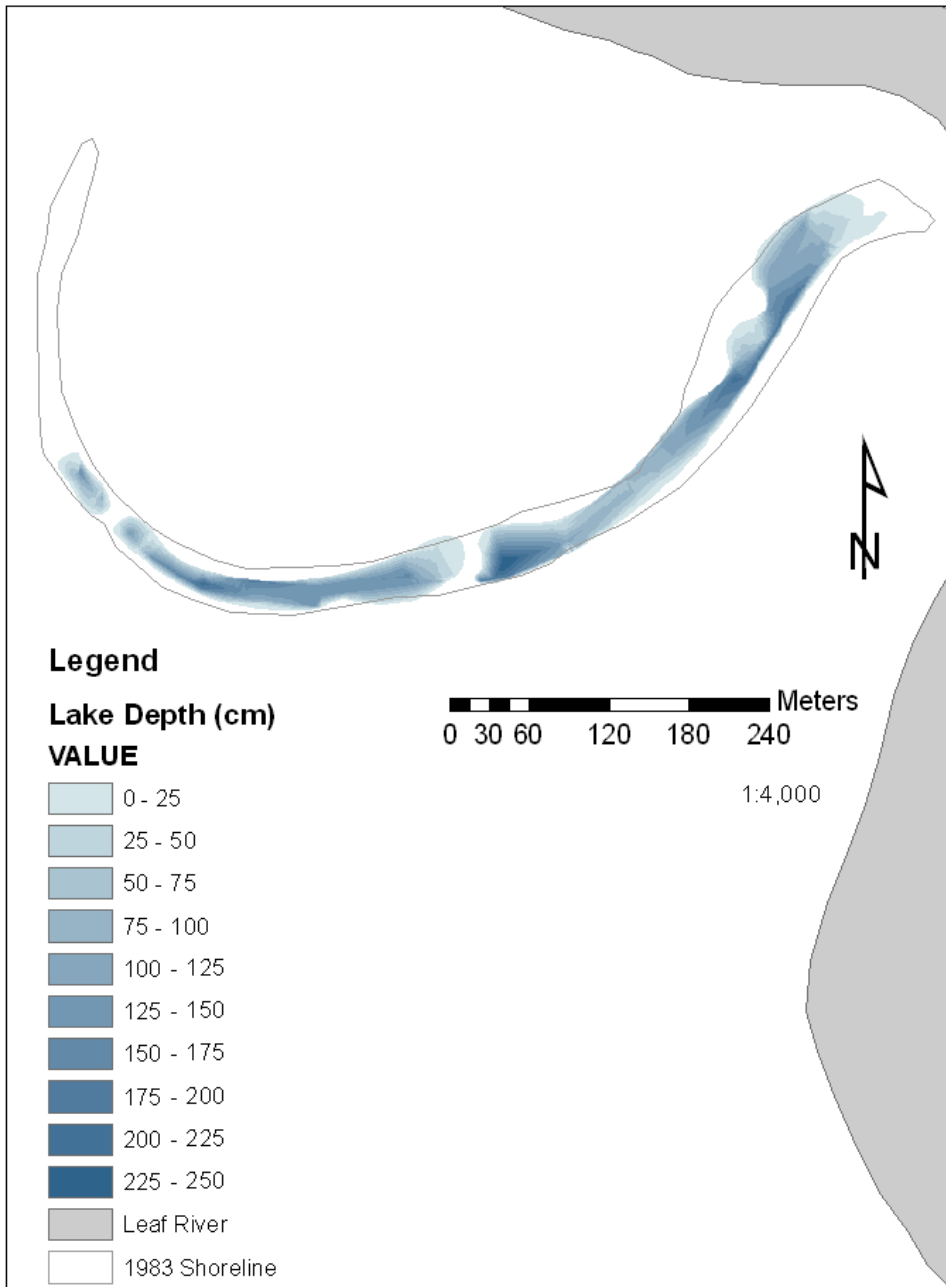


Figure 4-12. Bathymetry map for Owens Bluff Lake

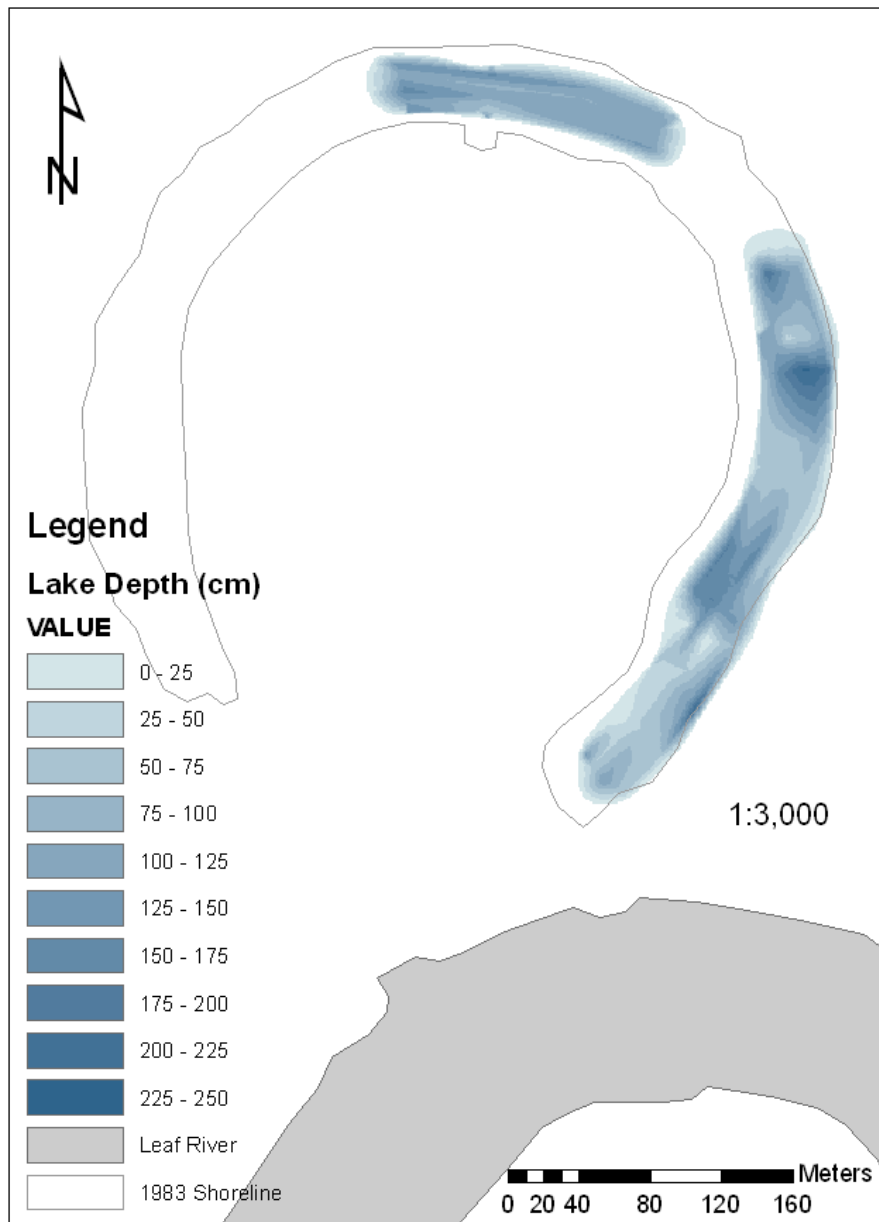


Figure 4-13. Bathymetry map for Wedgeworth Lake

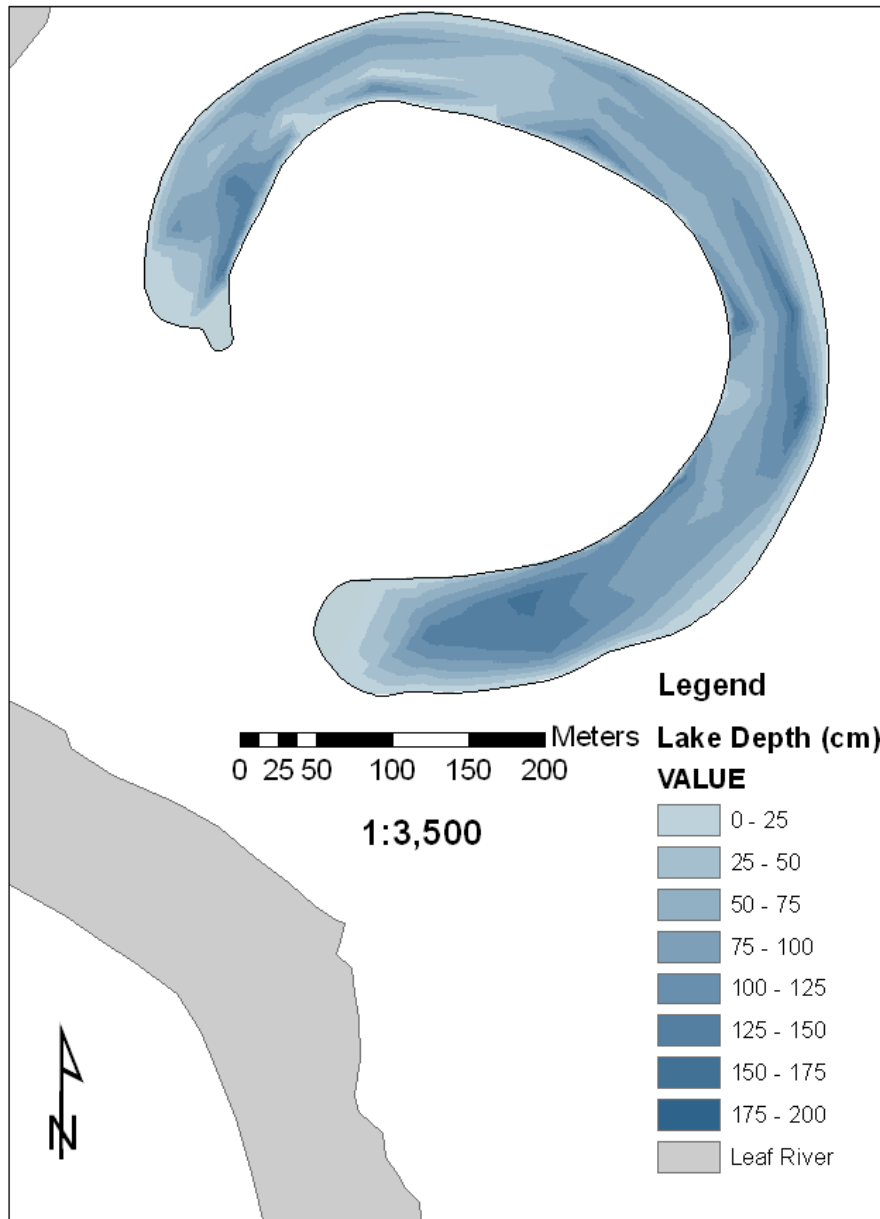


Figure 4-14. Bathymetry map for Sims Lake

Table 4-8. Estimate of time required to fill in each lake given average sedimentation since cutoff and current lake volume

Lake	Estimated age (years)	Cutoff sediment volume (m ³)	Rate of sedimentation (m ³ yr ⁻¹)	Total cutoff volume (m ³)	Years for lake to fill completely
Aldrich	95	10982	116	40133	252
Owens Bluff	79	24498	310	40878	53
Wedgeworth	67	34273	512	60570	51
Sims	58	21059	363	55418	95

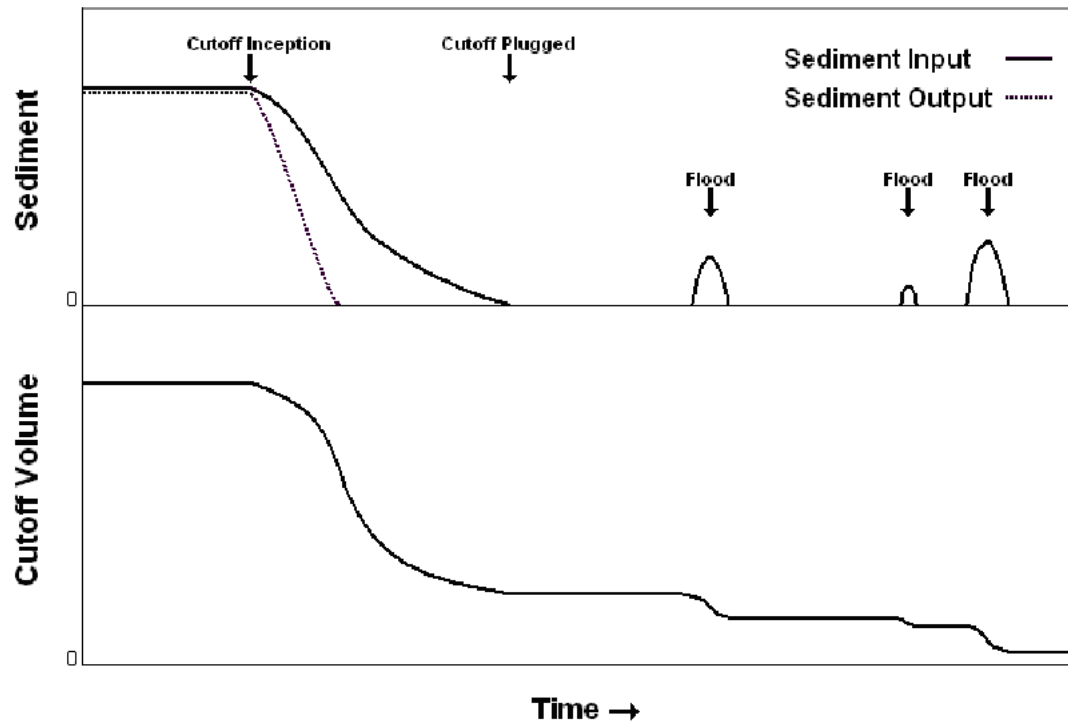


Figure 4-15. Conceptual model of alluvial cutoff sedimentation

CHAPTER 5 CONCLUSION

Recommendations for Future Work

In the proposal that began this work, I promised to examine the potential of oxbow lakes as indicators of past channel form, to investigate the role of channel sinuosity in the creation of oxbow lakes and oxbow lake clusters, and to look at what information the sediments of these lakes could provide about flood history, and basin erosion with land cover change. In some respects this work morphed into something different than what was initially envisioned. However, what was accomplished adds a great deal to the existing knowledge that we have on oxbow lakes. More importantly, these efforts suggest a number of opportunities to both improve upon the designs employed in this study and to engage in previously unimagined research.

Oxbow Lakes as Indicators of River Channel Change

My efforts on the usage of oxbow lakes as indicators of river channel change demonstrate that the approaches presented in this study will work. This research was able to show that oxbow lakes and alluvial cutoffs can provide both cross-sectional geometry data and bed elevation data for past stream conditions particularly where channel degradation is occurring. In this respect this work echoes and adds to the work of Erskine et al. (1992). However, this success was not definitive, and additional work should be attempted in streams of differing size and in other environments to determine at what scales this technique is viable and over what environmental conditions it remains reliable.

This portion of the study also exhibited how profound the change in conditions on the Leaf River has been over the past half century. It would be a missed opportunity to

not revisit the study area because the Leaf River below Hattiesburg provides a great opportunity to study the effect that sediment deprivation can have on the geomorphology of a river both over space and time. In systems theory parlance, we have the opportunity to examine a system exposed to disturbance with no end to the relaxation in sight.

The transport of bedload out of the Bowie River and into the Leaf River has been crucial to the formation of the geomorphology of the lower Leaf River and its floodplain. The Bowie River bed material is 70% gravel by volume whereas the Leaf Rivers bedmaterial is only 22% gravel. With the avulsion of the Bowie River into floodplain gravel pits, the Leaf River has been cut off from its primary source of coarse bed material and sediment load. These conditions are unlikely to change until sediment flow out of the Bowie resumes. Until then, the Leaf will remain deprived of sediment and should continue its recent pattern of degradation in the study area and by extending these effects further downstream. Discovering over what time frame and how far these effects eventually reach downstream is a worthy question.

The phenomenon examined in this study is also worthy of additional attention because it is unique. The avulsion of the Bowie River into the gravel pits effectively stops sediment transport without governing the stream flow downstream. The geomorphic effects of sediment deprivation in stream reaches downstream of reservoirs are well documented; but these situations are fundamentally different from the situation on the Leaf River because the river's flow remains unregulated. Much of the work on the effects of sediment deprivation on stream geomorphology has been limited by the

inability of investigators to differentiate the dam's effects through sediment deprivation from the effects of an altered flow regime.

Sinuosity and the Clustering of Alluvial Cutoffs

The work on channel sinuosity and its influence upon planform geometry and the creation of alluvial cutoffs proved to be largely successful. This study found empirical evidence for self-organization and expanded the study of cutoff clusters from one reach in the River Bollin to an entire basin of over 18000 km². We also introduced the use of the sum of cumulative deviations from zero change function to assess the criticality portion of SOC. With this function we found the value of channel sinuosity where the river system encounters the critical threshold between meander elongation and alluvial cutoff. The introduction of this function necessitates further study in other basins to determine how it will differ from basin to basin.

We have already engaged in some additional work on this topic by calculating the function for each of the tributary streams of the Pascagoula. It is already apparent that the function varies within the Pascagoula Basin and even within different portions of the same stream. Schumm (1963) found that channel sinuosity in streams upon the Great Plains was a function of the cohesiveness of the banks; going so far as to fit a power function of sinuosity to the percent of silt and clay in the channel margin. It seems likely that channel sinuosity in the Pascagoula is also influenced by the bank material.

Additional work is needed to determine the spatial differences in this function with changing soil character and vegetation along the channel margin. It is also likely that there are temporal variations in the function that are driven by changing hydrologic conditions. Historical work on basin sinuosity before and after major flood events should

reveal how strongly floods of differing sizes can influence the inflection points within this function.

The Infilling of Oxbow Lakes

Of all the sections in this dissertation, the work on sediment deposition in oxbow lakes changed the most from inception to completion. Difficulties in the field necessitated shortcuts in both the scope and precision of the work. Even so, the value of this study was that it attempted to apply a paleolimnological perspective to investigating heretofore-unstudied small lakes on floodplains. Some of the failings of this portion of the study can be attributed to the sedimentologically dynamic environment found on river floodplains. However, the majority of the inadequacies in this study stem from the fact that the techniques employed by me did not measure up to the established standards of paleolimnological inquiry.

The coarse sampling techniques used in the field did provide enough information to give some insight into the processes governing oxbow lake sedimentation but they could have been conducted with much greater precision in the field and with higher technological analytical techniques in the lab. The application of quality paleolimnological investigations into the floodplain environment could greatly improve our understanding of how these systems operate; so further work of a higher quality is needed.

Future work on the sedimentation of oxbow lakes should be performed with a refined sampling regime using 1cm increments on the extruded sediment cores. This will greatly improve our resolution on the physical characteristics of the sediment. This may then afford us a more detailed record of the history of deposition in these lakes and

hopefully shed some light on the suitability oxbow lake sediments for use as a source of information on historic and prehistoric basin sedimentation and hydrology.

This topic would also benefit from utilizing additional methods to analyze sediments. Bio-turbation and sediment translocation will remain a persistent problem in oxbow lake sediment cores, but some sites may be suitable for analysis using radioisotopes of lead or cesium. OSL analysis on sand grains has also been shown by Rowland et al. (2005) to be a viable method for dating sediments on the floodplain and should be tested for use in oxbow lake sediment cores.

Finally, any follow up work should focus on collecting additional bathymetry data. Sixty or so observations of lake depth and lake sediment thickness proved sufficient to estimate the volume of a cutoff and the sediment that accumulates in the resulting lake. But increasing the number of observations by an order of magnitude will provide a much more reliable approximation of the bathymetry and sedimentation pattern within the lake. Furthermore, these data could be coupled with increased precision in analyzing the lake sediment cores; providing a much improved portrait of not only the lake but also the processes that govern its sedimentation over time.

Concluding Thoughts

With the closing of this study of alluvial cutoffs and their resulting oxbow lakes I will set aside the specifics of the research that has been completed and reflect on a deeper view of the river. In this deeper view, it all still seems to come down to the Schumm and Lichty (1965) description of space and time in geomorphology. Both the incidence of cutoffs and the persistence of oxbow lakes are likely the result of the spatial scaling of processes and how these influence the persistence of landforms over time.

In Chapter 3 of this work, we observe the incidence of alluvial cutoffs over the 50-year span of aerial imagery and find that planform change via cutoff is predominately occurring in the upper portion of the basin, irrespective of changes in geology and land cover. In Chapter 4, when we observe the landscape for oxbow lakes and evidence of alluvial cutoffs, we find that the lower basin contains a far greater number. Together these may perhaps prompt the casual observer to believe that the accelerated rate of alluvial cutoffs in the upper basin in recent years is a product of external factors, either climatic or anthropogenic. I think this is unlikely. After noting the processes involved in the sedimentation and removal of oxbow lakes from the landscape, it seems more apt to believe that the incidence of alluvial cutoffs and oxbow lake formation do follow the power law distribution suggested by Stolum (1996). Our casual observer is misled because our snap shot view of the watershed in time misses the overall pattern of high frequency small cutoffs in the upper basin and lower frequency larger cutoffs in the lower basin because of the persistence of the larger landforms in the lower basin.

This persistence or resistance to infilling or landform destruction is most likely a result of the byplay of varying processes with scale. Large oxbow lakes have great volume and after they are closed to the active channel of the river, they require a long period of time to accumulate enough fine sediment via overbank flooding to fill. Smaller oxbow lakes on the other hand are low volume and can be more fully filled by the bedload sediments that are so prevalent in the years immediately following cutoff. This factor creates a shallow bathymetry early in the lakes existence, encouraging vegetation and infilling. These taken with lower lake volume at the start ensures that smaller oxbow lakes are removed fairly quickly from the landscape, rapidly infilling, colonized with

vegetation, or being reworked by the river; all of which speed the destruction of the landform and remove evidence of a past cutoff.

Much of what is written in this section could be labeled as conjecture and it certainly lacks scientific rigor. But this final reflection reminds me of what I feel are the main problems in the study of fluvial geomorphology; a lack of perspective and the inherent complexity of the river system. Perspective in the study of landforms requires a long period of study. It is my hope that in the case of oxbow lakes, the techniques pioneered by paleolimnology will take root wherever possible and allow fluvial geomorphologists to use these lakes to look deeper into the past. By the same token, I hope that the complexity of the river system can be better understood through the application of the spatial analytical principles founded in geography. Hopefully this dissertation is a contribution to the ongoing effort to develop perspective and to better understand complexity.

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BIOGRAPHICAL SKETCH

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