Planform evolution of neck cutoffs on elongate meander loops, White River, Arkansas, USA

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ABSTRACT: During the formation of a neck cutoff on a compound elongate loop, the upstream and downstream limbs can become oriented roughly subparallel with flow in opposite directions separated by a narrow meander neck. Immediately following cutoff of this thin neck, flow from the upstream limb is sharply redirected into the downstream limb over a short distance, leading to complex patterns of three-dimensional velocities that have implications for the evolution of the cutoff channel and the transformation of the abandoned bend into an oxbow lake. This paper investigates the process dynamics and planform evolution of neck cutoff and oxbow lake formation using measurements of flow velocities and time-series analysis of aerial photography for three neck cutoffs along the White River, Arkansas (USA) — each representing a different stage in the morphologic evolution from cutoff to oxbow lake. Results from this study suggest that the planform geometry of neck cutoff on an elongate meander loop can influence the spatial patterns of sediment erosion and deposition within the abandoned loop leading to increased hydrologic connectivity to the main channel, and contribute to the overall morphodynamics of highly sinuous meandering rivers.

1 INTRODUCTION

Meander cutoff and oxbow lake formation are essential components of alluvial architecture and riverine habitat of meandering river floodplains. Yet, despite their ubiquitous presence within active floodplains, the detailed processes involved in the initiation of cutoffs and oxbow lakes remain incompletely understood, primarily due to the intermittent nature of such events. Furthermore, studies of meander cutoff have primarily focused on chute cutoffs and relatively simple planform geometries, with less attention given to neck cutoffs occurring on highly sinuous meandering rivers with complex planform morphology.

The continued planform evolution of meandering rivers increases sinuosity and thus the length of the channel, until the channel path is shortened by one of two primary cutoff mechanisms. Chute cutoffs occur when an incipient channel is incised into the floodplain connecting the upstream and downstream limbs during an overbank flood event, whereas neck cutoffs occur through the continued migration and eventual intersection of the upstream and downstream meander limbs (Constantine et al., 2010; Fisk, 1947; Gagliano and Howard, 1984; Hooke, 2004; Lewis and Lewin, 1983; Zinger et al., 2013).

A considerable amount of research has been aimed at improving our understanding of the evolution of meandering rivers (Brice, 1974; Ikeda et al., 1981; Parker and Andrews, 1986; Sun et al., 1996; Peakall et al., 2007; Parker et al., 2011), however our current understanding of the detailed processes that occur during and after cutoff events remains incomplete. Conceptual models of meander cutoff and oxbow lake formation have been primarily developed for chute cutoffs and relatively simple planform configurations. In these situations, the upstream and downstream limbs of the meander are connected by a relatively straight cutoff channel (Figure 1A). However, during the formation of a neck cutoff on a compound elongate loop, the upstream and downstream limbs are roughly subparallel with flow in opposite directions, forcing flow redirection over a short distance (Figure 1B). These conditions of tight bend flow should become more pronounced as the ratio of radius of curvature to channel width becomes smaller, leading to complex patterns of three-dimensional velocities that could potentially influence the evolution of the cutoff channel and the transformation of the abandoned bend into an oxbow lake.

In this paper, the formation and evolution of neck cutoffs and their associated oxbow lakes are
explored through detailed field measurements of three-dimensional velocities and time-series analysis of aerial photographs for three cutoffs along a highly sinuous river, each representing a different stage in the morphologic evolution from cutoff to oxbow lake.

2 STUDY AREA

The study area for this investigation includes three cutoff sites in Arkansas, USA along the White River, between De Valls Bluff and Clarendon (Figure 2). The White River is a tributary to the Mississippi River and in its lower reaches has bankfull width and depth of roughly 170 m and 7 m, respectively, and flows through the forested Dale Bumpers White River National Wildlife Refuge. The lower White River is a highly sinuous meandering river with numerous compound and elongate loops and several neck cutoffs. Within the study reach, three neck cutoffs have occurred since 2000, each representing a different stage in the development toward bend abandonment and oxbow lake formation (Figure 2). Sinuosity and slope within this are $-2.2$ and $6 \times 10^{-4}$, respectively.

Based on analysis of aerial photography from 1996 to 2015, Franklin Bend Cutoff (Figure 2, A1/A2) occurred at some point between 2000 to 2006 and appears to be in the process of straightening the path from the upstream limb to the downstream limb. Seven Mile Bend Cutoff (Figure 2, B1/B2) occurred between 2010 to 2011 and shows evidence of bank erosion on the downstream limb as a result of tight bend flow. The most recent neck cutoff, Pumps Bend Cutoff (Figure 2, C1/C2), occurred in 2013 and is in the initial stages of cutoff channel widening. While these three neck cutoffs each have slightly different planform configurations and are at different planform evolutionary stages, they all display connectivity of the prior meander loop with the main channel.

Figure 1. (A) Simple meander bend with chute cutoff showing relatively straight flow path from upstream to downstream limb. (B) Neck cutoff on an elongate meander loop showing tight bend flow from upstream to downstream limb. The arrows in both illustrations indicate flow direction.

Figure 2. A. Map of the location of the neck cutoffs in the United States. B. Orthophotographs of three neck cutoffs on the White River, Arkansas. The left panel shows 2006 imagery and the right panel shows 2013 imagery. Sites are described in the text.
3 METHODS

Three-dimensional velocities and general bed morphology were measured using a boat-mounted RDI-Teledyne Workhorse Rio Grande Acoustic Doppler Current Profiler (ADCP) with an integrated Hemisphere A100 dGPS antenna. These data were collected along predetermined cross sections oriented roughly perpendicular to the channel centerline and longitudinally along the stream center and banks in the bends at a sampling frequency of ∼1 Hz on April 6–7, 2015 during an approximate bankfull flow discharge of ∼1600 m$^3$ s$^{-1}$. At each cross section, 2–4 transects were obtained, and then spatially and temporally averaged using the Velocity Mapping Toolbox (VMT), a MATLAB-based software designed for processing and visualization of boat-mounted ADCP data (Parsons et al., 2013).

Channel bathymetry data acquired from ADCP measurements were exported from VMT, processed and visualized using Caris Bathy DataBASE Editor. These data were interpolated using a Triangulated Irregular Network (TIN), and a raster surface with 10 m resolution was prepared from the TIN. The bathymetric maps and depth-averaged velocity vectors were then brought into ArGIS for combined visualization of the channel morphology and flow structure through each cutoff site.

4 RESULTS

4.1 Pumps bend cutoff

Pumps Bend cutoff is the farthest upstream neck cutoff within the reach and is in the early stages of cutoff widening and deepening (Figure 3). In contrast to Franklin and Seven Mile bends that displayed strong redirection of the flow through the cutoff, depth-averaged velocity vectors at Pumps Bend display some flow traveling through the cutoff with maximum velocity ∼1.75 m s$^{-1}$, while a substantial portion of the flow still moves through the original loop with velocities up to ∼1 m s$^{-1}$. Downstream of the cutoff, the flow exhibits a zone of recirculation along the outer bank, however this zone is much smaller in extent (∼75 m) compared to the other two cutoffs.

The channel bathymetry of Pumps Bend resembles that of typical elongate meander bends, with a pronounced scour pool along the outer bank downstream of the loop apex (Figure 3). Within the cutoff, bathymetric measurements reveal shallow flow depths of ∼1–2 meters with scour pools adjacent on either side inherited from pre-cutoff meander morphology. The scour pool downstream of the cutoff is much more pronounced than the pool upstream, however it does not extend to the far bank as it did at the other two sites. Instead, the zone of scour is adjacent to the outer bank, with the exception of a region of low flow depth < 3 m present immediately downstream of the cutoff along the outer bank (Figure 3).

4.2 Seven mile bend cutoff

Seven Mile Bend Cutoff is the middle cutoff in terms of age and shows bank erosion caused by tight bend flow. Depth-averaged velocity vectors show a similar pattern of the flow turning tightly through the cutoff as was observed at Franklin Bend Cutoff, with the high velocity core being shifted from the outer bank upstream of the cutoff to against the far bank downstream of the cutoff (Figure 4). This pattern of tight bend flow produces a zone of separation and flow recirculation that extends over 300 m downstream of the cutoff and has a maximum lateral extent of ∼150 m, roughly half the bankfull width. While patterns of flow through the cutoff are similar to Franklin Bend, maximum velocities at Seven Mile Bend reach ∼2 m s$^{-1}$, a roughly 25% increase. Additionally, in contrast to Franklin Bend which displayed low velocities within the entrance and exit of the original loop, at Seven Mile Bend a portion of
the flow that travels through the cutoff is directed upstream through the original loop with velocities \( \sim 1 \text{ m s}^{-1} \). The depth-averaged velocity vectors display this upstream oriented pattern throughout the loop, where the flow interacts with the downstream oriented flow and produces a recirculation cell (Figure 4).

Bathymetric measurements at this site also show a deep scour pool (\( \sim 19 \) m) within the cutoff and a shallow region forming along the outer bank of the downstream limb of the meander loop downstream of the cutoff (Figure 4). This scour hole does not exhibit a sharp increase in channel depth from the upstream limb into the cutoff as shown at Franklin Bend, but rather shows a transition from a pool present along the outer bank of the upstream limb (Figure 4). Downstream of the neck cutoff, the region of scour is adjacent to the far bank and extends downstream along this bank throughout the mapped area. Within the original meander loop, an outer bank pool is present with maximum depths of \( \sim 18 \) m found downstream of the loop apex.

4.3 **Franklin bend cutoff**

Franklin Bend Cutoff is the oldest cutoff and is in the process of straightening the channel path. Depth-averaged velocity vectors at the farthest upstream cross section display a strong cross-stream asymmetry with the highest velocities \( \sim 1.25 \text{ m s}^{-1} \) located along the outer bank, due to inherited flow structure from the upstream meander bend (Figure 5). As flow travels downstream toward the cutoff, the orientation of the velocity vectors shift from being roughly perpendicular to the cross section to becoming highly-skewed in the direction of the cutoff. As flow moves through the cutoff, velocities increase to a maximum value of \( 1.5 \text{ m s}^{-1} \), and high momentum fluid is advected against the far bank, forcing the majority of the flow to quickly redirect downstream. The path of the high velocity core through the cutoff results in a zone of flow separation and recirculation on the downstream end of the upstream junction corner that persists downstream \( \sim 200 \) m. An additional zone of flow recirculation occurs near the downstream junction corner as a portion of the high momentum fluid against the far bank is redirected upstream. Depth-averaged velocity vectors at the entrance and exit to the original loop suggest minimal discharge through the loop.

The channel bathymetric map for Franklin Bend reveals a scour pool \( \sim 20 \) m deep that develops within the downstream limb of the loop immediately adjacent to the cutoff, with a relatively sharp increase in flow depth from the upstream channel bed (Figure 5). This scour pool covers an area from the cutoff to the far bank, with a zone of scour extending downstream along the bank for \( \sim 350 \) m. Along the opposite bank from this zone of scour (downstream of the upstream junction corner), an area of shallow flow depths \( < 3 \) m is present along the bank (Figure 5). Channel bed morphology

![Figure 4](image1.png)  
**Figure 4.** Depth-averaged velocity vectors and channel bathymetry derived from ADCP measurements at Seven Mile Bend Cutoff, April 6th, 2015.

![Figure 5](image2.png)  
**Figure 5.** Depth-averaged velocity vectors and channel bathymetry derived from ADCP measurements at Franklin Bend Cutoff, April 6, 2015.
through the original meander loop shows little infilling at the loop entrance and exit, and still displays a broad pool along the outer bank.

5 DISCUSSION

Measurements of velocity and channel bathymetry at three different neck cutoff sites on the White River, Arkansas, each in a different morphologic stage of evolution, provide a means for evaluating the morphodynamic adjustments of a highly sinuous meandering river following neck cutoff. The most recent neck cutoff in the study area occurred on Pumps Bend in 2013 and is still in the early stages of adjustment. At the time of data collection, the neck cutoff had widened ~90 m, less than half the distance of bankfull width, and had scoured a maximum of ~6 m from top of bank. On the upstream limb of this meander loop, the outer bank scour pool is ~10 m deep, indicating that the cutoff is still within its incipient incision into the floodplain. Within the downstream limb of the loop, immediately adjacent to the cutoff, scour depths reach ~19 m. It is uncertain how much of this scour is related to pre-cutoff bed morphology and how much subsequent scour has resulted from accelerated flow through the cutoff channel. However, outer bank pool depths downstream of the loop apex, as well as the outer bank pool downstream of the cutoff, show areas of bed topography as deep as ~17 m, suggesting the deep scour adjacent to the cutoff was partially established prior to cutoff initiation, and may have contributed to the location of the neck cutoff.

While the data from Pumps Bend provide evidence for the early morphologic adjustments following neck cutoff on elongate meander loops, the data from Seven Mile and Franklin bends offer insight into the planform dynamics of these loops. As observed at all three cutoff sites, as flow travels toward the cutoff from the upstream limb, the increased water surface gradient through the cutoff results in strong curvature of the flow streamlines toward the downstream direction. This tight bend flow through the cutoff causes advection of high momentum fluid against the far bank (previously inner bank of downstream limb), resulting in locally increased rates of bank erosion. Along the opposite bank immediately downstream of the cutoff, the zone of flow separation and recirculation leads to deposition of sediment and the development of a bar attached to the bank. These patterns of erosion and deposition are contrary to the pre-cutoff bed morphology, and result in scouring of previous inner bank point bar deposits and infilling of the outer bank scour pool. The increased growth of the bar progressively confines the flow toward the far bank resulting in a shift in the location of the channel thalweg from outer bank (e.g. Pumps Bend) to inner bank (e.g. Franklin Bend). The planform response to the coevolution of flow and bed topography is the development of a meander bend with low radius of curvature that actively rotates downstream (i.e. Franklin and Seven Mile bends).

An interesting finding from this study is the apparent lack of deposition within the entrance and exit to the original meander loop. In contrast, evidence from chute cutoffs typically show rapid deposition of sediment and development of bars (< 3 years following cutoff) that plug the entrance and exit of the bend, causing the majority of the flow to be redirected through the cutoff and resulting in the abandonment of the original bend (Gay et al., 1998; Zinger et al., 2013). However, the planform geometry of the elongate meander loops in the present study, and the resulting tight bend flow through the neck cutoff, allow for a substantial portion of the discharge to travel through the original loop, maintaining hydrologic connectivity and restricting the abandonment of the loop. In the extreme case of Seven Mile Bend, the location of the cutoff within the neck of the loop combined with the tight bend flow, results in reversed flow (upstream oriented) through the original loop, producing multiple zones of recirculating fluid.

6 CONCLUSION

This study presents spatial patterns of depth-averaged velocity vectors and channel bathymetric measurements for three neck cutoffs on a highly sinuous meandering river, each of which is in a different evolutionary stage of development. The major hydrodynamic processes revealed by this investigation include 1) tight bend flow as flow is sharply curved through the neck cutoff, 2) high momentum fluid being advected against the inner bank of the downstream limb of the elongate meander loop, 3) a zone of flow separation and recirculation along the outer bank of the downstream limb located immediately downstream of the cutoff and extending up to ~ downstream, and 4) hydrologic connectivity being maintained between the primary channel and the original meander loop.

The morphologic adjustments associated with these spatial patterns of flow show deposition of sediment within the zone of recirculation and the development of a bar attached to the pre-cutoff outer bank. As well as, a zone of increased erosion along the pre-cutoff inner bank where high velocity impinges against the bank. These patterns of inner bank erosion and outer bank deposition
suggest that as the neck cutoff and channel evolve, the downstream limb of the meander loop will develop a new bed and bend morphology to match the new hydrologic conditions and that this bend migrates initially through downstream rotation.

The findings from this study shed light on the morphodynamic response of elongate meander loops following neck cutoff, however provide limited details about the conditions that promote the development of such narrow floodplain necks. The White River exhibits numerous bends with floodplain necks that are less than \(\sim 50\) m, or roughly 25\% of the bankfull channel width. More work should be done to investigate the resistance to erosion properties of the banks and floodplains, and the pre-cutoff channel bed morphology that contribute to the location and formation of neck cutoffs on these highly sinuous bends.

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