Channel Morphology at a Meander Bend Chute Cutoff Partially Obstructed by Woody Debris

Drew Sobczak

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Channel morphology at a meander bend chute cutoff

partially obstructed by woody debris

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BY

Drew Sobczak

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Abstract

Field and flume experiments have examined the conceptual model for a meander bend in depth. Large woody debris piles are often associated with the development of a chute cutoff due to local aggradation and deflection of flow. This paper examines the bed morphology of a meander bend chute cutoff that is partially obstructed by woody debris. The bed morphology of the channel around the woody debris pile as well as the head of the cutoff are mapped. The pile is shielding the point bar immediately behind it and causing a narrow, deep channel on either side of the pile. The head of the cutoff is eroding leading to a widening of the cutoff. The results indicate that the large woody debris pile is deflecting flow into the cutoff.
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Channel morphology at a meander bend chute cutoff partially obstructed by woody debris

I. Introduction

Meandering streams have frequent planform changes due to their low energy, often resulting in neck and chute cutoffs. The conceptual model of a meander bend is well documented (Dietrich et al., 1979; Frothingham and Rhoads, 2003), as is the formation of cutoffs (Parker, 1996; Gay et al., 1998). In the conceptual model of a meander bend, the cut bank pushes flow downward and towards the point bar, creating a pool near the cut bank. The flow exhibits a helical motion while heading downstream, which erodes the cut bank and deposits sediment at the point bar. Cutoffs of meander bends have been studied in depth by means of investigation in the field (Frothingham & Rhoads, 2003) as well as laboratory flume experiments (Dijk et al., 2012). Many studies have described the factors that lead to the formation of a cutoff in a meander bend, such as vegetation (Rowntree and Dollar, 1999) and woody debris (Keller and Swanson, 1979). However, recent photographic evidence suggests that woody debris may also be a factor that limits the development of a cutoff channel. The role that woody debris plays in the development of cutoffs needs to be more fully understood.

Meandering streams are very common in the Midwest, USA due to the lack of large and sudden elevation changes. Consequently, meandering streams are often low gradient and low energy, so woody debris in the stream can be captured and accumulated in these streams fairly easily. Undercut trees falling into the channel cannot be kept entrained by the low energy of the stream, so they often become caught and lead to the formation of a
woody debris pile. Thus it is reasonable to assume that woody debris piles occur frequently in this region. The relationship between cutoffs and debris piles needs to be investigated more fully, especially in regards to the role debris piles play in the evolution of cutoff channels. This paper examines how the buildup of woody debris affects the development of a cutoff of a meander bend on the Embarrass River in east central Illinois. The bend likely has intricate flow dynamics that have not previously been documented. This study provides information enabling a more detailed conceptual model for the geomorphic evolution of a channel obstructed by woody debris.

II. Literature Review

Meandering rivers are described as alluvial channels. Alluvial channels are made of sediment that is light enough to be transported by the stream to a location further downstream (Schumm, 1985). Due to the fact that the stream forms by erosion, sediment transport, and deposition, meandering streams tend to be very dynamic, and channel paths change frequently. Low energy meandering streams are frequently changing planform because they are highly susceptible to local environment change such as large woody debris entering the channel (Frothingham et al., 2002). A high energy stream might be able to easily remove the debris from the system with its large flow rates, whereas a low energy stream will have much more difficulty, resulting in a greater chance of the debris affecting the planform. It is true that channel factors such as width, depth, meander amplitude, and meander width are affected by the quantity of water discharged, but the overall pattern of the channel will not be affected by quantity of discharge (Schumm, 1985). When analyzing the planform of a meandering stream,
magnitude can be ignored, as the river planform for all meandering streams follows similar patterns, regardless of size (Parker, 1996).

The planform and morphology of a channel are heavily reliant on their sediment transport process (Church, 2006). Dissolved sediment can play a role in the planform and morphology of a channel, but the two main types of visible sediment transported through rivers are suspension and bed load. Suspended sediment (suspension) is a fine material supported by the turbulent upward flow of the stream and can be carried long distances in the stream before being deposited. Bed load is larger, coarser material that gets transported along the bed of the stream by means of sliding, rolling, or bouncing and typically only moves a short distance downstream. A further and more helpful classification of sediment for fluvial systems uses the terms bed material and wash material (Church, 2006). Bed material is the material that makes up the bed and lower banks of a stream and is the primary factor controlling the morphology of the channel. Bed material can constitute both bed load and heavier suspended particles. Wash material is material that gets carried long distances downstream by means of suspension and is only a small fraction of the sediment in the stream. Wash material can potentially make up a large portion of the upper banks and floodplain of a stream due to deposition at times of overbank flooding.

A stream is, in part, characterized by its sinuosity, which is the channel path length distance - the distance the river travels along its course divided by the linear distance between two measured points on the river (Figure 1). Deviations from a sinuosity of 1
depict increasing amounts of curvature in the river path. Meandering streams tend to organize themselves around a steady state (Parker, 1996). The steady state of a stream is the stream’s threshold sinuosity. A sinuosity higher than the steady state often leads to the formation of a cutoff that in turn decreases the sinuosity. The formation of a cutoff can often trigger other cutoffs to form in the same region because of the accelerated change to the surrounding planform. Consequently, a lower sinuosity than the steady state often promotes elongated, overdeveloped bends. Regardless of initial conditions, the formation of cutoffs paired with the elongation of bends will keep the sinuosity of a meander stream around the steady state (Parker, 1996). It has been suggested by Stølum (1996) that the average steady state for all rivers added together to be around 3.14, the sinuosity of a circle, but there is insufficient data to support this claim. Thus, the exact sinuosity of a river’s critical state is still unknown at this time and likely depends on the characteristics of the stream such as flow, width, and bed and bank material.

Figure 1: Sinuosity of a stream is calculated by dividing the distance the river travels along its course (L) by the linear distance (d) between two measured points.
In the conceptual model for a meander bend (Dietrich et al, 1979; Frothingham and Rhoads, 2003), flow undergoes a centrifugal acceleration caused by the curvature of the bend. Going into the bend, water has momentum flowing straight ahead and will continue to flow in that same direction. The bend of the outer cut bank forces the water to change directions and flow towards the point bar along the inner bank. This is a continuous force experienced by all water hitting the cut bank of the bend. Due to this centrifugal acceleration, the water level near the outer bank becomes super-elevated compared to the water level of the inner bank. This super-elevation puts the stream in a state of disequilibrium and creates a hydraulic gradient which leads to a pressure difference between water at the cut bank and water at the point bar. A pressure gradient force is generated which pushes the water at the outer bank downward in an effort to balance the water level. This leads to the creation of a pool on the outside of the bend where water gets pushed downward and towards the point bar, scouring the bed. Near the surface of the cut bank, flow moves downward and gets pushed towards the point bar. Near the bed of the point bar, flow moves upward and towards the cut bank at the surface (Figure 2). Because flow continues to be headed down stream, the water moving towards the point bar is a secondary motion, which ultimately results in the flow following a helical motion around the bend. The strength of the helicity increases during higher stages, such as during floods. However, the helicity of the flow decreases rapidly as the width of the channel increases or as the sinuosity of the bend decreases. Thus, helical motion dissipates at the downstream end of a bend until a new bend is reached and the process begins again.
Figure 2. (a) A plan view of a meander bend with a marked cross-section. (b) The cross-section from (a) is shown. Arrows indicate direction of flow at this point. Near the surface of the cut bank, flow moves downward and get pushed towards the point bar. Near the bed of the point bar, flow moves upward and towards the cut bank at the surface.

Figure 3. Topographic steering. Flow moving away from the point bar.
Topographic steering can, however, divert flow away from the point bar, essentially causing the flow to travel around the bar (Dietrich and Whiting, 1989). In the situation of topographic steering, as flow approaches the more shallow bed of the point bar, shoaling generates a convective acceleration which causes a rise in pressure at the point bar. This rise in pressure at the bar leads to a drop in pressure over the corresponding pool near the cut bank. If the centrifugal force generated by the shoaling becomes large enough, the outward force pointing away from the point bar will surpass the pressure gradient force and flow will begin to move away from the point bar (Figure 3). 

Because the curvature of the channel induces centrifugal acceleration of the flow, erosion occurs along the outer bank. High velocity along the cut bank leads to low velocity on the corresponding point bar. When the pressure gradient force pushes the water downward and towards the point bar, it generates friction from contact with the bed. Friction slows down the velocity of the water and, when it reaches the point bar, the water is moving at a lower velocity than at the cut bank. This low velocity causes sediment to be deposited. Over time, the cut bank and point bar migrate laterally, increasing the sinuosity of the stream. Sediment deposited at the point bar comes from the cut bank a bend or two upstream. It has long been unknown whether the sedimentation of the point bar triggers the erosion of the cut bank or vice versa (van de Lageweg et al., 2014), but in a recent study utilizing a Eurotank basin, van de Lageweg et al. (2014) have concluded that the erosion of the cut bank triggers sedimentation deposition at the point bar. As with many complicated systems, it is likely that deposition and erosion both play a large role in the process of channel migration. As this
process continues and the sinuosity of the stream increases, the probability of a cutoff forming also increases.

Typically, there are two ways that a cutoff in a meander stream can form - a neck cutoff and a chute cutoff (Gay et al., 1998). A cutoff that forms when the up-stream and down-stream paths of the river are within one channel width apart is referred to as a neck cutoff (Lewis and Lewin, 1983). Erosion of the cut bank occurs in a bend, leading to a gradual decrease in the width of a meander neck until the two sides of the channel connect. The formation of a cutoff when the up-stream and down-stream paths of a river are greater than one channel width apart is referred to as a chute cutoff (Lewis and Lewin, 1983). Chute cutoffs commonly form in channels that are around their steady state (Rowntree and Dollar, 1999) and are usually created during high water levels that are often associated with floods. There are three distinct ways in nature a chute cutoff can form (Dijk et al., 2012). First, during times of increased volume, water breaches the up-stream cut bank and flows over the meander neck to the down-stream cut bank, creating a shallow swale across the neck. Eventually this path gets scoured enough to where water can flow at low stages, bypassing the bend entirely. Second, a jam creates localized bed aggradation which prevents flow from flowing downstream and forces the flow overbank. As flow rejoins the main channel, an incision over the neck (known as a headcut) forms along the downstream cut bank. As flow plunges down to the stream over the cut bank, the flow erodes some of the surface soil that overlies a layer of sand. This sand is carried into the stream by the flow plunging over the bank, causing the headcut to move upstream. This process continues until the headcut reaches the upstream channel (Gay et
al., 1998). Third, flood-initiated erosion on the upstream cut bank can form an embayment (Constantine et al., 2010). In this case, flow carves out a portion of the cut bank by means of erosion. Over time subsequent floods continue to enlarge the embayment until it has extended far enough downstream to intersect the main channel, forming a chute cutoff. Overbank flow is not necessarily required for the formation of an embayment, whereas in the first case explained a swale is formed across the neck due to overbank flow. The research in this study is based on the mechanism of a chute cutoff.

Vegetation can act to both stabilize a river bank as well as contribute to channel instability (Rowntree and Dollar, 1999). The roots of plant and tree life on the bank of a river can help prevent erosion of that area, promoting stability and decreasing the probability of a cutoff forming. Different types of vegetation will promote different levels of stability due to their varying root systems and growth patterns. In the Midwest, common types of riparian vegetation that will promote bank stability are cottonwood, willow, and sycamore trees which have the ability to quickly grow deep root systems (Schultz, 1996).

Unstable channels rapidly change planform making it difficult for large vegetation to grow and stabilize the channel banks. Thus, the channel often remains wide and shallow with constant fluctuation, whereas a channel lined with thicker vegetation is narrower and deeper with relatively high stability (Rowntree and Dollar, 1999). Due to thick vegetation promoting bank stability, the channel cannot widen as much as an area lacking vegetation. Because the channel cannot widen yet still must accommodate the flow, the
bed is scoured deeper. However, because the addition of vegetation often leads to a lower width/depth ratio, the possibility for overbank flooding increases (Rowntree and Dollar, 1999). Overbank flooding can lead to the formation of a chute cutoff, which would be an example of vegetation decreasing the overall stability of the channel.

Vegetation, sediment discharges, and bed and bank material affect the channel form of a meandering stream, but large organic debris in streams can also greatly affect channel formation (Bevan, 1948-49). Woody debris moving in the channel itself can build up at a point of low velocity, which can then divert flow and potentially lead to local avulsion or the formation of a chute cutoff (Keller and Swanson, 1979). Keller and Swanson (1979) found that a dominant factor in deducing stream debris conditions is the magnitude of the stream. Small streams lack the power, even at peak flow, to move large pieces of debris, thus the debris tends to be randomly found near where it fell. Intermediate-sized streams do have the power to move large debris, often resulting in large woody debris piles that can greatly affect the flow and formation of the channel. Large rivers have such great power and flow that they tend to deposit large debris high on the banks, scarcely affecting the channel flow. Thus, intermediate-sized streams are the most likely to be affected by accumulation of woody debris. The Embarras River is considered to be an intermediate-sized river in terms of width and discharge. Although various factors can lead to large organic debris ending up in a stream, such as tree collapse due to ice or winter storms and blowdowns caused by high winds, the most common in low energy meandering streams is bank failure triggered by lateral erosion of the cut bank (Keller and Swanson, 1979). Lateral erosion undercuts the vegetated bank, eventually resulting in the trees falling into
the stream. Debris can also roll down steep slopes and get carried into the channel, effectively increasing the area in which fallen debris can enter the channel, accelerating the rate at which debris enters the stream. It is typical that many of these processes act together to bring organic debris into a stream (Keller and Swanson, 1979).

A large woody debris pile often begins when a key member (usually a large log) gets caught in the stream and reduces the effective flow width of the channel (Abbe and Montgomery, 1996). Because of the reduced effective flow width, the key member can now more easily capture subsequent debris, causing the pile to grow and further reduce the effective flow width of the channel. Organic materials that would typically have been carried through this section of the stream now have a greater likelihood of being deposited to the debris pile. The larger the debris pile becomes, the more it will affect the flow of the stream. At times of flood, the flow may get diverted across the neck of a meander bend and begin to develop a chute cutoff by scouring a more efficient, steeper gradient path (Rowntree and Dollar, 1999). As time passes, more flow will pass through the chute cutoff, and the scoured path will enlarge, enabling even more flow in this positive feedback loop. The more flow that passes through the chute cutoff means that less flow will follow the bend, and this process will continue until all of the flow takes the path of the chute cutoff. When all flow travels through the cutoff, it is referred to as part of the main channel and an oxbow lake is the remnant of the bypassed meander bend.
III. Field Site

The Embarras River is a 314 km long meandering stream in east central Illinois. It begins in Champaign County on the Urbana Moraine and is a tributary of the Wabash River. About 18,000 years ago, the area surrounding the Embarrass River was impacted by the migration of the Laurentide ice sheet (Hansel and Johnson, 1992). The location of the study site rests near the southern edge of the terminal Wisconsin glacial episode moraine known as the Shelbyville Moraine (Ebinger, 1985), resulting in many rolling hills throughout the region. As the glacier moved through the area, till was deposited which constitutes much of the corresponding soil.

The Embarras River ranges from 38 m to 45 m wide at the study site. The field study site is a chute cutoff that has formed about 3 kilometers downstream of Lake Charleston in Charleston, Illinois (Figure 4). At this location, the Embarras River has a drainage area of 2,310 km². Much of the land use in the area is agricultural, and the river and its tributaries have been channelized to facilitate land drainage, especially in its headwaters region. The immediate area around the study site has not been channelized. Some local land owners have made attempts to control the lateral migration of the stream so as to not lose land, but these efforts appear to be ineffective. As the Embarras River passes Lake Charleston, there is an uncontrolled overflow spillway (Figure 4). In 1985, the spillway failed and much medium and coarse sediment was carried downstream (Demissie et al., 1988). Lake Charleston is the only major impoundment along the Embarrass River.
Currently, there is a substantial amount of woody debris that has accumulated at the head of the cutoff (Figure 5), but it is uncertain for how long this has been present. A study of aerial photographs indicates that this cutoff may have begun to develop as a swale prior to 1938. Since the cutoff began forming prior to 1938 it should have either fully formed or completely healed itself. Thus it appears that this debris might be acting as an obstruction, preventing at least some flow from entering the cutoff channel.
Figure 4. An aerial photograph and enlargement showing the location of the cutoff. Photo is from Google Earth, taken on April 18, 2014.
IV. Methodology

Field data for the study site included bed morphology data as well as an analysis of the planform change. Historical aerial photos ranging from 1938 to 2014 were used to analyze planform change. ArcGIS was used to align the photos based on stationary landmarks such as the crossing of two streets. ArcGIS is geographic information system software that can utilize global positioning system (GPS) data to create, analyze, and manipulate maps and geographic information.

To obtain bed morphology data, longitudinal transects of the Embarras River were taken using a 3.6 m long aluminum jon boat. Figure 6 highlights the area of the river where data were collected. Data were acquired with an acoustic Doppler current profiler
(ADCP) that was mounted to the boat with a metal pipe 0.59 m below the surface of the water. The ADCP used was a 1,200 kHz Workhorse Rio Grande ADCP made by Teledyne RD Instruments. An ADCP sends four sound waves downward at an angle of 20° from vertical from just below the water surface to the channel bed. The ADCP measures the time it takes each sound wave to bounce off the river bed and return. Knowing the velocity of sound waves in water and the time it took for the sound waves to return, the distance of the bed from the ADCP was calculated. The ADCP was set up on the port side of the boat and was integrated with a GPS. The antennae for the GPS was mounted directly above the ADCP and enabled the ADCP to assign a GPS coordinate to each measured depth, making it possible to create an accurate map of the river bottom.

ADCP data were collected using WinRiver II, a software package developed by Teledyne RD Instruments. Data were input into an ADCP post-processing software, Velocity Mapping Toolbox (VMT). VMT converted the recorded depths into elevations based on flow stage data at the time of data collection. The elevation for each GPS location was then entered into ArcGIS. A map depicting the elevations of the river bed was produced by kriging and contouring the bed elevation data.
Figure 6. Highlighted area shows the location on the Embarras River where bed topography data were collected.

V. Results

Bed morphology

Bed morphology field data of the Embarras River were collected on March 19, 2015. Data were taken over a three hour period during which the stage decreased 0.0225 m. According to a United States Geological Survey (USGS) river gage on the Embarras River at Camargo, IL roughly 40 km north of the study site, the discharge was about 4.96 cubic meters per second. Comparing that value to the USGS calculated mean daily value taken over the last 54 years of 4.39 cubic meters per second, it can be determined that March 19, 2015 was a slightly above average day in terms of discharge for the Embarras River but nowhere near the discharge associated with a flood. The generated map of the bed morphology is shown in Figure 7.
Figure 7. Bed morphology of the channel created using ArcGIS.
The downstream cut bank (Location A in *Figure 7*) of the main channel has a pool at its base that begins as the channel begins to bend. Throughout this curve, depth is the lowest along the cut bank, and the channel shallows towards the inner bank point bar. This broad point bar is positioned immediately downstream of the woody debris pile (Location B in *Figure 7* depicts the woody debris pile). On either side of the woody debris pile, the channel is narrow and deep. To the east of the pile, the elevation gets as low as 138.53 m while to the west of the pile the elevation gets as low as 138.26 m. After the bifurcation, the elevation of the bed of the cutoff is shoaled with particles of much greater size such as large gravel and cobbles.

At Location C, there is a sharp increase in elevation of the bed that appears to be circular in nature. Location C is about 3.1 m in diameter and reaches a maximum elevation of 140.29 m. The pool formed immediately upstream of this location has an elevation of 138.48 m. Comparing these values gives an elevation change of 1.81 m occurring in a horizontal distance of less than 7 m.

Location D labels the upstream cut bank of the Embarras River in the study area. There is a pool along the cut bank, and the elevation of the bed increases across the channel to the adjacent upstream point bar. The upstream point bar is not as broad as the downstream point bar, and the elevations vary as well. Each point bar reaches a similar maximum elevation, but the downstream point bar has much more area. The upstream bend and downstream bend of the main channel have a similar pattern with the elevations, but vary slightly in how those elevations are distributed. Furthermore, the
pool at the upstream cut bank has more area at lower depths than the pool at the downstream cut bank.

Location E labels an oddly shaped feature in the bed morphology that seems to be a parabolic shaped U of lower elevation. A closer look at Figure 7 shows that there are other similarly shaped patterns around Location E, but they only slightly drop in elevation. The elevation drop at Location E around the entire U shape is about 0.23 m from the surrounding and happens very abruptly.

Channel Planform

Figure 8 shows four aerial photographs of the study site taken in 1938, 1953, 2005, and 2011. It is clear to see that the planform of the Embarras River around the cutoff has changed greatly. The upstream channel (Location F in Figure 8) has shifted to the west in each photo shown, but the shape of the channel at this location has been inconsistent. From 1938 to 1953 the channel straightened out considerably but then reverted to a more sinuous state. The 2005 photo shows that the channel at this location is even more sinuous than it was in 1938 and may be even more sinuous in the 2011 photo. However, due to tree cover in the 2011 photo the channel itself is somewhat difficult to see. The apex of the bend before the cutoff (Location G in Figure 8) appears to have shifted westward as well.

Location H in Figure 8 shows what is believed to be the cutoff in an early stage of formation in 1938. The 1938 photo shows what appears to be a swale, a precursor to the
cutoff, and a corresponding small path in the tree line going across the neck. It is difficult to see if there is any woody debris causing the cutoff to form. The 1953 photo still shows the cutoff, but it does not appear to have grown much, if at all. However, by 2005 the cutoff is well developed and remains well developed in 2011. There was some woody debris present in 2005, but there is clearly a great deal of debris present in 2011.

The sharp downstream bend (Location I in Figure 8) may have had the most change since 1938. The bend has shifted considerably in many ways. In each photo, the bend shifts farther south and farther east, increasing the sinuosity of the channel. The change of the planform at this location from 1953 to 2005 shows great erosion occurring at the cut bank of Location I. Even in the short six years from 2005 to 2011, the cut bank has migrated noticeably further southeast. As the bend has continued to erode, Location J in Figure 8 is of interest in 2005 and 2011. This section of the channel is much larger in 2011 than in 2005. The point bar next to the island at this location is getting eroded quickly, leading to what looks like an embayment being carved into the island.
Figure 8. Aerial photographs of the Embarras River at the cutoff showing planform change over a period of 76 years. Photos a, b, c are courtesy of Coles County Soil and Water Conservation District. Photo d is from Google Earth.
Figure 8 shows three aerial photographs of the upstream cutoff (Location H in Figure 8) in 2007, 2010, and 2014. In 2005, there is a single tree that has fallen into the channel perpendicular to the flow and some small debris has accumulated on it. In 2010, it appears that the original tree in 2005 is gone or has broken down, but there is even more accumulation of debris at the start of the cutoff. By 2014, there is more debris at this location than any of the other photographs, and it is confirmed that the original tree cannot be seen. In the seven year timespan represented by the photos in Figure 9, it does not seem like the cutoff itself has changed much, but the accumulation of debris certainly has.
Figure 9. Accumulation of woody debris at the cutoff. Photo (a) is from Coles County Soil and Water Conservation District. Photos b and c are from Google Earth.
VI. Discussion

The bed morphology of the channel at the downstream bend (Location A in Figure 7) conforms to the conceptual model for a meander bend (Dietrich et al, 1979; Frothingham and Rhoads, 2003). Near the cut bank, there is a pool formed by the erosion of downward moving water caused by the pressure gradient force. The elevation of the bed increases toward the inner bank point bar because the flow slows down due to friction with the bed enabling deposition onto the point bar. The aerial photographs also confirm the conceptual model for a meander bend applies to this section of the stream. Location I of Figure 8 shows the channel shifting southeast which is what is to be expected of a meander bend. The flow erodes the cut bank and deposits the material on the point bar causing the bend to elongate in the direction of the cut bank.

The parabolic shape of lower elevation at Location E of Figure 7 does not fit into the conceptual model for a meander bend. It is possible that the woody debris and cutoff are causing intricate flow dynamics that have not yet been adequately studied. It is also possible that there is a fallen piece of debris resting on the point bar, or it could be an artifact of the software interpolation process when data were used to create the bed morphology map. A 3-dimensional study of the flow at this bend would provide more insight as to what is causing the irregular bed morphology.

The point bar immediately after the large woody debris pile (Location B in Figure 7 depicts the debris pile) is broader than to be expected. The debris pile is shielding the point bar, slowing down flow and enabling sediment to be easily deposited. In the future,
it would seem that if the debris pile remains roughly the same size or larger, then the point bar will either remain the same size or continue to grow. A growing point bar could lead to many outcomes. One outcome could be a lateral migration of the channel caused by the flow being pushed outward from the point bar, which might be contributing to the migration of Location I in *Figure 7*. However, this would go against the findings of van de Lageweg et al. (2014) that the erosion of the cut bank causes deposition on the point bar, not vice versa. The findings of van de Lageweg et al. (2014) utilized a laboratory flume so it is possible that the results of this paper based on collected field data do indeed differ. If the channel is unable to migrate laterally, then the river bed west of the debris pile could scour even deeper to accommodate the necessary flow, thus increasing the local stability of the channel. Either of these outcomes would likely not allow the chute cutoff to fully form because it would not be able to capture all of the flow. The last outcome of the increasing point bar could be effectively sealing off the main channel. The point bar could continue to enlarge and aggradation of the main channel would then force most of the flow through the cutoff. This diversion of flow could enlarge the cutoff to the point where it captures all of the flow becoming part of the main channel and creating an oxbow lake where the original bend was. The bed morphology around the debris pile seems to point to the last option of diverting flow into the cutoff, but a conclusive result cannot be made with the data at hand.

Location C in *Figure 7* shows a sharp increase of elevation caused by erosion of the bank. The bank material at Location C is loosely consolidated sand and is easily erodible. The bed morphology suggests that flow is hitting the bank at this location and...
causing large chunks of the bank to fall into the channel. If this continues, the cutoff will grow and capture more flow leading to more erosion and possibly the capture of all flow. However, it is uncertain what type of bank material is behind the sand and if it will be eroded just as easily or not.

Another determining factor that will affect the formation of the cutoff is the bed material comprising the cutoff. Much of the cutoff consists of rocks, many of which are 20 cm wide. It is likely that these rocks were carried by the stream at times of floods and deposited in the cutoff where the channel shoals and energy decreases. It is also possible that the rocks were present before the cutoff began to form and are hindering the cutoff becoming fully formed. Data collected does not shed any light as to how these rocks came to be and thus further investigation is needed.

The cut bank shown at Location D in Figure 7 seems to have been altered by the woody debris and cutoff. The pool ends fairly abruptly and likely sooner than it would have without the debris and cutoff. This could be a contributing factor for the migration of the channel at Location F in Figure 8. If the pool is forced to end early, then the bend would likewise shift west. However, it is still uncertain what triggered the formation of the cutoff. There may not have been any woody debris when the cutoff began to form, but the pool shifting west could still occur with only the cutoff present. Collecting bed morphology data at a later time and comparing the changes in the location of the pool in regards to the cutoff would give insight into whether or not the cutoff is causing the shift in the channel.
A comparison of the upstream and downstream bed morphology at the bends (Locations D and A respectively in Figure 7) shows that the upstream pool is deeper than the downstream pool. Taking into account the cutoff, this makes perfect sense. Because the cutoff is capturing some of the flow, the downstream bend does not have as much flow as the upstream bend. Thus the downstream bend does not have to scour the ground as deeply as upstream because there is less flow to erode the bed.

Although it is difficult to confirm with the data collected, it seems that the embayment at Location J in Figure 8 implies part of the bank is more difficult to erode than the surrounding areas. It is reasonable to assume that the bank directly across from the embayment has very cohesive material, perhaps clay. Erosion is occurring immediately upstream of this location but is having difficulty eroding the bank across from the embayment, causing the flow to be pushed towards the island. If this continues, the cutoff will have less and less distance needed to scour to reach the main channel, thus possibly accelerating the development of the cutoff.

The first appearance of any woody debris at the cutoff is unknown. However, an analysis of Figure 9 shows how the current woody debris has come to be. Figure 9 depicts what the literature suggests happens in the event of a large woody debris pile (Abbe and Montgomery, 1996). In 2007, it is clear that a single tree has fallen into the channel perpendicular to the direction of flow. This tree is referred to as the key member. There is small debris that the key member has captured and added to the pile, and a chain reaction has been started. As the debris pile grows larger, it has the capability to capture
even more, larger debris, thus continuing the cycle. The bigger the pile is, the more it will affect the bed morphology and flow dynamics at that location. In 2010, the key member no longer appears to be in the debris pile. This does not matter because it had already collected much debris by 2010. It is uncertain as to how the large debris made it to the debris pile, but a search of flow using the USGS river gage at Camargo can provide some information (Figure 10). In 2008 and 2009, there were seven floods where discharge was over 57 cubic meters per second. This is well above the average, and each flood easily has the power to move large debris in the river. Of the seven floods, there were two in 2008 that had a discharge of over 140 cubic meters per second. One maxed out at 148.95 cubic meters per second, while the other reached a maximum discharge of 155.46 cubic meters per second. Since the Camargo river gage is upstream of the study site, the discharge at the study site on these occasions should be larger than the measured discharge at Camargo. Whether or not these flood events carried the debris to the pile is unknown, but it is the most likely scenario.
Figure 10. USGS flow data at the Camargo river gage taken between January 2008 and December 2009. The seven large flood events are circled on the graph.

Because the sinuosity of the channel has increased as shown in Figure 8, the literature states the likelihood of a cutoff forming also increases (Parker, 1996). The more sinuous a stream is the greater the possibility of a cutoff forming. Thus, it would make sense that as the bends elongate, the cutoff becomes more dominant and eventually captures all of the flow. However, the results do not seem to support this. The 1938 photo in Figure 8 shows what appears to be the cutoff in its early stages. At this time the local sinuosity of the stream was much lower than it is today, and yet the cutoff is still not fully formed today. In the 76 years since 1938 (Figure 8), the cutoff has certainly grown but still has failed to capture all of the flow. During this long time period, one would assume that
either the cutoff would fully form and capture all of the flow or begin to heal itself and have the main channel convey all of the flow. Neither of these options have occurred, which leads to the idea that there are intricate fluid dynamics happening at the study site that have not yet been fully studied.

VII. Conclusion

This research adds to the knowledge of large woody debris piles affecting the formation of a chute cutoff in a meander bend. The results show that the debris pile is affecting the formation of the channel and chute cutoff, but it is unclear as to how great or in what manner of an effect the pile is causing. The bed morphology data collected in this study show that there is a broad point bar immediately behind the debris pile and the channel is narrow and deep on either side of the pile. Near the intersection of the main channel and the head of the cutoff there is a sharp increase in bed elevation caused by erosion of the cut bank. Although there is a deep scour next to the debris leading into the cutoff, the bed elevation of the cutoff increases drastically thereafter. The bend upstream of the cutoff follows the conceptual model of a meander bend (Dietrich et al, 1979; Frothingham and Rhoads, 2003); the pool near the cut bank is deepest and the channel shallows towards the inner point bar. The bend downstream of the cutoff displays similar qualities as the upstream bend but with some variances. The pool is deepest and the channel does indeed shallow towards the inner point bar, but there is a parabolic scour in the point bar that cannot be fully explained with the data collected. Furthermore, the bed elevation of the downstream bend is not as deep as the bed elevation of the upstream bend. It is still unknown whether the large woody debris pile is deflecting flow into the
chute cutoff or away from the chute cutoff. The results indicate that the debris pile is shielding the main channel from flow and deflecting that flow into the cutoff, but more data is needed to make a confident conclusion.

The accumulation of the large woody debris pile conforms to the existing literature (Abbe and Montgomery, 1996) in that a key member falls into the channel perpendicular to the direction of flow. In high stage events, debris is carried downstream and captured by the key member leading to an accumulation of debris that, in turn, can capture more debris. However, this does not give any insight into what originally caused the cutoff to form. It is possible that there was no woody debris at the formation of the cutoff and the debris is preventing the cutoff from becoming fully formed. It is also possible that the woody debris triggered the original formation of the cutoff and, at times of lesser debris, the cutoff begins to heal itself. Radiometric dating of deeply buried logs in the pile could help to see when the pile truly began to form, if before the key member in 2007. Tracking of large logs in the pile would provide insight to the evolution of the pile and how it might be affecting the formation of the cutoff.

It is also uncertain if the chute cutoff will heal itself entirely, continue to convey a portion of the flow, or catch the flow entirely and become part of the main channel creating an oxbow lake in the abandoned channel. A study of the 3-dimensional flow at the site as well as subsequent studies of the bed morphology will yield more conclusive data allowing a detailed interpretation of what is happening at the cutoff and what will happen in the future.
VIII. References


