THE FLUVIAL DYNAMICS OF CONFLUENT MEANDER BENDS

BY

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DISSERTATION

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ABSTRACT

Planform geometry is a controlling factor that influences flow structure, sediment transport, and bed morphology at river confluences. Previous experimental, field, and modeling studies of confluence dynamics have focused mainly on junctions formed by straight approach channels that meet at angular configurations before entering a straight receiving channel. In contrast, natural rivers often meander and tributaries can enter meandering rivers on the outside of bends to form a junction planform known as a confluent meander bend. Experimental and numerical modeling studies have begun to document flow structure at confluent meander bends with fixed boundaries and rectangular channel cross sections. The research presented here complements this modeling work with field data from natural confluent meander bends to evaluate flow dynamics in channels with erodible boundaries, to document morphologic features of the bed, and to evaluate changes in bed morphology with changing flow conditions.

The research is comprised of two field investigations. In the first study, field measurements of three-dimensional velocity components and bed topography at a small confluent meander bend with a 90° junction angle reveal a complex hydrodynamic environment that responds to changes in momentum-flux ratio. Flow from the tributary deflects high-velocity flow and helical motion in the curving main river toward the inside of the bend, inducing bed scour and inhibiting point-bar development. The high junction angle forces the tributary flow to abruptly realign to the orientation of the downstream channel, initiating a counter-rotating helical cell over the outer portion of the bend. Two surface-convergent helical cells persist through the downstream channel, where the combined flows accelerate as the channel cross-sectional area is constricted by a bar along the downstream junction corner, precluding flow separation. Long-term stability
of its planform suggests that this confluent meander bend represents a quasi-stable channel configuration.

The second field study examines the influence that the angle of entry of the tributary flow has on mutual deflection of confluent flows and the spatial extent of confluence hydro- and morphodynamic features at confluent meander bends. Measurements of three-dimensional flow structure and bed morphology were obtained for high and low momentum-flux ratios at two large-river confluent meander bends with different tributary entry angles. At the high-junction angle confluent meander bend, mutual deflection of converging flows abruptly turns fluid from the tributary into the downstream channel, while flow in the main river is deflected away from the outer bank of the bend where a bar extends downstream of the junction corner from the inner bank of the tributary. Two counter-rotating helical cells inherited from upstream flow curvature flank the mixing interface which overlies a central pool. Substantial morphologic change due to the development of a meander cutoff upstream of the confluence during large, tributary-dominant discharge events results in displacement of the pool inward from the influx of large amounts of sediment into the confluence and substantial erosion of the point bar in the main channel. In contrast, flow deflection is less pronounced at the low-angle junction, where the converging flows almost parallel each other upon entering the confluence. A large helical cell induced by upstream flow curvature in the main river occupies most of the downstream channel for prevailing low momentum-flux ratio conditions and a weak counter-rotating cell forms during infrequent tributary-dominant flow events. Bed morphology remains relatively stable and does not exhibit extensive scour that often occurs at confluences with concordant beds. The mixing interface at both confluences persists through the downstream channel, indicating helical motion does not produce substantial mixing of the flows within the confluence hydrodynamic
zone. Together, the results from the two studies indicate that the dynamics of confluent meander bends differ greatly from the dynamics of bends without tributaries and can be characterized as an amalgamation of the dynamics of confluences and meander bends.
For Leanne, Jakob, and Grace
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1.1 Motivation

River confluences are focal components of fluvial systems where convergence between separate channel flows produces a complex hydro- and morphodynamic environment. Rapid changes in fluid motion, sediment transport, and channel morphology occur at confluences in order to accommodate the influx of water and sediment supplied to the main river by a tributary. While confluences are ubiquitous features of drainage networks that are critically important in regulating the longitudinal distribution of flow and sediment (Richards, 1980; Ashmore and Parker, 1983; Rhoads, 1996), scientific research on the dynamics of confluences is a relatively recent undertaking. Much of what is known about confluences has been established at experimentally derived junctions in the laboratory, from which several factors have been identified that control patterns of flow and the configuration of the bed, including junction planform symmetry, junction angle, and the momentum flux ratio \( (M_r) \) of the confluent flows (Mosley, 1976; Ashmore and Parker, 1983; Best and Reid, 1984; Best, 1986, 1987, 1988; Best and Roy, 1991; Biron et al., 1996a,b; McLelland et al., 1996). Field investigations have been performed primarily at small stream confluences to evaluate the relevance of experimental and numerical models on flow structure and morphology under natural conditions (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Biron et al., 1993a,b, 2002; Bristow et al., 1993; Kenworthy and Rhoads, 1995; Rhoads and Kenworthy, 1995, 1998; McLelland et al., 1996; Rhoads, 1996; DeSerres et al., 1999; Rhoads and Sukhodolov, 2001, 2004; Boyer et al., 2006; Rhoads et al., 2009). In recent years, a growing theoretical framework has emerged to integrate experimental and field studies with numerical modeling in the study of confluences (Weerakoon
and Tamai, 1989; Weerakoon et al., 1991; Bradbrook et al., 1998, 2000, 2001; Constantinescu et al., 2011). These studies of confluence dynamics have focused mainly on junctions formed by straight approach and receiving channels in a symmetrical (Y-shaped) or asymmetrical (y-shaped) planform. However, natural rivers often meander and tributaries can enter meandering rivers on the outside of bends to form a junction planform known as a confluent meander bend.

The development of confluent meander bends was first described over a century ago (Callaway, 1902; Davis, 1903), but these fluvial features have received little modern scientific attention. Reference to confluent meander bends has been limited to field observations of channel curvature at confluences and identification of this planform during studies of tributary development along meandering rivers (Flint, 1980; Hills, 1983; Abrahams, 1984a,b). The findings of much of this research suggest that confluent meander bends may be a regular confluence planform, especially in meandering river systems, and may represent a quasi-stable channel configuration (Parker, 1996). Recent work based on laboratory experiments and numerical modeling of a 90°, fixed-boundary confluent meander bend has been the only process-based investigation of confluent meander bends to date and provides critical information on the complexities of its three-dimensional (3-D) flow structure (Roberts, 2004). The large junction angle of the confluent meander bend produces similar hydrodynamic zones to those found at asymmetrical confluences, but the presence of curvature in the main channel upstream of the junction imparts secondary circulation and generates a strong lateral pressure gradient that results in deviations in the spatial extent and position of some of these features compared to patterns at other types of confluence planforms.

The control-feedback relationship between flow dynamics and bed morphology produce complex fluvial conditions at both confluences and meander bends. While previous experimental
and numerical work has begun to reveal flow dynamics at confluent meander bends (Roberts, 2004), there has yet to be a field-based approach of investigation at these junctions. A need exists for field data to evaluate flow dynamics in channels with erodible boundaries where sediment transport occurs and to identify the morphologic features of the bed.

1.2 Research objectives

The primary goal of this research is to advance understanding of 3-D flow structure and channel morphology at natural confluent meander bends. This focus reflects the intrinsic connection between flow structure, which controls patterns of local shear stress and sediment transport that shape the banks and bed, and channel morphology, which influences fluid motion and sediment transport. The complexities of the relationship between flow structure and channel form have not been studied at confluent meander bends. The research is guided by the following objectives:

1) obtain field data on 3-D flow structure at a $90^\circ$ confluent meander bend with erodible channel boundaries for different $M_r$ to evaluate the findings of previous experimental and numerical research,

2) ascertain patterns of bed morphology at natural confluent meander bends, as the design of previous modeling work used fixed boundaries with rectangular channel cross sections, and document the effect of variation in $M_r$ on the configuration of the bed,

3) examine the influence of variation in planform geometric characteristics, such as differences in junction angle and the location of tributary entry around bends, on 3-D flow structure and bed morphology,
4) determine if hydro- and morphodynamic features at confluent meander bends translate across spatial scales,

5) compare repeat aerial photographs to determine if the meander bends at each site are migrating over time or if the confluent channels remain relatively stable, and

6) integrate collected field data with results from laboratory experiments and numerical modeling to develop a conceptual model of confluent meander bend dynamics.

Completion of these objectives will contribute to fluvial geomorphology by advancing knowledge of flow structure and bed morphology at a seemingly common, yet largely overlooked type of confluence planform in meandering river systems. This research fulfills a critical need for field studies not only to supplement existing experimental and numerical models of confluent meander bends, but to identify how patterns of 3-D flow structure and bed morphology at these distinctive fluvial features differ from patterns observed at junctions formed by straight channels and meander bends without inflowing tributaries.

1.3 Research organization

Confluent meander bends have been shown to generate complex patterns of fluid motion (Roberts, 2004), as flow through this type of confluence planform is influenced by both the convergence of two streams at a junction and curvature induced by a meander bend. Accordingly, Chapter 2 provides a brief review of research on flow structure and bed morphology at confluences and meander bends to facilitate conceptualization of confluent meander bend dynamics presented in Chapter 3 and expanded upon in Chapter 4. This overview is supplemented with a summary of the findings of the experimental and numerical research on confluent meander bends by Roberts (2004).
The next two chapters, Chapters 3 and 4, contain the results of rigorous process-based field investigations at three confluent meander bends within the Wabash River drainage basin. These studies advance understanding of confluent meander bend hydro- and morphodynamics by providing a field component to existing research that examines the relationship between flow patterns and erodible channel boundaries for different hydrological conditions and geometric properties. Both chapters were prepared as manuscripts to be submitted to peer-reviewed journals for publication.

Chapter 3 presents a conceptual framework of flow structure at confluent meander bends from which to evaluate results from the first field study of these fluvial features. The chapter then focuses on identifying the 3-D flow structure and morphological features of the bed at a small, natural confluent meander bend with a 90° junction angle. Field measurements of 3-D velocity components and bed topography reveal a complex hydrodynamic environment that responds to changes in $M_r$, while channel morphology remains relatively stable. The results of this study indicate that an inflowing tributary near the apex of a bend affects patterns of flow and bed morphology in ways that are quite different from typical patterns in most meander bends. Tributary flow deflects high-velocity fluid and a helical cell inherited from upstream channel curvature in the main river toward the inside of the bend, inducing bed scour and inhibiting point bar development. A second counter-rotating helical cell develops as the tributary flow abruptly realigns to the orientation of the downstream channel, and combined with prevailing low $M_r$, protects the outer bank of the bend from erosion. This balance between erosional and depositional forces and the long-term planform stability of this confluent meander bend supports the concept that these features represent a quasi-stable channel configuration in meandering river systems (Parker, 1996). Overall, the observed patterns of fluid motion are generally consistent
with the conceptual model and the study provides the first insight into the spatial distribution of morphologic features at a confluent meander bend.

Chapter 4 expands upon the conceptual framework by integrating some of the findings from the field results described in Chapter 3 and including a bed morphology component to the model. The chapter continues by examining the control that the location and angle of tributary entry around bends have on 3-D flow structure and bed morphology for high and low $M_r$ at two large confluent meander bends with different junction angles. The results of the field study presented in Chapter 3 and modeling investigations of confluent meander bends have focused entirely on the fluvial dynamics of a straight tributary channel that enters a meandering river near the apex of a bend at a 90° junction angle (Roberts, 2004; Riley and Rhoads, 2012). The angle of tributary entry at junctions with asymmetrical and symmetrical planforms has been shown to largely control the degree of deflection between confluent flows and the spatial extent of confluence hydro- and morphodynamic features (Mosley, 1976; Best, 1987). The results are consistent with this assessment, as increased deflection at the high-angle junction leads to similar flow and morphologic structures identified at a small confluent meander bend in Chapter 3, whereas less pronounced flow deflection at the low junction angle confluent meander bend and prevailing low $M_r$ produce a relatively stable bed that lacks significant scouring that usually occurs at confluences with concordant beds. The results are also notable for documenting 1) the response of bed morphology at the high-angle junction to a large influx of sediment following the development of a meander cut-off upstream of the confluence during large, tributary-dominant discharge events (Zinger et al., 2011) and 2) the development of large-scale helical motion at two large river confluences.
Chapter 5 provides a summary of the findings of this research and proposes future work. The significance of this research to 1) evaluating laboratory and numerical simulations from field results, 2) identifying the response of flow structure and bed morphology to differences in hydrological and geometric control factors, and 3) the development of a conceptual model of confluent meander bend dynamics, are reviewed. Limitations of these field studies and possible directions for further research are discussed.
CHAPTER 2. A CONCEPTUAL FRAMEWORK FOR NATURAL CONFLUENT MEANDER BENDS – FLOW DYNAMICS AND BED MORPHOLOGY AT RIVER CONFLUENCES AND MEANDER BENDS

2.1 Introduction

Although confluent meander bends appear to be a common type of junction configuration found in many meandering river systems (Callaway, 1902; Davis, 1903; Flint, 1980; Hills, 1983; Abrahams, 1984a,b), the mechanics of flow and patterns of bed morphology in these fluvial features have not been investigated extensively. Recent experimental and modeling research of flow dynamics is the only process-based work on confluent meander bends to date (Roberts, 2004). However, the body of literature on flow structure and bed morphology at meander bends and confluences with asymmetrical and symmetrical planforms is substantial. The purpose of this chapter is to provide an overview of this literature to facilitate the development of a conceptual model of confluent meander bend dynamics and provide context for the field research presented in Chapters 3 and 4.

2.2 Controlling factors at confluences: planform geometry, junction angle, and momentum flux ratio

A growing body of research focused on confluence dynamics has revealed the complexity of flow structure at laboratory junctions (Mosley, 1976; Ashmore and Parker, 1983; Best and Reid, 1984; Best, 1987, 1988; Best and Roy, 1991; Biron et al., 1996a,b; McLelland et al., 1996), small natural confluences (Roy and Bergeron, 1990; Ashmore et al., 1992; Biron et al., 1993a; McLelland et al., 1996; Rhoads, 1996; Rhoads and Kenworthy, 1995, 1998, 1999; DeSerres et al., 1999; Rhoads and Sukhodolov, 2001, 2004; Sukhodolov and Rhoads, 2001), and through numerical simulations (Weerakoon and Tamai, 1989; Bradbrook et al., 1998, 2000, 2001). The
findings of these studies have identified a sequence of distinct hydrodynamic zones that are the basis for conceptual models of flow structure through confluences (Figure 2.1A). As channels converge at junctions, incoming flows initially meet and deflect one another along a mixing interface. Stagnant or low velocity fluid envelops the junction apex and a zone of lateral flow separation from the banks of the downstream junction corner(s) may develop. The combined flows accelerate through the turbulent central region of the confluence before recovering further downstream in the receiving channel. The spatial properties of these zones are largely controlled by geometric and hydrological relationships between the confluent flows (Mosley, 1976; Best and Reid, 1984; Best, 1987), including 1) confluence planform geometry, which consists of the spatial configuration of the approach channels with the receiving channel and the geometric angle between the approach channels as they converge, or junction angle, and 2) the momentum flux ratio ($M_r$) between the incoming flows, defined as:

$$M_r = \frac{\rho Q_2 V_2}{\rho Q_1 V_1}$$

(1)

where $\rho$ is water density (kg m$^{-3}$), $Q$ is discharge (m$^3$ s$^{-1}$), $U$ is cross-sectional mean velocity (m s$^{-1}$), and the subscripts 1 and 2 refer to the main river and tributary respectively. Other variables that may exert control over confluence flow structure include 3) the extent of bed elevation difference, or discordance, between the confluent channels upon entering the junction (Biron et al., 1993a; Biron et al., 1996a,b; DeSerres et al., 1999; Boyer et al., 2006), 4) feedback mechanisms of bed morphology on fluid motion (Best, 1987, 1988; Best and Roy, 1991; Biron et al., 1993b; Rhoads and Kenworthy, 1995), and 5) density differences between converging flows, especially at the junction of large rivers (Parsons et al., 2008). Variation in these factors can effect major changes in flow structure and bed morphology at confluences.
Figure 2.1. Flow structure (A) and channel morphology (B) at an asymmetrical confluence. Blue arrows depict flow direction, dashed black line represents the mixing interface, and white dashed lines denote extent of stagnation and separation zones.
Most confluence research has focused on assessing the effects of variation in junction angle and $M_r$ on hydro- and morphodynamics at either asymmetrical or symmetrical junction planforms with straight approach and receiving channels. Planform symmetry and junction angle dictate the geometric relationship between the approach channels, thereby directing the orientation of the converging flows and imposing physical control on deflection of these flows within the confluence. At asymmetrical confluences (Y-shaped), flow from the lateral tributary is forced to turn rapidly to align with the orientation of the receiving channel. Penetration of tributary flow into the confluence is enhanced by increases in the junction angle or $M_r$, which deflects the mixing interface toward the outer bank and produces slight curvature of main river flow (Best, 1987; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads and Sukhodolov, 2001). As planform symmetry increases, the confluence becomes more Y-shaped and both incoming flows must curve to align with the downstream channel. High junction angles intensify flow deflection and the position of the mixing interface shifts away from the incoming flow with the greatest momentum flux (Mosley, 1976; Best, 1986; Bradbrook et al., 2000).

Opposing patterns of streamline curvature generated as the tributary and main river converge and mutually deflect one another through the central region of confluences with concordant beds subject water from the incoming flows to a centrifugal acceleration. At symmetrical junctions, water surface superelevation occurs along the mixing interface, where the convergence of near-surface flow increases fluid pressure and induces a transverse pressure-gradient force resulting in divergence of near-bed flow toward the comparatively low pressure zones near the banks of the receiving channel. The imbalance between these forces over depth within the center and downstream channel of the confluence initiates secondary circulation on either side of the mixing interface (Mosley, 1976; Best, 1986; Ashmore et al., 1992). When $M_r \approx 1$, well-developed twin
counter-rotating helical cells flank the centrally positioned interface and occupy equal proportions of the channel cross-section, leading to the hypothetical analogy that helical motion at confluences resemble that of two meander bends placed back-to-back (Ashmore and Parker, 1983). Fluctuation of $M_r$ above and below one produces a dominant helical cell that occupies a greater portion of the flow width (Mosley, 1976; Ashmore et al., 1992).

Streamline curvature also occurs at asymmetrical confluences, especially within the tributary flow that must abruptly turn into the downstream channel, but spatial patterns of water surface topography and helicity differ from symmetrical junction planforms. Superelevation of the water surface progressively shifts from the center of the channel near the upstream junction corner toward the bank of the receiving channel that is opposite from the incoming flow with the greatest centrifugal acceleration (Bradbrook et al., 2000). For $M_r > 1$, strong penetration of tributary flow into the confluence forces the ridge of superelevated water toward the outer portion of the confluence and away from the downstream junction corner, where a zone of low pressure develops. The cross-stream pressure gradient induces the formation of a single, large helical cell that persists through the downstream channel (Rhoads and Kenworthy, 1995, 1998). Advection of downstream momentum from the high-velocity core of the tributary by this helical cell drives near-surface flow outward across the confluence and downward along the flanks of the mixing interface. Fluid from the main river is transported inward along the bed and upward near the inner bank by the rotational motion of the cell (Rhoads and Kenworthy, 1995).

For $M_r < 1$, penetration of tributary flow into the confluence is reduced and the position of the mixing interface shifts toward the center of the confluence. Two counter-rotating, surface-convergent helical cells emerge on opposite sides of the interface as the converging flows mutually deflect one another (Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads and
Sukhodolov, 2001). However, the extent of flow curvature is greater in the tributary than the main river, resulting in a stronger helical cell on the tributary side of the confluence than the adjacent cell associated with flow from the main river. This weaker cell over the outer portion of the confluence dissipates as the mixing interface shifts outward in the downstream channel. Thus the pattern of helicity evolves from dual helical cells within the confluence to a single cell in the downstream channel.

Deflection-induced streamline curvature is not the only means hypothesized to produce helical motion of flow at confluences. Changes in bed topography, especially at confluences with discordant beds (Best, 1987; Best and Roy, 1991; Biron et al., 1996a,b) or steep-sided central scour holes (McLelland et al., 1996), may generate helical motion as a result of an adverse pressure gradient induced by flow separation from the bed. Near-surface fluid downwells over a separation zone in the lee of the tributary-mouth step or avalanche face at the center of the confluence, and near-bed fluid upwells near the bank of the downstream channel, laterally distorting the mixing interface. Secondary circulation may be negligible at low-angle symmetrical junctions where flow deflection is limited by the nearly parallel arrangement of the converging flows (DeSerres et al., 1999), and has also been minimal or absent at some large river confluences (Parsons et al., 2007; Szupiany et al., 2007, 2009), perhaps due to increased distortion of channel shape or increased bed roughness.

The high-velocity cores of converging rivers are initially separated from each other by a zone of flow stagnation near the upstream junction corner at a confluence. The zone is characterized by low-velocity or recirculating fluid that develops as the rivers mutually deflect one another away from the junction apex and into the downstream channel (Best, 1987; Rhoads and Kenworthy, 1998). The size of the flow stagnation zone increases in response to enhanced flow
deflection and curvature toward the center of the confluence when the junction angle or $M_r$ increases. Convergence-induced distortion of the water surface near the upstream junction corner may generate a downstream gradient that accelerates flow through the junction (Bradbrook et al., 2000).

The mixing interface, positioned immediately downstream of the stagnation zone, is characterized by increased turbulence intensity generated by the lateral shear between the convergent flows and rotating vortices associated with the Kelvin-Helmholtz instability of flow within the shear layer (Best and Roy, 1991; Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2004; Constantinescu et al., 2011). At discordant confluences, progressive distortion of the shear layer in the downstream direction occurs due to lateral movement of fluid from the base of these initially vertical vortices toward the flow separation zone in the lee of the step at the mouth of the shallower tributary (Best and Roy, 1991). As a result, the vortices are stretched horizontally in the cross-stream direction and cause the shear layer to tilt (Biron et al., 1996a,b; DeSerres et al., 1999). Vortex decay and upwelling of fluid from the main river within flow from the tributary may enhance mixing (Best and Roy, 1991). The shear layer remains vertically aligned at concordant junctions where differences in bed elevations of the approach channels are negligible. Large-scale coherent turbulent structures within the shear layer are generated by transverse shear, whereas small-scale turbulence is related to bed friction (Sukhodolov and Rhoads, 2001). Recent work has shown that lateral fluxes of momentum related to mean flow convergence cause oscillations of the mixing interface, but expansion of turbulent vortices in the downstream direction is limited (Rhoads and Sukhodolov, 2004, 2008). The turbulence of the shear layer does not induce substantial mixing of the converging flows. Rather, the mixing interface, identified by contrasts in water temperature, conductivity, or
suspended load between the flows (Rhoads and Sukhodolov, 2008), may persist beyond the large-scale eddies of the shear layer within the center of the confluence and far into the downstream channel (MacKay, 1970). Alternatively, distortion of the mixing interface resulting from transverse advection associated with helical motion can increase rates of mixing within the confluence (Rhoads and Kenworthy, 1995, 1998; Rhoads and Sukhodolov, 2001).

Penetration of flow from the approach channels into the confluence, coupled with abrupt changes in channel geometry, can produce lateral flow separation from the bank of the receiving channel below the downstream junction corner(s). This zone of separated flow, characterized by low-velocity or recirculating fluid, expands at asymmetrical confluences when flow from the lateral tributary penetrates further into the confluence during high $M_r$ events or at confluences with large junction angles (Best and Reid, 1984; Best, 1987). At symmetrical confluences, increases in junction angle result in increased flow separation at both of the downstream junction corners (Best, 1986). While the separation zone has been documented at experimental confluences with angular junction corners (Best and Reid, 1984; Best, 1987) and at a natural asymmetrical confluence for $M_r > 1$ (Rhoads and Kenworthy, 1995; Rhoads, 1996), it oftentimes is not observed at natural confluences where rounded junction corners may preclude lateral flow separation from the channel bank (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Rhoads and Sukhodolov, 2001). Additionally, distortion of the shear layer at discordant confluences has been shown to disrupt the separation zone, especially in upwelling fluid near the bed (Biron et al., 1993a).

Advection of downstream momentum causes the high-velocity cores of the confluent rivers to migrate laterally toward the mixing interface and coalesce, resulting in flow acceleration through the central region of the confluence and into the downstream channel. Fluid velocity also
increases through the confluence to maintain continuity if channel width does not increase downstream of the tributary entrance. Constriction of the combining flows within the receiving channel due to the presence of a flow stagnation zone at the downstream junction corner (Best and Reid, 1984; Best, 1987) or deflection of flow due to the development of a lateral bar along the bank (Rhoads and Kenworthy, 1995) augments acceleration of the adjacent freestream through the confluence. This zone of maximum fluid velocity is followed by flow recovery downstream from the junction as turbulence subsides and the rivers eventually mix (Best, 1987).

Hydrodynamic features at confluences influence spatial patterns of shear stress, sediment transport, and channel morphology. In turn, morphodynamic features enact a feedback response on confluence flow structure by influencing the vertical and lateral interaction between the converging flows. A region of central bed scour, flanked by tributary-mouth bars that descend into the hole from one or both of the upstream channels (Figure 2.1B), is a prominent feature observed at many natural and experimental junctions with symmetrical and asymmetrical planforms (Mosley, 1976; Ashmore and Parker, 1983; Best, 1986, 1988; Bristow et al., 1993; Rhoads and Kenworthy, 1998; Rhoads and Sukhodolov, 2001; Parsons et al., 2007; Szupiany et al., 2007; Best and Rhoads, 2008). Flow convergence produces a complex hydrodynamic environment at the center of confluences where bed shear stresses may be enhanced by flow acceleration (Rhoads and Kenworthy, 1995), increased turbulence intensity within the shear layer (Best, 1987; Biron et al., 1993b; DeSerres et al., 1999, Rhoads and Sukhodolov, 2008), and the downward motion of fluid along the mixing interface associated with helical motion of the flow (Rhoads, 1996; Rhoads and Kenworthy, 1998). These fluvial processes, which are responsive to changes in $M_r$ and junction angle, affect sediment transport through the center of the confluence and control the depth and position of the scour hole (Best and Rhoads, 2008).
While the depth of the scour hole generally increases at confluences with large junction angles (Mosley, 1976; Best, 1988), spatial patterns of scour and fill through the central region of a junction differ between laboratory and field studies. Experimental modeling has shown that bed scour aligns with the tributary of dominant flow (Best, 1988), whereas the protrusion of a wedge of sediment into a natural asymmetrical confluence shifts the zone of scour away from the mouth of the dominant tributary (Rhoads et al., 2009). High $M_r$ conditions produce a narrow region of bed scour confined between the sediment wedge protruding from the mouth of the tributary and the outer bank, resulting in alignment of the scour hole with the upstream channel of the main river. Frequent flows with $M_r > 1$ have led to erosion of the outer bank and widening of the downstream channel at this location over the long term (Rhoads et al., 2009). The scour hole migrates to the center of the confluence when $M_r < 1$ and truncates the face of the downstream junction corner bar. Bed scour is not a ubiquitous geomorphic feature at all confluences. Scour can be shallow or absent from discordant junctions (Biron et al., 1993b) or confluences with low junction angles (Roy et al., 1988).

The bedloads of the converging flows are initially transported around the margins of the central scour hole at concordant confluences (Best, 1988; Rhoads, 1996; Rhoads et al., 2009). Segregation of the sediment loads is enhanced by increases in junction angle or $M_r$ at laboratory junctions (Best, 1988), but spatial patterns of surficial bed material at a natural asymmetrical junction indicate bedloads remain segregated through the confluence before mixing in the downstream channel for low $M_r$ due to the central position of the scour hole (Rhoads et al., 2009). For high $M_r$, migration of the zone of bed scour toward the outer bank enables the bedloads of the tributary channels to intersect through the center of the confluence and upstream portion of the receiving channel, producing a region of mixed surficial bed materials. Similar
patterns have been identified at a discordant confluence without appreciable bed scour for both high and low $M_r$, where bed material from the dominant tributary is deposited on the opposite bank of the downstream channel (Biron et al., 1993b). High sediment transport rates at the edges of the shear layer prompt mixing of sediment within the confluence (Boyer et al., 2006).

Deposition may occur adjacent to the scour hole in the flow separation zone below the downstream junction corner(s) of symmetrical and asymmetrical confluences and lead to the development of a bar. Enlargement of the separation zone due to greater penetration of tributary flow into the center of the confluence for increases in $M_r$ or junction angle promotes increased deposition and bar growth (Best, 1988). Bar development has also been attributed to net sediment flux convergence during high $M_r$ events in which bed shear stress decreases around the junction corner (Rhoads and Kenworthy, 1995; Rhoads, 1996). A second, smaller bar has been shown to develop in the lee of this main bar due to topographic steering of flow away from the junction corner (Rhoads and Kenworthy, 1995). For low $M_r$, realignment of the scour hole to the center of an asymmetrical confluence erodes the face of the junction-corner bar (Rhoads et al., 2009). Deposition may also occur in the middle of the downstream channel at symmetrical confluences, possibly due to convergence of sediment transport pathways (Best, 1988) or immobilization of bedload sheets (Ashmore, 1991).

The deflection and turning of tributary flow into the downstream channel at confluences can produce similar hydro- and morphodynamic features to those resulting from channel curvature at meander bends. Deflection-induced streamline curvature generates a transverse pressure gradient between the superelevated flow at the center of a confluence and the banks of the receiving channel. This gradient initiates secondary circulation at some confluences that is comparable to patterns of curving flow at meander bends (Bridge, 1993; Rhoads and Kenworthy, 1995),
especially when $M_r > 1$, although the intensity of rotation is reduced at confluences due to superelevation of flow within the fluid mixing interface as opposed to a solid bank (Weerakoon and Tamai, 1989). Advection of downstream momentum outward toward the center of the junction and downward toward the bed by helical motion is similar to patterns of momentum transfer at bends that submerge the high-velocity core over the outer portion of the channel cross section. Large bed shear stresses at both locations produce scour resulting in pool development and cut bank erosion at meander bends and a scour hole at many confluences. Sediment flux convergence related to patterns of decreasing bed shear stress within the flow separation zone below the downstream junction corner has been shown to lead to deposition of bedload at an asymmetrical confluence (Rhoads and Kenworthy, 1995; Rhoads, 1996), similar to the mode of point bar development at meander bends (Dietrich, 1987). These linkages underscore the significance of flow convergence and deflection at confluences in producing curvature-related flow and geomorphic features.

2.3 Curvature-induced patterns of secondary flow and bed morphology at meander bends

Flow dynamics at meander bends are largely controlled by curvature-induced centrifugal and pressure gradient forces that produce transverse variations in bed topography, which in turn have a feedback effect on fluid motion through the bend. Channel curvature initially subjects flow to a centrifugal acceleration that directs water from the inner bank at the entrance of a bend, across the channel at high velocity, toward the outer bank. The pressure gradient force generated by the superelevated water surface at the outer bank redirects flow toward the inner bank near the bed, where velocity and centrifugal effects are lowest (Dietrich, 1987). The local imbalance between centrifugal and pressure gradient forces over depth produces secondary currents that flow in
opposing directions over the channel cross section, resulting in outward movement of near surface flow and inward directed near bed flow. The mean three-dimensional (3-D) flow structure is thus characterized by helical motion through the bend (Rozovskii, 1957; Bathurst et al., 1977; Thorne and Hey, 1979; Thorne et al., 1985). Shoaling of flow over the face of the point bar adjacent to the inner bank of the bend confines helicity to the thalweg (Dietrich and Smith, 1983; Dietrich, 1987), where rotational motion redistributes momentum outward and downward, submerging the high-velocity core over the center and outer portion of the channel cross section below the bend apex (Ikeda et al., 1981; Frothingham and Rhoads, 2003). Inner-bank flow separation may further concentrate flow toward the outer bank and strengthen secondary circulation (Leeder and Bridges, 1975; Nanson, 2010; Blanckaert, 2011), especially at sharp meander bends where the ratio of channel width to the radius of curvature at the centerline is high (Leeder and Bridges, 1975). A small counter-rotating helical cell may develop along the outer bank of the bend possibly due to boundary roughness or flow stagnation (Bathurst et al., 1979; Thorne and Hey, 1979; Thorne and Rais, 1984; Markham and Thorne, 1992), although the dynamics of this cell and its role in promoting bend stability have only recently been investigated (Blanckaert and de Vriend, 2004; Blanckaert, 2011).

Transverse variations in boundary shear stress and bedload transport parallel the cross-stream movement of high velocity flow and control spatial patterns of erosion and deposition through a bend. Curvature-induced acceleration of flow directs surface water toward the outer bank, leaving a zone of comparatively lower velocity along the inner bank. Shear stress on the bed decreases in this zone of shallow, low velocity flow, where sediment flux convergence prompts deposition (Nelson and Smith, 1989). Conversely, the location of the submerged high-velocity core and superelevation of the water surface along the opposite bank increases boundary shear
stress, causing sediment flux divergence and promoting bed scour and outer bank erosion (Dietrich, 1987; Nelson and Smith, 1989). The presence of an outer bank helical cell has been thought to decrease bank stability by advecting high-momentum fluid from the surface toward the bank toe (Bathurst et al., 1979), but recent laboratory experiments have shown that this cell protects the outer bank from the outward shifting of the high-velocity core arising from redistribution of momentum within the main helical cell (Blanckaert and Graf, 2004; Blanckaert, 2011). Sediment sorting patterns correspond to the transverse deviation in boundary shear stress. Large, coarse particles are distributed across the channel from the inner bank at the entrance of a bend downslope toward the outer bank, coinciding with the spatial pattern of maximum boundary shear stress (Bridge and Jarvis, 1982; Dietrich and Smith, 1984; Dietrich and Whiting, 1989). Near bed movement of fine material follows the distribution of minimum shear stress in the opposite direction across the bend, where net sediment flux convergence culminates in the development of a bar.

The resulting morphologic structure of meander bends consists of point bars and cut banks, coupled with alternating pool-riffle sequences (Figure 2.2). Point bars form along the convex inner bank of bends, which topographically steer flow laterally toward the outer portion of the channel cross section; thereby curving the plane of flow and confining helical motion to the thalweg (Dietrich and Smith, 1983; Dietrich, 1987). The convergence of high velocity flow around bends initiates erosion of the concave outer bank, or cut bank, and scouring of the bed produces a pool. Riffles, topographic high areas that extend diagonally across the stream, gradually emerge from pools as flow diverges in a widening of the channel at the inflections between bends. This sequence of geomorphic features through meander bends – pool, riffle and point bar – is referred to as a bar unit, a 3-D functional form that relates the pattern of bed shear
stress and sediment transport that shapes each of these features as a collective unit (Dietrich, 1987). The bar unit extends the length of an entire meander, from the narrow pool at the upstream end of the bar that widens and shoals downstream through the riffle, concluding at the oblique and shallow point bar. Upstream erosion of the bar unit at the pool and cut bank is compensated by deposition at its terminus, imparting downstream and lateral components to channel migration over time (Hooke, 1995). Thus, fluvial processes and forms are interrelated between bends and can evolve to produce compound bends (Hooke, 1995; Zolezzi and Seminara, 2001; Frothingham and Rhoads, 2003; Güneralp and Rhoads, 2010) and patterns of increasing planform migration complexity (Brice, 1974; Hooke and Harvey, 1983).
2.4 Initial modeling work at confluent meander bends

Many of the hydrodynamic features documented at river confluences have also been shown to occur in laboratory experiments and numerical simulations at a 90° confluent meander bend with rectangular, non-erodible channels (Roberts, 2004) (Figure 2.3). A flow stagnation zone surrounds the upstream junction corner and initially segregates the high-velocity cores of the converging streams upon entering the junction. The zone is enlarged by additional pressure exerted near the junction apex due to a transverse water surface gradient generated by curvature of flow through the meander bend of the main channel immediately upstream of the confluence. Downstream of the stagnation zone, a shear layer extends into the zone of mutual flow deflection, which is enhanced by the superelevated flow over the outer portion of the main stream and contributes to the rapid alignment of tributary flow to the orientation of the downstream channel. Flow deflection also redirects the high-velocity core of the main channel toward the inner bank of the bend. Lateral separation of flow from the bank at the angular downstream junction corner promotes acceleration by constricting flow through the receiving channel, although abrupt turning of tributary flow into the confluence and decreased areal capacity below the junction corner due to continued channel curvature suppress the size of the separation zone. Increased penetration of tributary flow into the confluence shifts the flow stagnation zone toward the main channel, displaces the shear layer toward the inner bank of the bend, and increases flow separation from the downstream junction corner (Figure 2.3B).

Roberts (2004) found that two helical cells develop on either side of the downstream channel, although the size and intensity of the cells depend largely on prevailing hydrological conditions. Helical motion along the inner bank is inherited from curvature of the main channel upstream of the confluence. This cell extends across most of the cross section of the downstream channel.
during flow conditions when the main river is dominant, which confines tributary flow to a narrow region near the outer bank and inhibits development of the flow separation zone (Figure 2.3A). However, patterns of secondary circulation are reversed within the cell compared to fluid

![Flow structure diagram](image)

Figure 2.3. Flow structure at a confluent meander bend for (A) $M_r < 1$ and (B) $M_r > 1$, based on the results of Roberts, 2004.
rotation at typical meander bends. A spatial lag in the response of cross-stream velocity to force imbalances at bend inflections arises from the physical design of the channel, which includes a 180° bend preceding the junction and a fixed channel cross section that collectively restrict the high-velocity core to the inner bank at bends. This design allows secondary flow from the previous bend to perpetuate downstream and impede the expected rotation of the inner bank helical cell at the junction. The presence of bed material and development of a point bar along the inner bank at natural meander bends have been shown to topographically steer flow laterally toward the center of the channel and confine helicity to the thalweg by increasing cross-sectional channel asymmetry (Dietrich and Smith, 1983; Dietrich, 1987). Thus, the presence of a point bar at natural confluent meander bends is likely to deflect the inner bank helical cell toward the mixing interface.

Helical motion over the outer portion of the downstream channel is the result of deflection-induced curvature of the tributary flow. The outer bank helical cell occupies a greater portion of the flow width in the downstream channel compared to the weak counter-rotating inner bank cell during tributary-dominant flow conditions and when discharge between the converging flows is comparable. Roberts (2004) attributed the prevalence of the outer bank helical cell to a strong transverse pressure gradient generated between the flow stagnation and separation zones that force tributary flow to curve into the downstream channel. Flow separation from the downstream junction corner increases as tributary flow penetrates further into the confluence and opposes the lateral shift of flow momentum from the main channel, which may limit bend migration by protecting the cut bank from erosion.

Little is known about how flow processes relate to the morphologic structure of confluent meander bends. Previous modeling work focused on fluid dynamics at confluent meander bends
with rectangular channels and fixed boundaries (Roberts, 2004). The development of a conceptual model in Chapter 3 draws upon documented patterns of flow through confluent meander bends (Roberts, 2004) and knowledge of hydro- and morphodynamics at both confluences and meander bends to provide a framework for field results.

2.5 Summary and components for a conceptual framework

Spatial patterns of flow at confluent meander bends produce a complex hydrodynamic environment (Roberts, 2004) that includes aspects of flow convergence between two streams at a junction and curvature induced by a meander bend. Channel curvature of the main river upstream of the confluence subjects flow to a centrifugal acceleration and induces a counterbalancing pressure-gradient force that generates secondary circulation. The high-velocity core and secondary flow imparted by the curving main river persists through the junction, but are deflected by tributary flow away from the outer bank. This inward displacement of high-velocity flow and helical motion deviates from typical patterns in meander bends without inflowing tributaries.

The remainder of confluent meander bend flow structure largely resembles that of an asymmetrical confluence. A zone of flow stagnation at the upstream junction corner segregates the high-velocity cores of the confluent streams before mutually deflecting one another along a mixing interface at the center of the junction. Tributary flow is abruptly turned into the downstream channel and streamline curvature induces the development of a second helical cell over the outer portion of the channel cross section. Increased penetration of tributary flow into the confluence shifts the mixing interface toward the inner bank and enhances a zone of flow
separation at the downstream junction corner. The high-velocity cores of the confluent flows coalesce and accelerate through the downstream channel.

The extent to which the findings of Roberts (2004) are applicable to natural confluent meander bends with erodible channel boundaries is unknown. Channel morphology at both meander bends and confluences has a significant influence on fluid motion through these features. Field data are needed to evaluate flow structure at natural confluent meander bends and establish how flow processes and channel morphology are related. The body of literature on meander bends and confluences and the important modeling work of Roberts (2004) provide the necessary background from which to derive a conceptual model of confluent meander bend dynamics – a model that can be used to evaluate the results of field investigations.
CHAPTER 3. FLOW STRUCTURE AND CHANNEL MORPHOLOGY AT A NATURAL CONFLUENT MEANDER BEND

3.1 Introduction

Meander bends and river confluences are fluvial features that have been the focus of a considerable amount of process-based research over the past thirty years. Work on meandering rivers has shown that channel curvature subjects flow through a bend to an outward-directed centrifugal force, resulting in superelevation of the water surface near the outer bank. Superelevation produces a counterbalancing, inward-directed pressure gradient force, but the local imbalance over depth between these two forces generates a secondary flow orthogonal to the primary flow direction (Prandtl, 1952; Rozovskii, 1957; Bathurst et al., 1977, 1979; Thorne and Hey, 1979; Thorne et al., 1985; Dietrich, 1987; Frothingham and Rhoads, 2003). As a result, the three-dimensional (3-D) structure of mean flow in meander bends is characterized by helical motion (Bathurst et al., 1979; Dietrich et al., 1979). Spatial variation in boundary shear stress and bedload transport corresponds to cross-stream movement of high velocity flow from the inner to outer bank around the bend. This pattern of spatial variation in shear stress and bedload transport produces erosion along the outer bank and deposition along the inner bank, especially downstream of the bend apex (Dietrich, 1987).

At stream confluences with concordant beds, mutual deflection of converging flows along a mixing interface generates transverse gradients of centrifugal and pressure-gradient forces resulting in curvature-induced helicity (Mosley, 1976; Ashmore and Parker, 1983; Best, 1987; Bridge, 1993; Rhoads and Kenworthy, 1995; Rhoads, 1996; Rhoads and Sukhodolov, 2001). Like in meander bends, downstream and cross-stream variations in bed shear stress and sediment-transport capacity produce zones of scour and deposition within confluences (Best,
1988; Rhoads and Kenworthy, 1995; Best and Rhoads, 2008; Rhoads et al., 2009). Major controls of flow structure and bed morphology at confluences include junction angle, the momentum-flux ratio of the confluent flows, and junction planform symmetry (Mosley, 1976; Best, 1987). Previous experimental and theoretical models of confluence dynamics have used straight approach channels and a straight receiving channel to investigate flow structure and bed morphology in relation to angular junction planforms (Mosley, 1976; Best and Reid, 1984; Best, 1986, 1987, 1988; Weerakoon and Tamai, 1989; Weerakoon et al., 1991; Biron et al., 1996a,b; Bradbrook et al., 2000, 2001). Most natural channels, however, curve and bend. Recent laboratory experiments and numerical modeling of confluent meander bends, a junction planform that develops when a tributary joins a meandering river along the outer bank of a bend, suggest that flow structure in such bends deviates from typical patterns in bends without inflowing tributaries (Roberts, 2004).

Although the dynamics of confluent meander bends have not been studied extensively, the occurrence of this type of fluvial feature has been documented in many meandering river systems (Callaway, 1902; Davis, 1903; Flint, 1980; Hills, 1983; Abrahams, 1984a,b). In early studies, Callaway (1902) and Davis (1903) hypothesized about the development and maintenance of confluent meander bends. Callaway (1902) proposed that the entrance of tributaries on the outer bank of meander bends is related to deposition of sediment on the bank of the main river across from the mouth of the tributary. This deposition causes the main channel to curve in the direction of the tributary and induces straight channels to bend. Davis (1903) challenged Callaway’s (1902) hypothesis and suggested that down-valley migration of bends along a meandering main channel can account for the preferential location of tributaries along the outer bank of meander bends. According to Davis (1903), tributaries joining a meandering main channel are captured by
the outer banks of migrating bends that curve toward the side of the valley where the tributary is located because the distance to such banks is shorter than the distance to the inner banks of bends that curve away from this side of the valley. Moreover, as a confluent meander bend migrates down valley and the tributary path length increases, the tributary is eventually captured by the outer bank of the next bend upstream that curves toward the same side of the valley as the tributary, forming another confluent meander bend. Investigations of tributary development and arrangement (Flint, 1980; Abrahams, 1984a,b) and inventories of the locations of tributary junction along bends of selected meandering rivers (Hills, 1983) noted the preferential entry of tributaries on the outside of meander bends. These studies and speculation that confluent meander bends may represent a quasi-stable channel configuration (Parker, 1996) have been the only scientific references to this confluence planform for over a century. A recent experimental study that examined 3-D flow structure at a 90° confluent meander bend with fixed boundaries represents the only process-based investigation of this type of fluvial feature (Roberts, 2004). Field studies are needed to determine whether flow patterns documented in the laboratory and numerical simulations occur in confluent meander bends with erodible boundaries and to ascertain how flow processes are related to channel morphology and the stability of this morphology.

This paper examines 3-D flow structure and channel morphology at a small natural confluent meander bend in southeastern Illinois, USA. A general conceptual model of the dynamics of confluent meander bends is proposed to provide a hypothetical framework against which to compare field results. The model is based on experimental and numerical research (Roberts, 2004) and on current understanding of meander bend and confluence dynamics. Flow structure at the confluent meander bend is derived from field measurements of 3-D velocity components and
compared between two hydrological events. Variation in channel morphology is also related to these and other selected events during a broad period of data collection. Morphologic adjustment of the channel is then compared to the long-term planform stability of the confluent meander bend.

3.2 Conceptual model of flow structure at confluent meander bends

Only one study, the experimental and modeling investigation by Roberts (2004), has focused in detail on the hydrodynamics of confluent meander bends. This work, along with previous research on confluences and meander bends, provides the basis for the development of a general conceptual model of flow structure through confluent meander bends. Past work on confluence flow structure has identified several distinct hydrodynamic zones, including: 1) flow stagnation near the upstream junction corner, 2) mutual deflection within the confluence, 3) a shear layer or mixing interface between the two confluent flows, 4) flow separation at the downstream junction corner(s), 5) flow acceleration adjacent to the flow-separation zone, and 6) flow recovery (Best, 1987) (Figure 3.1). Key factors controlling the locations and dimensions of these zones include confluence planform geometry, junction angle, momentum-flux ratio, and bed morphology. The momentum-flux ratio ($M_r$) is defined as:

$$M_r = \frac{\rho Q_2 u_2}{\rho Q_1 u_1}$$

where $\rho$ is water density (kg m$^{-3}$), $Q$ is discharge (m$^3$ s$^{-1}$), $U$ is the mean velocity in a cross section, and the subscripts 1 and 2 refer to the main stream and tributary, respectively. As $M_r$ and junction angle increase for an asymmetrical (Y-shaped) confluence, penetration of flow from the lateral tributary into the main channel increases, the size of the separation zone increases, the flow stagnation zone shifts into the main channel, and the shear layer moves away from the
mouth of the lateral tributary. At symmetrical confluences, increases in junction angle result in enlargement of the zone of flow stagnation and increased flow separation at the downstream junction corners, whereas differences between the momentum fluxes of the incoming streams lead to enhanced flow deflection by the dominant tributary.

The basic hydrodynamic zones at confluences can also be identified for confluent meander bends (Figure 3.1). A confluent meander bend essentially is analogous to an asymmetrical confluence with a lateral tributary that joins a curved channel. Flow stagnation occurs near the upstream corner at the tributary entrance and a shear layer extends from this corner into the zone of mutual deflection within the curving main channel (Roberts, 2004). Flow separation can develop near the downstream junction corner, resulting in acceleration of the adjacent freestream. The extent to which a separation zone constricts flow at natural confluent meander bends is uncertain; field studies at natural confluences suggest that downstream junction corners are often rounded rather than angular as in laboratory channels – limiting or preventing the development of flow separation (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992). Downstream, in the zone of recovery, hydraulic effects induced by the confluence diminish and flow structure increasingly reflects the influence of the curved channel planform. Increases in $M_r$ (or junction angle) force the shear layer toward the inner bank of the bend, shift the zone of flow stagnation toward the main channel, and enhance flow separation along the outer bank downstream from the tributary entrance (Roberts, 2004).

The angled convergence of two streams generally produces highly 3-D fluid motion at and downstream of the confluence. In particular, previous research on confluence hydrodynamics has focused extensively on helical motion that arises when converging flows mutually deflect one another along a mixing interface and abruptly align with the downstream channel (Mosley, 1976;
Figure 3.1. Conceptual model of flow structure at confluences with (A) symmetrical (after Mosley, 1976; Best, 1986), (B) asymmetrical (after Best, 1987), and (C) confluent meander bend (after Roberts, 2004) planforms for $M_r = 1$. Shaded areas denote zones of recirculating flow.

Ashmore and Parker, 1983; Best, 1987; Bridge, 1993; Rhoads and Kenworthy, 1995; Rhoads, 1996; Rhoads and Sukhodolov, 2001). Planform geometry and prevailing hydrological conditions control the extent of deflection and subsequent curvature-induced transverse imbalances between centrifugal and pressure-gradient forces. Dual surface-convergent counter-rotating helical flow cells have been observed at the entrance to the downstream channel of
concordant junctions with symmetrical planforms (Mosley, 1976; Ashmore, 1982; Ashmore and Parker, 1983; Best, 1986; Ashmore et al., 1992; Bridge and Gabel, 1992; Bradbrook et al., 2000) and at asymmetrical junctions when momentum between converging flows is comparable (Best, 1986; Weerakoon et al., 1991; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Bradbrook et al., 2000; Rhoads and Sukhodolov, 2001) (Figure 3.1), leading to a hypothetical analogy that flow at confluences is similar to two meander bends placed back-to-back (Ashmore and Parker, 1983). Helical cells contribute to the segregation of sediment loads and bed scour by transporting sediment laterally away from the center of confluences (Mosley, 1976; Rhoads, 1996).

Laboratory experiments and numerical modeling of confluent meander bends have shown that twin helical cells can also develop on either side of the downstream channel (Roberts, 2004) (Figure 3.1). Like junctions with straight approach channels, helical motion over the outer portion of the downstream channel is the result of deflection-induced curvature of the tributary flow. Strong lateral pressure gradients develop across the tributary between the stagnation zone at the upstream junction corner and the zone of flow separation at the downstream junction corner, leading to abrupt turning of the tributary flow and the development of helical motion. A counter-rotating helical cell may develop on the opposite side of the mixing interface, especially when $M_r > 1$ and curving flow in the main channel is deflected strongly toward the inner bank. In the experiments of Roberts (2004), a weak counter-rotating cell was identified near the inner bank for runs with $M_r > 1$ and $M_r \approx 1$. For $M_r < 1$, the cell in the main channel occupied much of the cross section and exhibited rotation opposite from that expected in a natural meander bend. This pattern of secondary flow reflects the spatial lag between channel curvature and flow curvature arising from the physical design of the experimental channel, which had a rectangular cross section and included a 180° bend upstream from the confluent meander bend. Together
these channel characteristics resulted in the core of high downstream velocity remaining along the inner bank within the confluent meander bend, rather than crossing over to the outer bank. Moreover, secondary flow from the upstream bend extended downstream along the inner bank of the confluent meander bend. In natural meander bends, the presence of the point bar induces an abrupt shift of the core of high velocity toward the outer bank immediately downstream of the bend apex and restricts helical motion to the outer part of the channel cross section (Dietrich and Smith, 1983; Dietrich, 1987). Whether or not the point bar strongly influences patterns of flow at natural confluent meander bends has yet to be determined. Moreover, no studies, thus far, have focused on how flow patterns at confluent meander bends influence bed morphology.

3.3 Field site

The study site is the junction of the Little Wabash River (LWR) and Big Muddy Creek (BMC), located 70 km southeast of the city of Effingham, in southeastern Illinois (Figure 3.2). The confluence is situated within the gently rolling, low-relief Mt. Vernon Hill Country physiographic region, although much of the upstream watershed drains comparatively flat glacial till of the Springfield Plain (Leighton et al., 1948). Land cover consists mainly of cultivated uplands and wooded lowlands. Four small reservoirs are located in the headwaters of the watershed, but have little to no effect on the hydrological responses of the Little Wabash River and Big Muddy Creek at the confluence.

Big Muddy Creek enters the Little Wabash River near a local maximum of channel curvature on the upstream lobe of an elongated meander loop to form a confluent meander bend. Because the drainage areas of the confluent streams are not equal (BMC = 820 km²; LWR = 2,109 km²), the magnitudes of peak flows typically differ and the timing of peak flows is asynchronous. The
Figure 3.2. Location map of field site, orthophotograph taken on March 29, 2005, and map showing measurement cross sections.
streams meet at a junction angle of approximately 90°. Channel width of the Little Wabash River increases from 20 m in the curving upstream channel to 25 m at and immediately downstream of the junction before decreasing to 20 m farther downstream. Big Muddy Creek is 15 m wide upstream of the junction and broadens to 20 m at the entrance to the confluence. Bankfull channel depths generally range between 3 m to 4 m and increase to as much as 6 m in a region of central bed scour. Average channel gradients upstream of the confluence are 0.0002 for the Little Wabash River and 0.0007 for Big Muddy Creek. Bed material at the site consists primarily of fine sand with mud-draped channel banks.

3.4 Field data collection and analysis

Field measurements of 3-D velocity components and bed elevation were obtained on four dates between June 2007 and June 2008 with an acoustic Doppler current profiler (ADCP). A growing body of research has used ADCPs with moving-boat deployments to investigate 3-D characteristics of flow in rivers (Richardson and Thorne 1998; McLelland et al., 1999; Muste et al., 2004; Dinehart and Burau, 2005a,b; Parsons et al., 2005; Parsons et al., 2007; Szupiany et al., 2007). In this study, a 1200 kHz Workhorse Rio Grande ADCP manufactured by Teledyne RD Instruments (TRDI) was deployed along channel cross sections using a tethered boat to collect downstream, cross-stream, and vertical velocities and bottom depth. The broadband ADCP transmits acoustic pulses at a constant frequency along divergent beams from 4 transducers that are separated 90° azimuthally and oriented 20° from the vertical axis of the unit. The Doppler shift between the transmitted frequency and backscatter from suspended particles in the water column and from the stream bed is used to resolve the magnitude and orientations of velocity vectors, and the water depth.
ADCP operating parameters were configured similarly for each survey and data acquisition was monitored in real-time from an on-bank field computer running TRDI WinRiver software. The ADCP sampled 0.1 m bins throughout the water column (an ensemble of bins) at approximately 1 s intervals as the tethered boat was pulled steadily across the cross section by operators on opposing banks. The transducers were pointed downward 0.091 m below the water surface. The blanking distance immediately beneath the transducer, a zone of unmeasurable flow, was about 0.25 m. Also, velocity measurements from the bottom 6% of the measured water depth, where acoustic noise is high, were also eliminated (TRDI, 2007). Dense tree cover at the site prevented the use of an integrated global positioning system (GPS) to reference velocities collected by the moving sensor to an absolute geographic coordinate system. Instead, measured velocities were corrected for relative motion of the ADCP by referencing these velocities to bottom tracking. Such an approach is reasonable if the bed is not highly mobile at the time of measurements. Calibration studies conducted by holding the ADCP stationary at one position in the flow for a prolonged period of time showed no systematic trend in bottom tracking that would be suggestive of bed movement, indicating that velocities corrected using bottom tracking are not biased by motion of the channel bed. The orientation of the ADCP was measured with a built-in compass. Pitch and roll sensors also corrected for tilt and sway of the ADCP.

The small size of the confluence required deploying the ADCP on a tethered boat (Figure 3.3). The ADCP was housed in the center hull of a 1.2 m-long polyethylene trimaran equipped with a battery, wireless transceiver, and antennae to transfer data to the field computer. The boat was pulled across the channel by persons on opposite banks at cross-section endpoints, each holding a tether attached to the boat (Figure 3.3). Data were collected for multiple crossings, or transects, of each cross section and were spatially averaged during post-processing. Previous
studies of ADCP survey methods have found that averaging multiple transects at a cross section is necessary to obtain accurate representations of the time-averaged flow field, mitigate boat oscillations and random errors, minimize turbulent fluctuations in streamwise velocities, and resolve details of secondary flow cells (Lipscomb, 1995; Dinehart and Burau, 2005a; Szupiany et al., 2007). Measurements were repeated for five transects at each cross section in the field. Boat navigation was referenced to a local Cartesian coordinate system established at the site. The local coordinates of each measured ensemble were subsequently transformed to a geographic coordinate system during post-processing based on a few accurate GPS coordinates obtained at the site.

Several cross sections, positioned approximately 10 m apart at locations within and immediately upstream and downstream of the junction, were established at the site for the purpose of collecting data on flow structure and bathymetry (Figure 3.2). Cross-sections A-K and L-M are aligned approximately orthogonal to the orientation of the local channel centerlines of the Little Wabash River and Big Muddy Creek, respectively. The arrangement of cross sections through the confluence was designed to characterize flow structure inherited from the
curving main channel upstream of the junction (cross-sections A-D), flow structure imparted by the tributary (cross-sections L-M), and flow structure immediately downstream from the confluence (cross-sections E-K). Big Muddy Creek enters the Little Wabash River at cross-sections G and H, preventing the establishment of cross-section endpoints on the channel banks. Instead, the endpoints were marked on a taught rope spanning the mouth of Big Muddy Creek and measurements were obtained by personnel in a jon boat anchored at these endpoints. Hydrologic conditions at the site were remotely monitored from a real-time United States Geological Survey (USGS) stream gage located 500 m downstream of the junction. Measurements of water velocity and depth were obtained for hydrological events with different momentum-flux ratios to document the response of confluence flow structure and bed morphology to hydrological variability. ADCP measurements of discharge and mean velocity at cross-sections D and M were used to calculate the momentum-flux ratio for each survey.

Post-processing of ADCP data was performed with a series of algorithms in the Velocity Mapping Toolbox (VMT), a MATLAB-based application (Parsons et al., 2013). VMT was used to composite ADCP measurements for repeat transects into a single spatially and temporally averaged set of velocity data for the cross section. Time-averaged values of downstream ($U$), cross-stream ($V$), and vertical ($W$) velocity were calculated for each bin relative to the orientation of the cross section. VMT also uses the Rozovskii (1957) method to rotate the velocity vectors in all bins for each interpolated ensemble to the orientation of the depth-averaged vector, with secondary velocities ($V_s$) represented by the component orthogonal to this rotation. This approach has been shown to be particularly effective for analyzing secondary circulation and detecting helical motion at confluences (Rhoads and Kenworthy, 1998).
A detailed topographic survey of the confluence was conducted on 3 October 2006 using an electronic total station. Hundreds of points were surveyed with an error in horizontal position of less than 2 cm. Thereafter, bottom depth was measured simultaneously with 3-D velocities at channel cross sections with the ADCP. The depth and location where each beam of the ADCP reflects from the bed were corrected for the heading, pitch, and roll of the tethered boat. Depths obtained from individual beams and from the weighted average of the four beams were converted to bed elevations using measurements of water-surface elevations. Cross-section plots of the bed profile were generated for each averaged cross section using VMT. Topographic maps of the site were interpolated from bed elevations detected by individual beams of the ADCP via ordinary kriging using ESRI ArcGIS 9.3 software. The cross-section plots and topographic maps provide the basis for evaluating morphological change at the confluence between survey dates.

3.5 Results

3.5.1 Hydrologic conditions and hydraulic characteristics

The record of mean daily discharge from a USGS gage just downstream of the confluence provides hydrologic context for measurements of 3-D velocities and bed elevation (Figure 3.4). Snowmelt and heavy regional rainfall produced several high flows and widespread flooding in the vicinity of the confluence during the winter and spring of 2008. Data were collected on January 15, May 20, and June 16, 2008, during the receding stages of events in which peak flow had been out of bank. Data were also collected on June 28 during one of the few large discharge events of the comparatively dry summer of 2007.

Momentum-flux ratios less than one \( (M_r < 1) \) prevailed on each measurement date (Table 3.1). Because Big Muddy Creek has a smaller drainage area than the Little Wabash River, its
Figure 3.4. Mean daily discharge at USGS gage located downstream of confluence between June 2007 and August 2008. Dashed lines denote survey dates.

The hydrologic response is much faster, but usually smaller in magnitude, than the response of the Little Wabash River. Previous studies have documented a broad range of momentum-flux ratios at confluences with concordant and discordant beds, including flows with $M_r > 1$ (Biron et al., 1993b; Rhoads and Kenworthy, 1995, 1998; DeSerres et al., 1999), but flows with $M_r > 1$ are short-lived and difficult to capture for measurement at this junction. Considerable variation in momentum-flux ratios occurs among the set of measurements, including two flows with $M_r > 0.5$ and two with $M_r < 0.5$. The momentum-flux ratio approached one on June 16, 2008 – the only

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<tr>
<td></td>
<td>LWR</td>
<td>BMC</td>
<td>BMC/LWR</td>
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<tr>
<td>$Q$</td>
<td>13.71</td>
<td>5.62</td>
<td>0.41</td>
<td>10.27</td>
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<td></td>
<td>23.22</td>
<td>18.49</td>
<td>0.80</td>
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<td>$V$</td>
<td>0.33</td>
<td>0.22</td>
<td>0.67</td>
<td>0.29</td>
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<td></td>
<td>0.28</td>
<td>0.29</td>
<td>1.04</td>
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<tr>
<td>$M$</td>
<td>4524</td>
<td>1236</td>
<td>0.27</td>
<td>2978</td>
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<td>6502</td>
<td>5362</td>
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$Q$ = discharge (m$^3$ s$^{-1}$), $V$ = mean cross-sectional velocity (m s$^{-1}$), $M$ = momentum flux (kg m s$^{-2}$)
date when mean cross-sectional velocity was greatest in the tributary channel. Flow stage on this
date dropped by 45 cm during 7.5 hours of data collection. In contrast, the flow on January 15,
2008 had a lower discharge and lower momentum-flux ratio \( (M_r < 0.5) \) than the flow in June, and
the stage decreased by only 9 cm over 5 hours. Data collected on these two dates are
representative of the typical range of flow conditions at the junction and provide a framework for
evaluating the response of 3-D flow structure to variation in momentum-flux ratio.

3.5.2 Channel morphology

Morphological features are similar on all measurement dates and consist of a large scour hole
located between the center of the confluence and the inner (south) bank that extends into the
downstream channel and a bar below the downstream junction corner along the outer (north)
bank of the bend (Figure 3.5). On October 3, 2006 and June 28, 2007, the head of the scour hole
was oriented toward the tributary and a small secondary hole near the junction apex.
Downstream, the elongated scour hole turned into the confluence and stretched far into the
downstream channel. Cross-section profiles are generally symmetrical upstream and downstream
of the junction, but the location of maximum scour on the Little Wabash River side of the
channel (Figure 3.6) and the presence of a bar at the downstream junction corner (Figure 3.7)
results in asymmetry through the center of the confluence and upstream end of the downstream
channel. An accumulation of large woody debris was also present against the outer (north) face
of the scour hole (Figure 3.6, cross-section E) and extended into a zone of flow stagnation near
the upstream junction corner.

A series of events exceeding bankfull discharge during the winter and spring 2008 slightly
altered the bed morphology. The scour hole deepened by 0.25 m and the upstream axis of the
Figure 3.5. Bed topography on (A) October 3, 2006; (B) June 28, 2007; (C) January 15, 2008; (D) May 20, 2008; (E) June 16, 2008. (D) and (E) on following page.
Figure 3.5. (continued).
Figure 3.6. Channel cross-section profiles. Outer (north) bank is right, inner (south) bank is left; except cross-section M where outer (west) bank is left, inner (east) bank is right.
hole shifted progressively away from the tributary to align with the upstream junction corner over the course of the field campaign (Figure 3.5). Scouring along the inner (south) bank toe increased channel asymmetry at the entrance to the downstream channel (Figure 3.6, cross-section G). Upper bank erosion above the water surface was also visible along the inner bank of the Little Wabash River, across the channel from the mouth of the tributary (Figure 3.7). On the north side of the confluence, sediment was excavated near the mouth of Big Muddy Creek between January 15 and May 20, 2008, which increased channel depth by up to 1 m (Figure 3.6, cross-section F). Aggradation indicative of bar-building occurred further downstream below the downstream junction corner (Figure 3.6, cross-section I).

![Image](image.png)

Figure 3.7. (A) Bar at the downstream junction corner (outer bank) and (B) upper bank erosion along the inner bank of the Little Wabash River.

3.5.3 Depth-averaged velocity

Spatial patterns of depth-averaged velocity vectors converge near the center of the junction on both dates, initiating flow deflection that largely dictates flow structure through the confluent meander bend (Figure 3.8). As flow enters the confluence from the Little Wabash River (cross-section D), the largest vectors are positioned near the inner (south) bank of the bend and follow the curved channel planform, while vectors along the outer (north) bank are much smaller or
Figure 3.8. Depth-averaged velocity vectors on (A) January 15 and (B) June 16, 2008.
negative. High velocity flow in Big Muddy Creek is directed toward the center and downstream end of the confluence (cross-section M). As the streams converge and mutually deflect one another along a centrally located mixing interface, defined by a central region of diminished vectors on January 15 and by a strong transverse gradient in vector magnitudes on June 16, flow from the Little Wabash River is confined toward the inner (south) bank and vectors in Big Muddy Creek are forced to turn and align rapidly with the downstream channel (cross-sections E, F, and G). Flow deflection also leads to the development of a zone of stagnation surrounding the junction apex, illustrated by small or negative velocity magnitudes near the upstream junction corner (cross-sections D and M). Convergence is most pronounced within the confluence (cross-sections E and F), but is still evident at the entrance of the downstream channel (cross-section G). By cross-section I, velocity vectors are completely aligned with the downstream channel and the highest velocities are located near the center and outer (north) half of the channel. Flow separation is not apparent at the downstream junction corner, but small and negative vectors are present along the inner (south) bank (cross-sections F-J).

The effects of variation in momentum-flux ratio are reflected in differences in the position of the mixing interface and flow stagnation zone between measurement dates. During low momentum-flux ratio conditions on January 15 ($M_r < 0.5$), dominant flow from the Little Wabash River penetrates the center of the junction and deflects the mixing interface toward the tributary side of the channel (cross-section F). Flow from Big Muddy Creek is confined between the mixing interface and the outer (north) bank of the meander bend upon entering the confluence. Conversely, deflection of the Little Wabash River is comparatively weak, but main channel flow decelerates through the confluence and the tributary flow penetrates enough to confine the largest velocity vectors to the inner (south) portion of the channel. A large zone of
flow stagnation develops near the junction apex and extends across approximately one-third of the flow width (cross-sections D and M).

A momentum-flux ratio approaching one on June 16 ($M_r \approx 1$) results in the inward migration of the mixing interface to the center of the junction. Big Muddy Creek occupies the outer (north) half of the channel and deflection of the Little Wabash River is most pronounced on this date (cross-section F). Velocity vectors at the mouth of the tributary exhibit a greater degree of curvature oriented toward the downstream channel when compared to January 15 (cross-section M). Flow stagnation at the upstream junction corner extends upstream of the confluence along the outer (north) bank of the Little Wabash River (cross-sections C and D), but is much less prominent in Big Muddy Creek (cross-section M).

3.5.4 Downstream and cross-stream velocity

The most prominent feature of the downstream velocity field ($U$) on each date is a core of high velocity along the inner bank of the confluent meander bend. This core represents flow from the Little Wabash River that is confined between the center of the channel and the inner (south) bank (Figure 3.9, cross-sections D, E, and F). A zone of low velocity representing flow stagnation occurs along the outer (north) bank immediately upstream of the junction (cross-section D). This zone wraps around the junction apex along the outer (west) bank of the tributary when $M_r < 0.5$ (January 15), and restricts the comparatively small high-velocity core of Big Muddy Creek to the center and inner (east) portions of the channel (cross-section M). When $M_r \approx 1$ (June 16), increased penetration of tributary flow into the confluence diminishes flow stagnation at the outer bank and high velocities extend across most of the incoming flow from Big Muddy Creek (cross-section M).
Figure 3.9. Downstream velocities with cross-stream/vertical velocity vectors on (A) January 15 and (B) June 16, 2008. Looking upstream; outer (north) bank is right, inner (south) bank is left; except cross-section M where outer (west) bank is left, inner (east) bank is right.
Big Muddy Creek enters the Little Wabash River at approximately a right angle, such that the flow fields of the streams are oriented nearly perpendicular to one another as they abruptly converge at the center of the junction. Consequently, cross-sections E and F are nearly parallel to the mean flow direction of the tributary. Cross-stream/vertical ($V/W$) velocity vectors at the outer (north) portion of these cross-sections are oriented strongly inward on both measurement dates, reflecting strong penetration of flow from the tributary into the junction (Figure 3.9). Near the inner bank, the pattern of cross-stream/vertical vectors is more complex; magnitudes of these vectors decrease and near-surface vectors are oriented outward, whereas near-bed vectors are oriented inward, suggesting the development of helical motion of the flow (cross-sections E and F). The transition between inward oriented vectors over the outer portion of the flow and the more complex patterns over the inner portion of the flow marks the location of the mixing interface. This transition generally occurs at the outer margin of the core of high downstream velocity from the Little Wabash River. Vectors at this location also develop a net downward orientation, indicating a plunging aspect to the flow (cross-sections E and F). The position of the interface generally coincides with the outer (north) edge of a zone of central bed scour, but migrates approximately 2 m toward the inner (south) bank with greater tributary penetration into the confluence when $M_r \approx 1$ (June 16). Along the outer bank, downstream velocities increase through the junction as flow from Big Muddy Creek turns sharply around the downstream junction corner into the downstream channel.

Vectors in the cross-stream plane ($V_s/W$), defined by secondary velocities ($V_s$) computed from the Rozovskii (1957) method, illustrate clearly the patterns of secondary circulation in these converging flows. Two distinct counter-rotating, surface-convergent helical cells develop within the confluence and extend through the downstream channel on both dates. Upstream of the
junction, patterns of vectors for the Little Wabash River indicate that a helical cell with clockwise circulation has formed in the curving main channel (Figure 3.10, cross-section D). Within the confluence, this cell is confined to the inner portion of the channel cross section and its rotational motion intensifies, especially when $M_r < 0.5$ (cross-sections F and G). Advection of downstream momentum by this helical motion causes the high-velocity core to migrate laterally toward the center of the channel and extend downward into the scour hole (cross-sections F, G, and H on January 15). Similar patterns of downward transfer of downstream momentum by helical motion have been observed at an asymmetrical junction (Rhoads, 1996; Rhoads and

![Image](image)

Figure 3.10. Downstream velocities with Rozovskii secondary/vertical velocity vectors on (A) January 15 and (B) June 16, 2008. Looking upstream; outer (north) bank is right, inner (south) bank is left; except cross-section M where outer (west) bank is left, inner (east) bank is right. (B) on following page.
Figure 3.10. (continued).

Kenworthy, 1998). On the north side of the mixing interface, a second helical cell with counterclockwise rotation develops as Big Muddy Creek is deflected by the Little Wabash River and turned abruptly into the downstream channel.

Differences in the spatial extent of the helical cells through the downstream channel between measurement dates are attributable to the effects of momentum-flux ratio. The cell over the inner
portion of the confluence is noticeably larger for $M_r < 0.5$ (January 15) than for $M_r > 0.5$. For $M_r < 0.5$, the counter-rotating cell over the outer portion of the flow is poorly organized within the confluence (cross-sections F and G), but becomes more distinct downstream of the confluence (cross-section H). The opposing patterns of momentum advection of the twin surface-convergent helical cells lead to the development of a high-velocity core positioned over the outer portion of the channel cross section immediately downstream of the confluence (cross-section H). Further downstream (cross-section I), the counter-rotating cells are roughly equal in size, but have weakened, and flow has accelerated in response to a decrease in cross-sectional area of the channel.

For $M_r \approx 1$ (June 16), the strong penetration of the tributary flow and corresponding shift of the mixing interface toward the inner bank leads to a reduction in the size of the helical cell inherited from curving flow upstream in the Little Wabash River. Again, the counter-rotating helical cell over the outer portion of the channel within the rapidly curving flow from Big Muddy Creek is somewhat poorly organized initially, but flow clearly descends within the mixing interface, which is bounded by near-surface converging flow and near-bed diverging flow (cross-sections F and G). Further downstream (cross-section I), the helical cell over the outer portion of the channel is well-organized and extends over more than half of the channel cross section. The weak and less extensive helical cell on the Little Wabash River side of the downstream channel is displaced to the inner (south) bank. Shoaling of flow over the bar face along the outer bank at this location induces flow acceleration and the highest downstream velocities occur outward of the thalweg over this bar face. This marked acceleration clearly indicates that flow separation does not develop at the downstream junction corner. Patterns of secondary circulation begin to become disorganized at cross-section K and the downstream velocity field develops the
characteristic pattern of open-channel flow (high-velocity core in the center of the flow near the surface). Thus, the effects of the confluence on the flow are diminishing at this location.

3.6 Discussion

The results of this study indicate that patterns of 3-D flow structure at the confluence of the Little Wabash River and Big Muddy Creek generally conform to the conceptual model of flow through confluent meander bends (Figure 3.1), with some notable exceptions. The upstream junction corner of the field site is characterized by a broad zone of flow stagnation that segregates the high-velocity cores of the converging streams – a feature that routinely develops at this location at symmetrical and asymmetrical confluences (Best, 1987; Rhoads and Kenworthy, 1998; DeSerres et al., 1999; Rhoads and Sukhodolov, 2001) and at experimental confluent meander bends (Roberts, 2004). The field data suggest that the spatial extent of the zone is responsive to shifts in momentum-flux ratio, especially in the lateral tributary. For \( M_r < 0.5 \), the zone extends across a considerable portion of the mouth of the tributary, whereas for \( M_r \approx 1 \), stagnation diminishes and high velocities extend across most of the tributary channel. Flow stagnation is a consistent feature in the Little Wabash River that extends upstream of the confluence along the outer (north) bank, confining the high-velocity core to the inside of the meander bend immediately upstream of the confluence. This velocity distribution is similar to patterns observed in bends without inflowing tributaries, where the high-velocity core upstream of the bend apex often is located along the inner bank (Dietrich, 1987; Nelson and Smith, 1989; Daniels and Rhoads, 2003).

Entry of flow from Big Muddy Creek into the curving Little Wabash River at a high angle produces a highly complex hydrodynamic environment in the central region of the confluence.
The high angle of tributary entry deflects flow from the Little Wabash River toward the inner bank of the bend, even when $M_r < 0.5$ (Figure 3.9). As at high-angle asymmetrical confluences (Best, 1987; Rhoads and Sukhodolov, 2001), the amount of deflection is responsive to changes in $M_r$, which is reflected in the position of the mixing interface within the confluence. Increased penetration of tributary flow shifts the mixing interface toward the inner bank.

The 3-D velocity data confirm the development of coherent helical motion at this confluent meander bend. A clockwise-rotating helical cell is inherited from flow curvature in the Little Wabash River upstream of the junction and is deflected by tributary flow toward the inner (south) bank of the bend. Advection of momentum in this cell drives high velocity fluid outward toward the mixing interface near the center of the confluence and downward to a zone of underlying bed scour. A second helical cell with counterclockwise circulation emerges along the outer (north) bank where flow from Big Muddy Creek turns to align with the downstream channel. Both cells persist downstream, but the spatial extent of each cell is largely controlled by $M_r$. The development and evolution of twin surface-convergent helical cells at this confluent meander bend is comparable to patterns of helicity at high-angle symmetrical junctions (Mosley, 1976; Ashmore and Parker, 1983; Best, 1986; Ashmore et al., 1992; Bradbrook et al., 2000). Whereas helical motion is not a feature that arises at all confluences, such as junctions with discordant beds (Biron et al., 1993a, 1996b; DeSerres et al., 1999), the findings presented here support the assertion that flow curvature generates helical motion at confluences (Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads and Sukhodolov, 2001).

Flow acceleration through the downstream channel is associated with constriction of the combining flows by development of a lateral bar near the downstream-junction corner, a finding consistent with acceleration of flow through an asymmetrical confluence (Rhoads and
Kenworthy, 1995). As flow from the tributary moves over the bar along the outer bank of the channel downstream of the confluence, it is not deflected laterally toward the thalweg. Instead, flow accelerates to maintain continuity, and in so doing, precludes development of flow separation at the downstream junction corner. The absence of a separation zone is a significant deviation from the conceptual model (Figure 3.1) and findings of Roberts (2004), but is consistent with previous field studies at asymmetrical confluences in which flow separation did not occur (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Rhoads and Sukhodolov, 2001). The lack of pronounced flow separation at natural confluences has been attributed to rounded downstream junction corners compared to highly angular corners at experimental junctions (Rhoads and Sukhodolov, 2001).

This study is the first to provide insight into the configuration of bed morphology at a confluent meander bend. Whereas flows on all measurement dates were not effective at producing major changes in bed morphology, the hydrodynamics of these events are consistent with morphologic patterns. The close correspondence between patterns of fluid motion and bed morphology for the events measured in this study suggests that patterns during formative events may not differ fundamentally from those for the measured events. Bed scour in the central region of the confluence is generally located between the inner (south) bank of the bend and the mixing interface that overlies the outer (north) edge of the scour hole. Thus, the extent of the scour hole coincides with the position of the high-velocity core and the helical cell induced by curvature of the Little Wabash River. Advection of downstream momentum by helical motion drives high-velocity, near-surface fluid of the core outward across the channel and downward along the flanks of the mixing interface to the bed. The exact process that generates scour is unresolved, but high bed shear stresses in the region of scour likely are produced by acceleration of the flow.
(Rhoads and Kenworthy, 1995), the plunging effect of helical motion (Rhoads, 1996; Rhoads and Kenworthy, 1998), and turbulence within the well-defined shear layer (Best, 1987; Biron et al., 1993b; DeSerres et al., 1999). Fluid motion near the bed also is directed inward, which further contributes to scour by transporting sediment away from the mixing interface (Rhoads, 1996) – a pattern of fluid motion and scour that typically occurs over the outer portion of the channel in meander bends. The shift in the axis of the scour hole away from the mouth of the tributary for events with the largest momentum-flux ratios (Figure 3.5, Table 3.1) is consistent with findings from experimental studies on the response of scour hole orientation to increases in $M_r$ (Best, 1988).

The development of a bar along the downstream junction corner occurs at a location typically defined by bank erosion arising from increased boundary shear stress downstream of the apex of meander bends (Dietrich, 1987). Bar formation at downstream junction corners has been attributed to flow separation in experimental junctions (Best, 1988); however, separation was not observed during this study. Rather, tributary flow was confined against the outer (north) bank upon entering the downstream channel and accelerated over the bar face (Figure 3.10, cross-section I). The development of this bar presumably is related to net sediment flux convergence by formative flows, whereby sediment transport capacity decreases over distance along the outer bank below the downstream junction corner. This mode of bar development has been documented at an asymmetrical confluence for momentum-flux ratios greater than one (Rhoads and Kenworthy, 1995; Rhoads, 1996; Best and Rhoads, 2008). A similar process of bar-building may occur at this confluent meander bend when $M_r > 1$. The stability of the outer bank of the bend is reflected by the longevity of the bar, which remained largely unchanged between measurement dates. Stored sediment near the mouth of Big Muddy Creek was excavated during
springtime high discharge events and deposited downstream below the junction corner (Figure 3.6, cross-sections F and I). This minor adjustment in bed morphology is indicative of bar-building and may occur intermittently as sediment is stored in the tributary when $M_r < 0.5$ and flushed onto the downstream bar when $M_r > 1$.

Flow through natural meander bends is topographically steered toward the thalweg by a point bar that forms along the inner bank (Dietrich and Smith, 1983; Dietrich, 1987). The abrupt shift of high velocity fluid toward the outer bank is critical to the formation of helical motion within bends. In the confluent meander bend, deflection of flow by the high-angle tributary confines the high-velocity core of the Little Wabash River to the inner (south) portion of the channel cross section (Figure 3.9, cross-sections E and F). Confluence bed scour aligns with the high-velocity core in the main channel and impedes point-bar development. Consequently, channel cross sections through the central region of the junction are asymmetrical, with the largest channel depths occurring near the inner bank, rather than the outer (north) bank as at most meander bends (Figure 3.6, cross-sections E and F). The inner bank also shows active signs of erosion. Scouring along the bank toe at the entrance to the downstream channel progressively increased between measurement dates (Figure 3.6, cross-section G). Enhanced shear stress at this location likely arises from increased flow acceleration and confinement of the overlying helical cell when $M_r$ increases. Evidence of erosion is even found along the upper bank, which may occur during large discharge events when $M_r > 1$ or from large tensional stresses on the bank during hydrologic conditions that exceed bankfull discharge (Figure 3.7). Similar patterns of bank erosion and scouring of the bank toe opposite the mouth of the tributary have been observed at an asymmetrical confluence (Rhoads et al., 2009).
The overall stability of channel morphology at this confluent meander bend is tied to a balance between erosional and depositional forces that would otherwise induce meander migration. Tributary flow entering the bend near its apex, combined with the persistent effects of low momentum-flux ratio flows, leads to bar development along the outer bank, which protects it from erosion, and to scouring of the inner bank point bar. Tributary-dominant flow conditions, which have been shown to extensively alter bed morphology at other confluences (Best, 1988; Biron et al., 1993b; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads et al., 2009), are rare, have short durations, and, therefore, are not likely to significantly adjust the long-term morphologic structure of the bed. This assessment of the stability of channel morphology is supported by comparison of aerial photographs of the confluence between July 5, 1938 and March 29, 2005 (Figure 3.11). Minimal change in the position of the bend or the spatial

Figure 3.11. Aerial photographs of the confluent meander bend on (A) March 29, 2005 and (B) July 5, 1938. Sketch of channel banks was on the original photograph obtained from the Natural Resources Conservation Service.
relationship between the tributary and main channels suggests that the confluence planform has been stable for decades. This long-term planform stability seems to support Parker’s (1996) hypothesis that confluent meander bends represent a quasi-stable channel configuration in meandering river systems. Nominal channel change upstream and downstream of the junction, however, suggests that overall the Big Muddy-Little Wabash River systems have stable planforms and that other factors besides confluence effects likely also contribute to this stability.

3.7 Conclusion

This study has documented the response of 3-D flow structure and channel morphology at a confluent meander bend to changes in momentum-flux ratio. The results show that the entry of tributary flow near the apex of a bend greatly alters patterns of flow and bed morphology from patterns typically found in meander bends. The pattern of flow includes a region of stagnation near the junction apex that separates the high downstream velocity cores where the converging streams enter the confluence. The development of flow stagnation upstream of the confluence in the bend, along with deflection of the main flow by the tributary flow, confines maximum velocities of the main river to the inner bank within and immediately downstream of the confluence. Increases in momentum-flux ratio enhance penetration of tributary flow into the confluence, shifting the mixing interface toward the inner bank of the bend. An inherited helical cell arising from flow curvature in the main channel upstream of the junction is also displaced by tributary flow toward the inner bank. The location of prominent bed scour through the junction generally corresponds with the spatial extent of this cell. Scour along the inner bank impedes development of a point bar. Abrupt turning of the tributary into the downstream channel induces the formation of a counter-rotating helical cell along the outer bank of the bend. The size and
intensity of these dual counter-rotating, surface-convergent helical cells in the downstream channel are largely controlled by momentum-flux ratio. The development of a bar along the downstream junction corner decreases channel area, causing the combined flows to accelerate, thereby preventing flow separation along the outer bank. The formation of a bar at this location also protects the outer bank from erosion. Minor changes in bed morphology, even after high discharge and potentially formative flows, are consistent with long-term planform stability.

The flows measured in this study were not highly effective at reshaping channel morphology. Further research is needed to connect changes in channel morphology to spatial patterns of 3-D flow structure during channel-forming events at confluent meander bends. Improved understanding of the mechanisms that support bar development along the downstream junction corner at the outer bank of the bend is of particular importance, as this feature appears to be critical to long-term planform stability. The influence of tributary size relative to the main river and of variations in the location and angle of tributary entry around bends should also be investigated to supplement the results of this study in pursuit of a comprehensive model of confluent meander bend dynamics. An inventory of tributary locations along meandering rivers would be useful for evaluating the prevalence of confluent meander bends relative to other types of tributary configurations.
CHAPTER 4. INFLUENCE OF JUNCTION ANGLE ON THREE-DIMENSIONAL FLOW STRUCTURE AND BED MORPHOLOGY AT CONFLUENT MEANDER BENDS DURING DIFFERENT HYDROLOGICAL CONDITIONS

4.1 Introduction

The movement of water and sediment through drainage networks is invariably influenced by the merging of rivers at confluences. Flow convergence and inherent change in channel planform and geometry at junctions produce a complex hydro- and morphodynamic environment that has been the focus of substantial process-based research, including field investigations at small stream confluences (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Biron et al., 1993a,b; Bristow et al., 1993; Kenworthy and Rhoads, 1995; Rhoads and Kenworthy, 1995, 1998; McLelland et al., 1996; Rhoads, 1996; DeSerres et al., 1999; Rhoads and Sukhodolov, 2001, 2004; Boyer et al., 2006; Rhoads et al., 2009) and more recently large river junctions (Best and Ashworth, 1997; Parsons et al., 2007; Szupiany et al., 2007; Lane et al., 2008; Parsons et al., 2008; Szupiany et al., 2009). Field observations, complemented by laboratory flume experiments (Mosley, 1976; Best and Reid, 1984; Best, 1986, 1987, 1988; Best and Roy, 1991; Biron et al., 1996a,b; McLelland et al., 1996), have generated empirical insights that provide the basis for testing of numerical simulations (Weerakoon and Tamai, 1989; Weerakoon et al., 1991; Bradbrook et al., 1998, 2000, 2001; Constantinescu et al., 2011) in pursuit of a comprehensive model of confluence dynamics. Collectively, this work has demonstrated the importance of confluence planform geometry (symmetrical, or Y-shaped, versus asymmetrical, or y-shaped planforms), momentum flux ratio, junction angle, and equal (concordant) or unequal (discordant) bed elevations of the confluent channels as the primary factors influencing patterns of three-dimensional (3-D) fluid motion and bed morphology at junctions.
Confluence research has focused mainly on junction planforms with straight approach channels that meet at an angular configuration before entering a straight receiving channel. However, previous field observations and studies of tributary development in meandering river systems suggest that tributaries preferentially join main channels along the outer bank of bends (Callaway, 1902; Davis, 1903; Flint, 1980; Hills, 1983; Abrahams, 1984a,b), forming confluent meander bends. Experimental work and numerical modeling of the hydrodynamics of this type of confluence planform (Roberts, 2004), complemented by recent investigation of the flow structure and bed morphology at a small natural confluent meander bend (Riley and Rhoads, 2012), have begun to reveal the effects of channel curvature on confluence dynamics. This previous work has led to the development of a conceptual model defining the hydro- and morphodynamics of 90° confluent meander bends (Riley and Rhoads, 2012) (Figure 4.1). As flow from the tributary enters the apex of a meander bend, it deflects the high-velocity core and inherited helical cell in the curving main channel toward the inside of the bend within and immediately downstream of the junction. Increases in momentum flux ratio result in enhanced penetration of tributary flow into the confluence and shift the mixing interface between the confluent flows toward the inner bank of the bend. Field data show that flow in the main channel is deflected inward even when $M_r < 0.5$ (Riley and Rhoads, 2012). A second helical cell develops over the outer portion of the bend as a result of the abrupt turning of the tributary into the downstream channel (Riley and Rhoads, 2012), similar to the curvature-induced helicity observed at other junctions with concordant beds (Mosley, 1976; Ashmore and Parker, 1983; Best, 1987; Bridge, 1993; Rhoads and Kenworthy, 1995; Rhoads, 1996; Rhoads and Sukhodolov, 2001). For a fixed junction angle, the momentum-flux ratio also controls the spatial extent and strength of these twin counter-rotating, surface-convergent helical cells through the receiving channel. Flow separation can
Figure 4.1. Conceptual model of flow structure and bed morphology at confluent meander bends when (A) $M_r < 1$ and (B) $M_r \approx 1$ (after Roberts, 2004; Riley and Rhoads, 2012).
develop below the downstream junction corner, especially when $M_r > 1$ (Roberts, 2004), but separation may not occur when this junction corner is rounded (Riley and Rhoads, 2012) as noted in studies of natural asymmetrical confluences (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Rhoads and Sukhodolov, 2001). If channel width does not increase downstream of the tributary mouth, the combining flows will accelerate into the downstream channel to maintain continuity. A broad scour hole aligns with the high-velocity core of the main river within the center of the junction and extends toward the inner portion of the bend, where point-bar development is inhibited (Figure 4.1). Bar development along the outer bank downstream from the mouth of the tributary contributes to the stabilization of the confluence by protecting the outer bank from erosion (Riley and Rhoads, 2012).

To date, investigations of confluent meander bends have focused solely on tributaries that join a meandering river at the apex of a bend at a 90° angle (Roberts, 2004; Riley and Rhoads, 2012). Results from previous studies of the fluvial dynamics of asymmetrical and symmetrical confluences have shown that junction angle plays a critical role in controlling the degree of flow deflection and the spatial position and extent of hydrodynamic features (Mosley, 1976; Best, 1987). Research is needed to evaluate how differences in the location and angle of tributary entry around bends influence patterns of fluid motion in confluent meander bends and to relate these patterns of fluid motion to bed morphology.

This paper examines the response of flow structure and bed morphology to hydrological events at two large confluent meander bends with different tributary entry angles in the midwestern United States. Cross-sectional measurements of 3-D velocity components are obtained for high ($M_r > 1$) and low ($M_r < 1$) momentum-flux ratio conditions to evaluate similarities and differences in fluid motion and bed morphology at high- and low-angle
junctions. This study is also the first to document tributary-dominant flow conditions ($M_r > 1$) at natural confluent meander bends, which have been shown to significantly rearrange bed morphology at other confluences (Best, 1988; Biron et al., 1993b; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads et al., 2009). Morphologic variability is related to the hydrologic events measured in this study and compared to the long-term spatial evolution of the junction planform. The results provide critical information on the response of flow and morphologic features to variation in geometric and hydrological controlling factors, and contribute to the advancement of a comprehensive model of confluent meander bend dynamics.

### 4.2 Field sites

Two confluent meander bends with different junction angles along the Wabash River were selected as study sites for the research (Figure 4.2). At its mouth, the Wabash River (WR) joins the Ohio River (OR) slightly upstream of the apex of a meander bend at a junction angle of approximately 90°. At the confluence, the drainage area of the Ohio River (279,719 km$^2$) is over three times greater than the drainage area of the Wabash River (85,237 km$^2$). Differences in drainage area and the geographic extent of the watersheds result in disparities in the magnitude and timing of peak flows between the rivers at the junction. Wabash Island lies directly across from the mouth of the Wabash River and divides flow in the Ohio River into two channels upstream of the confluence. The main channel into which the Wabash River enters transports about two-thirds of the flow around the north side of the island, which comprises the inner bank of the meander bend. The width of this channel varies from 500 m in the curving upstream channel to as much as 600 m at the junction and 675 m downstream of the confluence. A straight secondary channel on the southeast side of the island conveys about one-third of flow in the Ohio
Figure 4.2. Location map of (A) field sites, (B) USGS and USACE river gages, and measurement cross sections at (C) ORWR and (D) WRVR confluences.
River. The two channels merge 5 km downstream of the junction. The channel of the lower Wabash River is sinuous and bends immediately upstream of the confluence. Curvature of the inner bank along this bend extends to the downstream junction corner and channel width increases from 300 m upstream of the junction to 475 m at the mouth of the river. Maximum channel depth is approximately 10.5 m at the mouth of the Wabash River and increases to as much as 15 m in the Ohio River.

A system of locks and dams on the Ohio River produces a series of pools to facilitate commercial navigation. The pool at the confluence is maintained by the Smithland Dam, located 113.5 km downstream. The John T. Myers Locks and Dam is 3.2 km upstream of the junction, but does not disrupt patterns of flow at the entrance of the confluence. The United States Army Corps of Engineers (USACE) periodically dredges the navigation channel to maintain adequate depth for barge traffic, but the bed morphology is highly responsive to sediment fluxes into the confluence (Zinger et al., 2011). Downstream of a mainstream reservoir in its headwaters, the Wabash River flows unimpeded for 661 km to the Ohio River. The average channel gradient of the Wabash River upstream of the confluence (0.0003) is steeper than the gradient of the Ohio River (0.0001) below the John T. Myers Locks and Dam. Bed material at the site is comprised primarily of coarse sand with fine gravel.

The second study site was selected to provide a contrast in tributary entry angle compared to the high-angle confluent meander bend of the Ohio and Wabash Rivers (ORWR). The confluence of the Wabash River and Vermilion River (WRVR) is located 375 km upstream of ORWR in west central Indiana. At this location, the drainage area of the Wabash River (21,481 km²) is nearly six times larger than the drainage area of the Vermilion River (3,714 km²). The Vermilion River enters the Wabash River downstream of the apex of a meander bend on the
Wabash River at an angle of 36°. The tributary is relatively straight and aligned with the downstream channel, whereas the main channel curves sharply immediately upstream of the confluence. Channel width of the Vermilion River is 60 m at the entrance of the junction. The Wabash River is approximately 140 m wide in the upstream channel and width increases to 175 m at and directly downstream of the confluence before decreasing to 140 m farther downstream. Bankfull channel depths range from 6 m in the Vermilion River and 6.75 m in the Wabash River downstream of the confluence to nearly 8 m upstream of the junction in a pool along the outer (west) bank of the Wabash River. Average channel gradients upstream of the confluence are 0.00007 for the Wabash River and 0.0001 for the Vermilion River. Bed material at the junction consists of a mixture of coarse sand and gravel.

4.3 Field methods and data analysis

Field data on 3-D velocities and bed morphology were collected on two survey dates during different hydrological events at both study sites. Flow conditions were remotely monitored from real-time United States Geological Survey (USGS) and USACE river gages near each confluence (Table 1). Measurements of discharge and mean velocity were obtained at two cross sections of the confluent rivers immediately upstream of each junction and used to compute the momentum-flux ratio ($M_r$) of the incoming flows:

$$M_r = \frac{\rho Q_2 U_2}{\rho Q_1 U_1}$$

where $\rho$ is flow density (kg m$^{-3}$), $Q$ is discharge (m$^3$ s$^{-1}$), $U$ is mean cross-sectional velocity (m s$^{-1}$), and the subscripts 1 and 2 refer to the main river and tributary, respectively. Flow stage data were acquired to estimate water-surface elevations during periods of field data collection at ORWR from the Ohio River at JT Myers L/D lower gage. At WRVR, water-surface elevations
were surveyed on the Wabash River near the upstream junction corner at the beginning and end of each measurement campaign.

Three-dimensional velocity and bathymetry data were obtained at several cross sections distributed throughout each confluence. Cross sections were located upstream of the confluence on the tributary and main channels to characterize inherited flow structure, within the central region of the junction, and across the downstream channel (Figure 4.2). Cross sections were generally positioned 40-50 m apart through the center of WRVR and 75-100 m apart upstream and downstream of the junction. Central cross sections at ORWR were 50-150 m apart, whereas the distance between cross sections on the upstream and downstream channels varied from 150 to 500 m. Cross sections at both sites were oriented orthogonally to the direction of the local channel centerline. At WRVR, cross-section J was aligned perpendicular to the orientation of the curving Wabash River, but extended completely through the center of the confluence so that it was skewed in relation to the orientation of incoming flow from the Vermilion River. At ORWR, endpoints of cross sections extending across the Ohio River at the entrance of the Wabash River (cross-sections J-M) were located within the Wabash River.

Simultaneous measurements of downstream, cross-stream, and vertical velocities and bottom depth were obtained at each cross section with an acoustic Doppler current profiler (ADCP). A Workhorse Rio Grande ADCP made by Teledyne RD Instruments (TDRI) was used to collect data along channel cross sections via a moving-boat deployment, similar to methods used in previous studies of coherent flow structures in rivers (Richardson and Thorne 1998; McLelland et al., 1999; Muste et al., 2004; Dinehart and Burau, 2005a,b; Parsons et al., 2005; Parsons et al., 2007; Szupiany et al., 2007). The ADCP was attached to a mount on the port side of the bow of a 5.79 m long, aluminum-hull boat. The four transducers of the ADCP were positioned 0.15-0.27
m below the water surface depending on flow conditions during each survey date. The ADCP cannot measure velocities within a blanking distance of about 0.25 m below the transducers. Also, the bottom 6% of the measured flow depth was removed to correct for acoustic side-lobe interference. The sampling interval of the ADCP ranged between 1.3-1.7 s and vertical bin sizes were either 0.1 m or 0.25 m within each ensemble. A 1200 kHz ADCP was used for measurement during low-momentum flux ratio flows \((M_r < 1)\), whereas a 600 kHz ADCP was used to survey high-momentum flux ratio conditions \((M_r > 1)\) to prevent signal loss associated with high acoustic backscatter caused by increased suspended sediment concentrations.

Boat position and velocity were determined using a Trimble AgGPS 132 differential global positioning system (DGPS) receiver. The DGPS-receiver contains both beacon and satellite differential receivers and is Wide Area Augmentation System (WAAS) enabled to correct for GPS signal delays and improve accuracy of position data. The DGPS-receiver provides time-stamped geographic coordinates at 10 Hz with up to sub-meter accuracy and was integrated with the ADCP to georeference velocity data at each ensemble. Real-time GPS data were also used to navigate the boat as accurately as possible along the predetermined cross sections. The DGPS-antenna was affixed to the port side mount directly above the ADCP.

Multiple traverses, or transects, of each cross section were surveyed to obtain spatially and temporally averaged values of velocity and to resolve details of secondary-flow patterns, while minimizing disturbances arising from turbulent velocity fluctuations and boat motion. At WRVR, measurements were typically repeated for five transects at each cross section in the field. Wide channel cross sections at ORWR increased the total time needed to survey each cross section. Thus, repeat measurements were limited to either two or four transects per cross section. Although five transects have been recommended for characterizing secondary flows, recent field
studies in large rivers have used only one or two transects to capture large-scale features of the flow field at a cross section (Parsons et al., 2007; Szupiany et al., 2007).

The Velocity Mapping Toolbox (VMT), an ADCP post-processing software package, was used to compute spatially and temporally averaged velocity data for each cross section from repeat transect measurements (Parsons et al., 2013). Velocity ensembles were interpolated to grid nodes using a least-squares regression line fit through transects at each cross section. Time-averaged values of downstream ($U$), cross-stream ($V$), and vertical ($W$) velocity were computed for bins within each ensemble in relation to the cross-section orientation. These velocity components were used to derive depth-averaged vector plots of downstream and cross-stream velocities for the junctions on each measurement date and contour plots of downstream velocity superimposed with cross-stream/vertical velocity vectors for individual cross sections. To identify secondary flow structures within complex converging flows at confluences, VMT also rotates velocity vectors for each bin in an ensemble to the direction of the depth-averaged velocity vector for that ensemble. Secondary flow is then defined by velocity components perpendicular to this rotation. Previous studies of confluence hydrodynamics have used this rotation method (Rozovskii, 1957) to detect helical motion in strongly converging flows (Rhoads and Kenworthy, 1998; Lane et al., 2000).

Measurements of near-surface water temperature were recorded at each ensemble by the ADCP transducers. Previous field investigations at confluences have used temperature contrasts between incoming streams to approximate the position of the mixing interface (Mackay, 1970; Rhoads and Kenworthy, 1995, 1998; Rhoads and Sukhodolov, 2001). Deviations between water temperatures at each ensemble and the mean temperature for the respective cross section were computed to limit the effect of diurnal variation in water temperature during the surveys.
Contour plots of the temperature data were produced for the confluences on each measurement date by kriging with ESRI ArcGIS 10 software. The mixing interface is defined by the location where temperature deviation from the cross-sectional mean is zero.

Reflections of acoustic beams emitted by the ADCP transducers from the channel bottom were used to produce cross-section plots of bed morphology and bathymetric maps of each confluence. Bed profiles for each averaged cross section were developed by computing in VMT a weighted average of the 4-beam depths at each ensemble and converting depths to elevations based on flow stage data. Besides data from the cross section surveys, longitudinal transects throughout each confluence yielded additional bathymetric data for mapping the topography of the channel bed. Topographic maps of the bed morphology at the junctions were generated by kriging and contouring bed elevation data collected at all transects on each survey date with ESRI ArcGIS 10 software.

4.4 Results

4.4.1 Hydrologic and hydraulic conditions

Field data on 3-D velocity fields and bed morphology were collected on two dates during different hydrological conditions at both sites: May 15, 2008 and January 6, 2009 at ORWR and January 9, 2007 and February 6, 2008 at WRVR. Hydrologic variability prior to and during the field campaign was estimated by deriving the discharge ratio of the converging flows from mean daily discharge data recorded at nearby river gages. The discharge ratio, a proxy for momentum-flux ratio, is calculated as:

\[ Q_r = \frac{Q_2}{Q_1} \]  

(2)
where $Q$ is discharge (m$^3$ s$^{-1}$) and the subscripts 1 and 2 refer to the main river (Ohio River at ORWR, Wabash River at WRVR) and tributary (Wabash River at ORWR, Vermilion River at WRVR), respectively. The discharge ratio at ORWR was approximated by summing mean daily discharge values from the Wabash River at Mt. Carmel, IL gage and the gaged tributaries of the lower Wabash River (Figure 4.1B) to determine $Q_2$. Two-thirds of the difference between $Q_2$ and the mean daily discharge recorded at the Ohio River at Old Shawneetown, IL-KY gage provided an estimate of the discharge of the Ohio River around the north side of Wabash Island ($Q_1$). For WRVR, mean daily discharges were obtained from an upstream gage on each river to calculate the discharge ratio (Table 1). Plots of discharge ratio against time provide a hydrological context for the ADCP measurement campaigns, and duration curves of discharge ratios derived for the periods of record from the nearby river gages show the frequency of the events measured in this study (Figure 4.3).

Table 4.1. River gages used to remotely monitor flow conditions at ORWR and WRVR

<table>
<thead>
<tr>
<th>Confluence</th>
<th>Gage</th>
<th>Approximate location relative to confluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORWR</td>
<td>Ohio River at JT Myers L/D lower</td>
<td>3.2 km upstream</td>
</tr>
<tr>
<td></td>
<td>Ohio River at Old Shawneetown, IL-KY</td>
<td>16.1 km downstream</td>
</tr>
<tr>
<td></td>
<td>Wabash River at Mount Carmel, IL</td>
<td>122.3 km upstream</td>
</tr>
<tr>
<td>WRVR</td>
<td>Wabash River at Covington, IN</td>
<td>24.4 km upstream</td>
</tr>
<tr>
<td></td>
<td>Vermilion River near Danville, IL</td>
<td>31.4 km upstream</td>
</tr>
</tbody>
</table>

At ORWR, low momentum-flux ratio conditions ($M_r < 1$) prevailed on May 15, 2008 (Table 2) during the rising stages of a hydrologic event produced by heavy precipitation throughout the Midwest in early May. Flow stage increased by 0.12 m at the JT Myers L/D lower gage during 7.5 hours of data collection. A series of tributary-dominant discharge events ($Q_r > 1$) followed during the late spring and summer of 2008 (Figure 4.3A). A second set of velocity data was collected on January 6, 2009 during high momentum-flux ratio conditions resulting from
Figure 4.3. Estimated discharge ratios during the field campaign for (A) ORWR and (B) WRVR and duration curves of discharge ratios for a period of 7.25 years for (C) ORWR and 68.5 years for (D) WRVR, derived from mean daily discharge data at nearby river gages. Dashed lines in A and B and tick marks on duration curves in C and D denote survey dates.

Snowmelt and intense rainfall generated by severe thunderstorms across the central and southern portions of the Wabash River drainage basin during late December 2008. Measurements were obtained over a 5-hour period during which stage decreased by 0.11 m. While flows with $M_r > 1$ have been documented at confluences with other types of planforms (Biron et al., 1993b; Rhoads
and Kenworthy, 1995, 1998; DeSerres et al., 1999), only flows with \( M_r < 1 \) had been investigated at a small confluent meander bend (Riley and Rhoads, 2012) prior to this study.

Tributary-dominant flow conditions are infrequent and short-lived at WRVR (Figures 4.3B,D). A period of sustained low discharge ratio conditions preceded the survey on January 9, 2007 (Figure 4.3B). Changes in stage were minor during measurement, dropping just 0.02 m over 5.5 hours. In contrast, surface runoff from thunderstorms over a widespread snowpack resulted in flooding throughout much of the Vermilion River drainage basin and produced flows with \( M_r > 1 \) at the confluence on February 6, 2008 (Table 2). Data were collected over 6 hours during the rising stages of this event, in which water levels increased by 0.5 m.

Table 4.2. Hydraulic conditions of measured flows at ORWR and WRVR

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q )</td>
<td>( V )</td>
<td>( M )</td>
<td>( Q )</td>
</tr>
<tr>
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<td>4,882</td>
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<td>0.94</td>
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</tr>
<tr>
<td>WR/OR</td>
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<td>1,446,460</td>
<td>1,890,000</td>
</tr>
<tr>
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<td>0.32</td>
</tr>
<tr>
<td>WR</td>
<td>2,193</td>
<td>2,100</td>
<td>1.02</td>
</tr>
<tr>
<td>OR/VR</td>
<td>0.45</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>WR/VR</td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VR/WR</td>
<td>1.31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( Q = \text{discharge (m}^3\text{ s}^{-1}) \), \( V = \text{mean cross-sectional velocity (m s}^{-1}) \), \( M = \text{momentum flux (kg m s}^{-2}) \)

4.4.2 Bed morphology

General morphological features and adjustment of the bed to varying flow conditions differ between the field sites. At ORWR, patterns of bed morphology on May 15, 2008 include the pool of the Ohio River’s navigation channel within the central region of the junction flanked by a broad point bar along the inner (south) portion of the bend and a long bar platform on the north side of the channel protruding slightly into the confluence from the Wabash River and extending below the downstream junction corner (Figure 4.4A). The pool turns inward at the upstream junction corner from a position against the outer bank, resulting in progressive symmetry of
Figure 4.4. Bed topography at ORWR on (A) May 15, 2008; (B) June 23, 2008; (C) January 6, 2009. Bed elevation data for June 23, 2008 was obtained from USACE.
Figure 4.5. Channel cross-section profiles at ORWR. Looking upstream; outer (east) bank is right, inner (west) bank is left for cross-sections A-C; outer (north) bank is left, inner (south) bank is right for cross-sections L, N, O, and P.

Channel cross-section profiles through the center of the confluence and upstream end of the downstream channel (Figure 4.5, cross-sections L, N, and O). The pool shifts back toward the outer bank farther downstream (Figure 4.4A, cross-section Q). In the curving tributary channel, a
bar wraps around the inner (west) bank of the bend and a pool is located along the outer (east) bank, leading to channel asymmetry (Figure 4.5, cross-sections A-C).

Large tributary-dominant discharge events and widespread flooding during June 2008 produced a meander cutoff approximately 2 km upstream of the junction on the Wabash River (Zinger et al., 2011). Large amounts of eroded sediment were transported downstream from the cutoff into the confluence and significantly altered the bed morphology. The United States Army Corps of Engineers surveyed the bed topography of the Ohio River with an echo sounder on June 23, 2008, before dredging the deposited material from the navigation channel.

The survey data for June 23, 2008 show that a wedge of sediment extends from the mouth of the tributary across the outer (north) half of the main channel and into the central region of the junction (Figure 4.4B, cross-sections K-N). The influx of sediment increased local bed elevations by over 6 m compared to May 15, 2008 and bisected the pool. The upstream segment of the pool has shifted 175 m toward the inner bank of the bend at the confluence and is confined to a narrow zone between the upstream edge of the sediment wedge and the inner bank point bar. Scouring of the point bar has occurred across the channel from the tributary entrance (Figure 4.4B, cross-sections K and L), but this scouring along the inner bank does not extend into the downstream channel (cross-sections M-P). The downstream portion of the pool within the bend is still located near the outer bank (cross-sections O-Q).

Although extensive dredging during the summer of 2008 removed most of the accumulated material from the confluence, the bathymetric data for January 6, 2009 show that the influx of sediment from the Wabash River persisted, producing a bed topography similar to that in June 2008. For the most part, the pool has the same alignment through the junction on the two dates, but the thalweg is wider and shifted closer to the outer bank in January 2009 than in June 2008.
(Figures 4.4B,C). As a result, the point bar is truncated by the pool toward the inner bank of the bend. Across the channel, the distinctiveness of the sediment wedge has diminished; instead an elongated body of sediment wraps around the downstream junction corner and extends downstream along the outer bank of the bend in the Ohio River (Figures 4.4B,C). Patterns of bed morphology in the tributary channel remain comparatively unchanged, although aggradation is evident along the inner bank at cross-section A (Figure 4.5). The net effect of the continued influx of sediment from the Wabash River is maintenance of the pattern of bed morphology in the confluence.

Figure 4.6. Bed topography at WRVR on (A) January 9, 2007 and (B) February 6, 2008.
Figure 4.7. Channel cross-section profiles at WRVR. Looking upstream; outer (west) bank is left, inner (east) bank is right; except cross-section B where north bank is right, south bank is left.
In contrast, morphological features at WRVR are similar on both measurement dates (Figure 4.6). A wide pool spans the center and outer (west) portion of the main channel upstream of the confluence. This pool ends within the confluence as the bed rises gradually by about 1.5 m from the deepest part of the thalweg upstream. A prominent point bar exists along the inner bank of the bend and a small region of scour is evident immediately downstream from the upstream junction corner (Figure 4.6). At the apex of the bend, the point bar narrows where the pool width is greatest, but widens through the confluence and the downstream channel. Minor degradation of the bar occurred between the January 9, 2007 and February 6, 2008 surveys (Figure 4.7, cross-sections J, K, and M) with up to 1 m of material excavated from the bar face in the confluence (cross-section J). The downstream end of the pool is shifted toward the center of the main channel and tapers where the tributary enters the confluence (Figure 4.6, cross-sections J and K). A low ridge on the bed separates the shallow scour hole in the confluence from the thalweg of the Wabash River (Figure 4.7, cross-section K). This ridge gradually widens into a broad platform extending across much of the channel downstream (cross-section M). Scour along the outer bank and in the center of the channel occurs downstream of the platform (cross-section N).

4.4.3 Depth-averaged velocity

The degree of convergence between depth-averaged velocity vectors and corresponding flow deflection along the mixing interface differ between the field sites. At ORWR, curvature both of the main channel and tributary immediately upstream of the junction, along with the curved planform of the downstream channel, produces complex spatial patterns of velocity vectors (Figure 4.8). The high-angle entrance of the Wabash River into the Ohio River initiates strong flow deflection through the central region of the confluence. On both measurement dates, the
Figure 4.8. Depth-averaged velocity vectors at ORWR on (A) May 15, 2008 and (B) January 6, 2009.
mixing interface is defined approximately by the boundary between inward oriented vectors reflecting penetration of flow from the Wabash River into the confluence and vectors that align with the curved planform of the Ohio River through the center of the channel and along the inner (south) bank (cross-sections J-N). Flow from the Wabash River is turned rapidly to align with the Ohio River immediately downstream of the confluence (cross-section O) and deflects vectors in the Ohio River away from the outer (north) bank of the meander bend. Vector magnitudes progressively increase through the confluence as the flows combine and accelerate, and are greatest through the center of the downstream channel (cross-sections O and P). Small or negative depth-averaged velocities near the junction apex and below the downstream junction corner are indicative of zones of flow stagnation and separation, respectively.

The orientation of depth-averaged velocity vectors and the position of the mixing interface at ORWR are responsive to changes in the momentum-flux ratio. Low momentum-flux ratio conditions on May 15, 2008 ($M < 1$) result in a distinct mixing interface on the tributary side of the channel characterized by abrupt lateral change in vector magnitudes, rapid change in orientation of velocity vectors characterizing flow from the tributary into the confluence, and minimal outward deflection of vectors in the main river (Figure 4.8A, cross-section L). Flow from the Wabash River is narrowly confined between the mixing interface and the outer (north) bank of the meander bend upon entering the confluence (cross-sections L and N), whereas high velocity flow in the Ohio River occupies most of the channel. A region of low velocities along the outer (east) bank of the curving Wabash River (cross-sections B-D) defines an elongated zone of flow stagnation extending upstream from the junction. The stagnation zone displaces the largest vectors in the Wabash River from the outer bank (cross-section A) to the inner (west) bank (cross-section D) as flow from this tributary enters the Ohio River. Flow accelerates across
nearly the entire channel cross section at the downstream end of the junction (cross-section N). Farther downstream (cross-sections O-Q), the largest velocities are positioned between the center of the channel and a small zone of low-velocity flow that develops against the outer bank.

During high momentum-flux ratio conditions on January 6, 2009 ($M_r > 1$), strong penetration of flow from the Wabash River into the confluence shifts the mixing interface toward the inner (south) bank (Figure 4.8B) compared to conditions for $M_r < 1$. Low velocity flow entering the junction from the Ohio River (cross-section J) is restricted to the inner part of the channel, where it accelerates to maintain continuity (cross-sections K and L). A large mid-channel bar that developed in the Wabash River between the survey dates in response to a meander cutoff immediately upstream (Zinger et al., 2011) produces strong flow convergence downstream of this feature (cross-section A). Large depth-averaged velocities persist over the central and outer (east) portion of the tributary channel (cross-section B), but flow in this part of the channel decelerates immediately upstream of the confluence (cross-sections C and E). Spatial patterns of tributary vectors near the mouth are aligned obliquely to the orientation of cross-sections K-M, indicating pronounced penetration of tributary flow into the confluence. The flow stagnation zone observed on May 15, 2008 is absent from the tributary channel. Instead, deceleration of flow occurs over the outer (north) portion of the Ohio River near the junction apex (cross-section J). Downstream of the confluence, a region of separated flow exists along the outer bank and the largest velocity vectors span the center and inner half of the channel (cross-sections O and P).

In contrast to vector patterns at ORWR, the low-angle entrance of the Vermilion River at WRVR leads to patterns of depth-averaged velocity vectors between the main river and tributary that are almost parallel to each other upon entering the confluence (Figure 4.9). Consequently, mutual deflection of the converging flows is much less pronounced than at ORWR. The mixing
interface is readily discerned from abrupt differences in vector magnitudes between the rivers on both measurement dates (cross-sections J-M). Flow curvature in the Wabash River upstream of the confluence is defined by a transverse gradient in depth-averaged velocities in which the largest vectors occur over the east side of the bend upstream of, at, and slightly downstream of the bend apex (cross-sections F-I). Depth-averaged velocities increase through the confluence and quickly align with the orientation of the downstream channel. The low junction angle of the confluence restricts flow from the Vermilion River to the outer (west) portion of the downstream
channel. Flow separation from the outer bank of the downstream channel was not observed on either date.

Dominant flow from the Wabash River occupies most of the confluence when $M_r < 1$ on January 9, 2007 (Figure 4.9A). The mixing interface shifts rapidly outward through the junction, coinciding with the transition of maximum depth-averaged velocities in the Wabash River from the inner (east) bank to the center of the downstream channel (cross-sections J-M). Low velocity flow occurs across the entire tributary (cross-sections A and B) and is confined against the outer (west) bank of the receiving channel. A narrow zone of small vectors associated with this tributary flow diminishes abruptly downstream of the confluence (cross-sections L and M).

Increased penetration of flow from the Vermilion River into the downstream channel forces the mixing interface toward the inner bank of the bend when $M_r > 1$ on February 8, 2008 (Figure 4.9B). High-velocity flow from the tributary prevents flow from the Wabash River from expanding outward across most of the flow width as on the previous measurement date. Instead, flow accelerates over the outer portion of the channel and an abrupt transition in vector magnitudes along the mixing interface persists well downstream of the confluence (cross-sections J-N). Deceleration of flow along the outer bank of the Wabash River upstream of the confluence is pronounced on this date, resulting in flow stagnation near the upstream junction corner (cross-section I).

4.4.4 Downstream and cross-stream velocity

Spatial patterns of downstream and cross-stream velocity vectors at ORWR are responsive to shifts in momentum flux ratio. Upstream of the junction, the downstream velocity field ($U$) is characterized by high-velocity cores in the Ohio and Wabash Rivers that are separated by a region of low-velocity fluid surrounding the junction apex. Flow stagnation, characterized by
velocities near 0 m s\(^{-1}\), extends upstream along the outer (east) bank of the Wabash River when \(M_r < 1\) (May 15, 2008) (Figure 4.10A, cross-section D). This region of stagnation generates a cross-stream pressure gradient that shifts the high-velocity core of the tributary from a position near the outer bank of the bend (cross-section A) to the inner (west) portion of the channel (cross-section D) as flow enters the Ohio River. Velocities are also small near the junction apex in the Ohio River, where the zone of stagnation is narrowly confined against the outer (north) bank (cross-section I). When \(M_r > 1\) (January 6, 2009), high velocities across most of the Wabash River reduce flow stagnation at the outer bank of the tributary (Figure 4.10B, cross-section E). Increased penetration of tributary flow into the confluence shifts most of the stagnation zone around the junction apex to the outer portion of the channel cross-section of the Ohio River, confining the highest downstream velocities in the main channel to the inside of the meander bend (cross-section J).

The channels of both rivers bend immediately upstream of the junction, resulting in curvature-induced secondary circulation within the converging flows on both measurement dates. Secondary velocity vectors (\(V_s\)), derived using the Rozovskii method, reveal the presence of a helical cell with clockwise circulation (looking upstream) in the Wabash River spanning most of the channel cross-section on May 15, 2008 (Figure 4.10A, cross-section A and D). A small counter-rotating cell is apparent next to the outer (east) bank upstream of the stagnation zone (cross-section A). On January 6, 2009, the development of a mid-channel bar in the tributary following cutoff of the bend upstream of the junction confines the main helical cell between the bar face at the center of the channel and the outer bank (Figure 4.10B, cross-section A). The resulting decrease in channel area accelerates the flow and intensifies helical motion in the thalweg. Channel width increases at the mouth of the tributary and patterns of secondary
Figure 4.10. Downstream velocities with Rozovskii secondary/vertical velocity vectors at ORWR on (A) May 15, 2008 and (B) January 6, 2009. Looking upstream; outer (east) bank is right, inner (west) bank is left for cross-sections A, D, and E; outer (north) bank is left, inner (south) bank is right for cross-sections I, J, L, N, O, and P. Dashed line indicates approximate location of mixing interface determined by measurements of near-surface water temperature. (B) on following page.
circulation become less organized (Figure 4.10B, cross-section E). Large-scale secondary circulation is also present in the Ohio River upon entering the confluence, where a counterclockwise rotating helical cell extends across most of the incoming flow on both measurement dates (Figure 4.10A, cross-section I; Figure 4.10B, cross-section J).

The high angle at which the Wabash River joins the curving Ohio River causes abrupt flow convergence and highly complex patterns of fluid motion at the center of the confluence.
Because the rivers meet at a junction angle of approximately 90°, the flow field of the Wabash River at the entrance of the confluence is aligned nearly orthogonal to the flow field of the Ohio River. Flow penetration from the tributary into the confluence is illustrated by strongly inward oriented cross-stream/vertical (V/W) velocity vectors over the outer (north) portion of cross-section L on both measurement dates (Figure 4.11). Vector magnitudes progressively decrease across the channel, indicating a decrease in deflection of flow in the Ohio River by flow from the Wabash River, and are low near the inner (south) bank.

![Figure 4.11. Downstream velocities with cross-stream/vertical velocity vectors at cross-section L at ORWR on (A) May 15, 2008 and (B) January 6, 2009. Looking upstream; outer (north) bank is left, inner (south) bank is right.](image)

Helicity from curving flow upstream in each river persists through the center of the confluence and is characterized by side-by-side counter-rotating, surface-convergent helical cells (Figures 4.10A,B, cross-sections L-O). The cell on the south side of the confluence that
originates in the Ohio River shifts away from the mouth of the tributary, especially when $M_r > 1$ (Figures 4.10A,B, cross-sections L and N). The helical cell originating in the Wabash River is confined to the north side of the confluence as flow from this tributary is forced to turn rapidly into the downstream channel. The spatial extent of this cell is smaller for $M_r < 1$ (Figure 4.10A, cross-sections L and N) than for $M_r > 1$, when flow from the Wabash River penetrates far into the confluence (Figure 4.10B, cross-section L and N). On both measurement dates, mutual deflection of flow between the tributary and main channel reinforces the upstream patterns of flow curvature, thereby strengthening fluid rotation within the counter-rotating helical cells within the confluence. Consequently, the transfer of downstream momentum is enhanced laterally toward the mixing interface, which is generally positioned between the twin helical cells and identified by a distinct difference in near-surface water temperatures of the two rivers (Figure 4.12).

The combined flows accelerate through the downstream channel on both measurement dates, but differences in the spatial extent of the helical cells and the size of a zone of flow separation at the downstream junction corner are largely controlled by momentum flux ratio. The well-organized counterclockwise-rotating helical cell inherited from upstream flow curvature in the Ohio River extends across nearly three-quarters of the flow width in the downstream channel when $M_r < 1$ (Figure 4.10A, cross-sections O and P). Lateral advection of downstream momentum by this helical cell directs near-surface high velocity fluid across the channel toward the mixing interface, which is positioned near the outer margin of the high downstream velocity core. Along the flanks of the mixing interface, fluid plunges toward the bed. Thus the high-velocity core is positioned in the center of the channel where flow accelerates due to the addition of flow from the Wabash River. Confinement of the mixing interface near the outer (north) bank (Figure 4.12A) restricts the smaller helical cell within flow from the Wabash River to the outer
Figure 4.12. Deviation from mean water temperature near the surface at ORWR on (A) May 15, 2008 and (B) January 6, 2009. Dashed line indicates approximate location of mixing interface.
portion of the bend. The clockwise circulation of this helical cell weakens and the cell decreases in size farther downstream (cross-section P). A small zone of low downstream velocities representing flow separation from the downstream junction corner develops adjacent to this cell along the outer bank (cross-sections O and P).

When $M_r > 1$, increased penetration of tributary flow into the confluence and subsequent shifting of the mixing interface to the center of the channel (Figure 4.12B) enhances flow separation along the outer (north) bank downstream from the tributary entrance (Figure 4.10B, cross-sections O and P). The helical cell on the tributary side of the channel extends inward from the separation zone across more than half of the downstream channel (cross-section P). The opposing helical cell is confined to the inner (south) portion of the channel and is clearly smaller than for $M_r < 1$. The counter-rotating cells are similar in size at the entrance of the downstream channel (cross-section N) and transfer downstream momentum laterally to the center of the channel cross-section where the combined flows accelerate. Further downstream (cross-section P), patterns of secondary circulation become less organized as the hydraulic effects of the confluence on the flow begin to wane.

The comparatively low junction angle at WRVR results in less direct flow deflection between the converging rivers and less complex patterns of downstream and cross-stream velocity vectors than at ORWR. The curving channel planform of the Wabash River upstream of the confluence subjects flow to an outward-directed centrifugal force. Near-surface secondary velocity vectors are oriented outward, and a counterbalancing pressure gradient force directs near-bed vectors inward, initiating counterclockwise helical motion of the flow across most of the main channel on both measurement dates (Figures 4.13A,B, cross-sections F and I). For $M_r < 1$ (January 9, 2007), a core of high downstream velocity in the Wabash River upstream of the
Figure 4.13. Downstream velocities with Rozovskii secondary/vertical velocity vectors at WRVR on (A) January 9, 2007 and (B) February 6, 2008. Looking upstream; outer (west) bank is left, inner (east) bank is right; except cross-section B where north bank is right, south bank is left. (B) on following page.
Figure 4.13. (continued).
confluence expands from the center and inner (east) portion of the channel (Figure 4.13A, cross-section F) toward the outer (west) bank at the entrance to the confluence (cross-section I), whereas low velocities extend across the entire mouth of the Vermilion River (cross-section B). For $M_r > 1$ (February 6, 2008), the highest downstream velocities in the Wabash River upstream of the confluence are located toward the inside of the meander bend due to the development of a zone of flow stagnation that extends upstream from the junction apex along the outer bank of the bend (Figure 4.13B, cross-sections F and I). Downstream velocities exceed 1.5 m s$^{-1}$ across most of the flow width of the tributary (cross-section B).

Contrasts in both downstream velocity and surficial water temperature between the converging flows define the position of the mixing interface through the central region of the confluence on both measurement dates (Figures 4.13A, 4.14A, cross-section J; Figures 4.13B, 4.14B, cross-sections J and K). Low velocity flow from the tributary is confined against the outer (west) bank by the outward expansion of the core of high velocity from the Wabash River when $M_r < 1$ (Figure 4.13A, cross-sections J-K). Downstream, the velocity differential between the flows diminishes (cross-sections K-N), even though the contrast in surficial water temperature lingers (Figure 4.14A), suggesting the mixing interface remains well-defined and precludes mixing of the contiguous flows in the vicinity of the junction. Temperature data show that the path of the mixing interface, although somewhat irregular, generally bows outward following a curved path that represents a continuation of the curving outer bank of the Wabash River upstream of the confluence.

The channel of the Vermilion River is relatively straight and aligns with the downstream channel of the Wabash River such that curvature of tributary flow at the confluence is minimal. The pattern of secondary flow within the tributary is disorganized and does not provide clear
evidence of large-scale secondary motion when $M_r < 1$ (Figure 4.13A, cross-section B). Instead, a counterclockwise-rotating helical cell inherited from curving flow upstream in the Wabash River occupies all but the outermost portion of the channel cross section upon entering the confluence (cross-section J). This large helical cell advects high-momentum fluid laterally to the tributary side of the mixing interface and is well organized in the downstream channel (cross-sections M and N) despite a lack of mixing near the surface (Figure 4.14A).
Flow deflection by the Vermilion River is enhanced when $M_r > 1$ and shifts the mixing interface more than 25 m toward the inner (east) bank in the downstream channel compared to its location when $M_r < 1$ (Figure 4.14B, cross-sections M and N). The mixing interface aligns with the inner margin of the high-velocity core from the tributary, which persists through the confluence (Figure 4.13B, cross-sections J and K) and over the outer portion of the downstream channel (cross-sections M and N). Lower-velocity flow from the Wabash River is confined between the mixing interface and the inner bank of the bend and gradually accelerates in the downstream channel (cross-sections M and N). Similar to patterns observed for $M_r < 1$, the contrast in downstream velocity between the flows weakens here (cross-sections M and N); yet surficial water temperature patterns again indicate a lack of mixing as the temperature differential extends linearly downstream (Figure 4.14B).

Two counter-rotating, surface-convergent helical cells are apparent within the central region of the confluent meander bend when $M_r > 1$ (Figure 4.13B, cross-sections J and K). The clockwise-rotating cell over the outer (west) portion of the confluence presumably forms when high-momentum fluid from the tributary undergoes slight curvature upon entering the junction. Helicity within both cells flanking the mixing interface is strongest at the upstream end of the confluence (cross-sections J and K), but weakens and becomes less organized in the downstream channel, especially within the cell on the tributary (west) side of the interface (cross-sections M and N).

4.5 Discussion

Analysis of patterns of 3-D fluid motion at the two sites investigated in this study reveal both similarities and significant differences in the response of flow structure between high angle and
low angle confluent meander bends to changes in \( M_r \). Patterns of flow are also generally similar between the high angle confluent meander bend and the conceptual model of confluent meander bend dynamics (Figure 4.1), especially for \( M_r < 1 \), but flow patterns deviate from the model at the low angle junction. At both high and low angle confluent meander bends, a zone of flow stagnation characterized by low-velocity fluid develops near the upstream junction corner and responds to changes in \( M_r \) by extending into the upstream channel of the river with the lowest momentum flux. Stagnation near the junction apex has been a feature routinely observed at confluences with symmetrical and asymmetrical planforms (Best, 1987; Rhoads and Kenworthy, 1998; DeSerres et al., 1999; Bradbrook et al., 2001; Rhoads and Sukhodolov, 2001; Weber et al., 2001), and appears to be common at confluent meander bends based on the results presented here and in previous experimental (Roberts, 2004) and field studies (Riley and Rhoads, 2012). For \( M_r < 1 \), high velocity flow extends across most of the curving main channel as it enters the junction, presumably increasing the curvature-induced cross-stream water surface gradient and enhancing the adverse pressure gradient that produces flow stagnation near the upstream junction corner. This effect has been shown to increase stagnation at experimental confluent meander bends (Roberts, 2004). For \( M_r < 1 \), the zone of stagnation can extend into the tributary channel. At ORWR, an elongated stagnation zone along the outer bank of the Wabash River segregates the high-velocity cores of the confluent rivers by displacing the core of the tributary inward (Figure 4.10A, cross-section D); whereas at WRVR, the momentum flux of the Vermilion River is so low compared to the main river that flow stagnates across nearly the entire tributary channel as momentum from the high-velocity core of the Wabash River expands rapidly outward in the downstream channel (Figure 4.13A, cross-sections B, K-N). For \( M_r > 1 \), flow stagnation is replaced by a broad zone of high-velocity flow across the tributary channel at both sites (Figure
4.10B, cross-section A; Figure 4.13B, cross-section B). A region of flow stagnation wraps around the upstream junction corner over the outer portion of the main channel, restricting the high-velocity core of the main river to the center and inner portions of the meander bend immediately upstream of the confluence (Figure 4.10B, cross-section J; Figure 4.13B, cross-sections F and I).

The mutual deflection of converging flows in the central region of each confluence generates a well-developed mixing interface defined at the surface by abrupt changes in surficial water temperature, the magnitude of depth-averaged velocity vectors, and patterns of secondary flow. Both the location and angle at which the tributary enters the curving main river largely control the extent of flow deflection. At the high-angle junction of ORWR, the Wabash River joins the Ohio River at the apex of a bend in the main channel such that the flow fields of the rivers are nearly orthogonal to one another as they converge. The abrupt turning of flow from the Wabash River to align with the orientation of the downstream channel is similar to patterns of deflection-induced curvature of the lateral tributary at asymmetrical confluences (Best, 1987; Rhoads and Sukhodolov, 2001). Turning of tributary flow is enhanced when $M_r < 1$ as a result of the outward shift of the mixing interface that confines flow from the tributary to a narrow path between the interface and outer bank of the bend (Figure 4.10A, cross-sections L and N). Increased penetration of tributary flow into the confluence when $M_r > 1$ deflects flow from the main river inward (Figure 4.15), although the presence of the inflowing tributary at the bend apex deflects main river flow away from the outer bank even for $M_r < 1$ (Figure 4.1A). This pattern of deflection is consistent with similar findings for $M_r < 0.5$ at a small natural confluent meander bend with a high angle of tributary entry (Riley and Rhoads, 2012) and is comparable to
Figure 4.15. Conceptual model of flow structure and bed morphology at high-angle confluent meander bends when $M_r > 1$.

deflection of main river flow away from the mouth of the lateral tributary at asymmetrical junctions (Best, 1987; Rhoads and Sukhodolov, 2001).

Flow deflection is less pronounced at WRVR, where the small angle of tributary entry downstream of a bend apex on the Wabash River results in converging flows that nearly parallel one another. Consequently, the position of the mixing interface at the upstream end of the confluence where the flows initially meet remains generally unchanged between measurement dates (Figures 4.13A,B, cross-section J). Because penetration of tributary flow into the confluence is greatly reduced compared to ORWR, the Vermilion River is ineffective at
Figure 4.16. Conceptual model of flow structure and bed morphology at low-angle confluent meander bends when (A) $M_r < 1$ and (B) $M_r > 1$. 
deflecting flow from the Wabash River away from the outer bank of the meander bend in the downstream channel when $M_r < 1$ (Figure 4.16A). The low frequency of flows at WRVR with discharge ratios greater than one (Figure 4.3D) indicates that momentum from the main river may routinely be transferred outward across most of the downstream channel and deflect tributary flow against the outer bank, much in the same way that flow is deflected toward the bank opposite from the dominant tributary at symmetrical confluences (Mosley, 1976). The geometry imparted by the confluence planform, including low junction angle and nearly linear alignment of the tributary with the downstream channel, prevents tributary flow from penetrating the center of the junction and downstream portion of the bend, even when $M_r > 1$ (Figure 4.16B). During these infrequent conditions, the high-velocity core of the tributary persists over the outer portion of the downstream channel and restricts flow from the main river to the center and inner portions of the bend.

This study is among the first to document coherent patterns of secondary circulation in confluences of large rivers with beds consisting of coarse sand and fine gravel. Large-scale helical motion at ORWR and WRVR appears to arise from local imbalances between centrifugal and pressure-gradient forces associated with channel curvature of one or both of the confluent rivers immediately upstream of the junction along with curvature of flow within the confluence. Spatial patterns of helicity differ between the high-angle (ORWR) and low-angle (WRVR) confluent meander bends due largely to the extent of upstream flow curvature and degree of turning of tributary flow into the downstream channel. Flow structure inherited from curvature of both the main and tributary channels upstream of ORWR yields two distinct counter-rotating, surface-convergent helical cells within the confluence (Figures 4.10A,B, cross-sections L and N). Opposing patterns of flow curvature within the central region of the junction, which have
been shown to induce helicity at asymmetrical and symmetrical confluences with concordant beds (Ashmore et al., 1992; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Bradbrook et al., 2000; Rhoads and Sukhodolov, 2001), reinforce patterns of fluid rotation within the dual helical cells and enhance lateral advection of near-surface downstream momentum toward the mixing interface. Both helical cells persist in the downstream channel, although the size of the cells depends strongly on $M_r$. The cells weaken substantially approximately 600 m (about 1 channel width) downstream from the center of the confluence as the hydraulic impacts of the confluence on flow patterns diminish.

The results indicate that when tributary channels are relatively straight (e.g., WRVR), helical motion does not develop in the tributary upstream of the confluence. In such cases, helical motion inherited from flow curvature on the main river occupies most of the downstream channel when $M_r < 1$ (Figure 4.16A). Low-velocity tributary flow is unable to deflect high-momentum, near-surface fluid advected laterally by the helical cell away from the outer portion of the channel. Thus the overall pattern of fluid motion at the junction for low $M_r$ is almost entirely dictated by helical motion through the meander bend (Figure 4.16A). For $M_r > 1$, the high-velocity core of the tributary confines a less organized helical cell from the main river to the center and inner portion of the bend (Figure 4.16B). A second helical cell with clockwise circulation emerges over the outer portion of the downstream channel as the accelerated tributary flow curves slightly upon entering the confluence. These counter-rotating cells weaken and begin to dissipate in the downstream channel.

The development and evolution of helical flow cells at high-angle (ORWR) and low-angle (WRVR) confluent meander bends for different $M_r$ is consistent with findings of channel-scale helicity at many small concordant-bed confluences (Mosley, 1976; Ashmore and Parker, 1983;
Best, 1987; Ashmore *et al.*, 1992; Bridge, 1993; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads and Sukhodolov, 2001; Riley and Rhoads, 2012). However, recent studies have asserted that nonlinear scaling relations between small and large channel confluences may preclude the development or significantly limit the size of such secondary flow cells at large river junctions. Field work at a large confluence-diffuence on the Paraná River in Argentina found no discernible pattern of helical motion (Parsons *et al.*, 2007), while further downstream, dual counter-rotating, surface-convergent helical cells were detected over a small proportion of the flow width adjacent to the shear layer at two braid bar confluences (Szupiany *et al.*, 2007, 2009). The reasons for the absence and diminished extent of helicity at these large confluences are not entirely clear, although increased distortion of channel shape in large rivers with high width-depth ratios (W/D) likely alters the relationship between flow and channel form observed at small confluences (Rhoads, 2006; Parsons *et al.*, 2008). Lower W/D at ORWR (W/D = 59-72) and WRVR (W/D = 31-36) compared to the Paraná River confluences (W/D ≈ 100-200) may explain in part the disparity in helical motion between these sites and indicates a W/D threshold may exist in rivers for the development of large-scale helical motion. The presence of dunes and bar forms may also inhibit the development of secondary flow cells by increasing bed roughness in large rivers that disrupts patterns of divergence between near-surface and near-bed fluids (McLelland *et al.*, 1999; Parsons *et al.*, 2007). Such dune forms were not observed at ORWR or WRVR.

Patterns of near-surface water temperature reveal a well-defined mixing interface between the converging flows at each site that extends through the cross sections of the downstream channel, indicating little mixing of the flows occurs within the vicinity of either confluence (Figures 4.12, 4.14). The mixing interface at the high-angle confluent meander bend (ORWR) is
roughly flanked by dual counter-rotating helical cells on each measurement date (Figure 4.10), similar to patterns identified at a small confluent meander bend with similar junction angle (Riley and Rhoads, 2012). At the low-angle confluent meander bend (WRVR), the interface aligns closely with the margin of the high velocity core of the dominant tributary and the lower velocity of the adjacent subordinate flow (Figure 4.13). Lateral advection of downstream momentum penetrates the interface, especially for low $M_r$, yet the temperature differential persists between the main river and tributary flow downstream of the confluence. This lack of mixing between incoming flows, despite the existence of secondary flow, differs from findings at a small asymmetrical confluence where helical motion appears to distort the mixing interface and enhance mixing (Rhoads and Sukhodolov, 2001).

Flow separation has been shown to develop at the angular downstream junction corner of experimental channels (Best and Reid, 1984; Best, 1987; Roberts, 2004), but often is not found at the more rounded corner of natural confluences where tributary flow may remain attached to the channel bank upon turning into the downstream channel (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Rhoads and Sukhodolov, 2001). Previous field work at a high-angle confluent meander bend found that tributary flow accelerated upon entering the confluence over the outer portion of the downstream channel to maintain continuity, thereby preventing flow separation (Riley and Rhoads, 2012). The absence of flow separation at the low-angle WRVR is largely attributable to minimal turning of tributary flow into the confluence. The nearly linear configuration of the Vermilion River with the downstream channel allows high velocity fluid from the tributary to remain attached to the bank when $M_r > 1$ (Figure 4.13B), whereas advection of downstream momentum from the Wabash River across the channel when $M_r < 1$ confines low velocity flow from the tributary to the bank below the downstream junction corner (Figure
4.13A). A flow separation zone is present on both measurement dates at the high-angle ORWR, although the zone is broader when $M_r > 1$ (Figure 4.10B). Fluid in the tributary is topographically steered toward the outer bank of the curving channel upstream of the confluence by a point bar along the inner bank. This lateral deflection of flow by morphologic features has also been shown to affect flow separation at a small symmetrical confluence (Rhoads and Sukhodolov, 2001). Increased flow deflection by the Ohio River when $M_r < 1$ forces tributary flow to turn more abruptly into the downstream channel and narrows the flow separation zone (Figure 4.10A).

The response of bed morphology to changes in $M_r$ differs between ORWR and WRVR, suggesting that differences in junction angle influence the development and spatial extent of geomorphic features at confluent meander bends. Compilation of the results of several studies have documented a general relationship between bed scour depth within the central region of many natural and laboratory junctions for a range of junction angles and channel sizes (Figure 4.17). The data exhibit a wide range of scatter, which can be attributed to other controlling factors, such as $M_r$, junction planform, and bed discordance. Data plotted for ORWR, WRVR, and the junction of the Little Wabash River and Big Muddy Creek (LWRBMC), the confluent meander bend investigated in Chapter 3, lie at the low end of the scour depth-junction angle range. Less pronounced bed scour at these field sites compared to confluences with other types of planforms may indicate that the intensities of mechanisms linked to enhanced bed shear stresses and scour development are not as great at confluent meander bends as at other confluences. Such mechanisms include helical motion that advects momentum of high-velocity near-surface flow downward toward the bed along the flanks of the mixing interface (Rhoads, 1996; Rhoads and Kenworthy, 1998), acceleration of flow through the central region of the
Figure 4.17. Relative scour depth ($d_r$) at natural and laboratory junctions plotted against confluence angle in degrees (after Sambrook Smith et al., 2005; Best and Rhoads, 2008). Relative scour depth is computed as the ratio of depth of the scour hole to the average flow depth in the upstream tributaries. Data sources include Mosley, 1975, 1976, 1982; Ashmore and Parker, 1983; Best, 1985, 1988; Klaassen and Vermeer, 1988; Roy et al., 1988; Roy and DeSerres, 1989; Orfeo, 1995; Delft Hydraulics and Danish Hydraulics Institute, 1996); McLelland et al., 1996; Sarker, 1996; Best and Ashworth, 1997; Rhoads and Sukhodolov, 2001; and research conducted at three natural confluent meander bends in this study (red filled symbols and labeled).

Confluence and downstream channel (Rhoads and Kenworthy, 1995), and turbulence within the shear layer (Best, 1987; Biron et al., 1993b; DeSerres et al., 1999; Rhoads and Sukhodolov, 2008). The results of this study do not provide sufficient information to comprehensively evaluate the relative effectiveness of scour mechanisms at confluent meander bends and other confluences. Further research is needed to determine whether confluent meander bends consistently exhibit less pronounced scour than other confluences and, if so, to fully elucidate the factors leading to diminished scour at these types of confluences.
At ORWR, the path of the navigation pool in the Ohio River through the confluence (Figure 4.4A) generally coincides with the position of its high-velocity core and helical cell for low $M_r$ (Figure 4.10A). Near-bed fluid is directed inward by this cell, sweeping sediment away from the center of the junction and over the face of the broad inner bank point bar. Extensive rearrangement of bed morphology due to an influx of sediment following a large tributary-dominant discharge event (Zinger et al., 2011) led to the protrusion of a wedge of sediment from the mouth of the Wabash River into the center of the confluence that disrupted the curvilinear path of the pool (Figure 4.4B). The continued influx of sediment from the tributary and increased penetration of tributary flow for high $M_r$ shifted the pool laterally to a position near the inner bank (Figure 4.4C). Truncation of the point bar increases channel asymmetry through the center of the confluence and upstream end of the downstream channel. This pattern of bed topography – where the deepest part of the channel is positioned against the inner bank and a bar platform extends over the outer bank – is opposite of the pattern found in most meander bends, but conforms to findings from a small natural confluent meander bend (Riley and Rhoads, 2012).

The comparative uniformity of the channel bed between measurement dates and absence of substantial bed scour at the low-angle WRVR contrasts substantially with the morphodynamics of the high-angle ORWR. While central bed scour is a common feature at many confluences and a tenet of the conceptual model of bed morphology at confluent meander bends (Figure 4.1), previous field studies have found that scour can be shallow or even absent from junctions with discordant beds (Biron et al., 1993b) and at confluences with high bed roughness (Roy et al., 1988) and low junction angle (Figure 4.17). At WRVR, the low angle of tributary entry at the downstream end of a meander bend limits the extent of deflection between the confluent flows, which has been shown to reduce scour depth at the junction of experimental channels (Mosley,
Furthermore, tributary-dominant flow conditions that may lead to the emergence of a second, counter-rotating helical cell are rare and too short-lived to significantly alter bed morphology (Figures 4.3B,D). Thus, a small, shallow (< 0.5 m) scour hole is positioned downstream of the junction apex (Figure 4.6) underlying the upstream end of the mixing interface (Figure 4.14) on each measurement date.

The relative stability of the bed and minimal scouring at WRVR results in persistence of the Wabash River point bar through the downstream channel. The persistence of the bar at low-angle confluent meander bends is a deviation from the conceptual model (Figure 4.1) and findings of Riley and Rhoads (2012) because tributary flow is ineffective at deflecting flow from the main river inward due to weak flow convergence, but is consistent with patterns of bed morphology typically found in meander bends (Dietrich, 1987). The point bar is constricted by a wide pool near the bend apex, but broadens downstream as channel width increases at the junction (Figure 4.6). Minor degradation of the bar arises from shifting of the high-velocity core of the Wabash River to the center and inner portion of the channel cross-section due to deflection from high-velocity flow in the Vermilion River when $M_r$ increases.

Two processes have been proposed to explain bar development along the downstream junction corner of confluences – deposition of entrained sediment within a low-velocity zone of separated flow (Best, 1988) and deposition of bedload due to reduced transport capacity (Rhoads and Kenworthy, 1995; Rhoads, 1996; Best and Rhoads, 2008). While Roberts (2004) documented flow separation from the downstream junction corner in laboratory experiments and numerical models of confluent meander bends, the presence of a junction corner bar at a small natural confluent meander bend is likely related to sediment-flux convergence when $M_r > 1$ (Riley and Rhoads, 2012). Bar formation at the junction corner of ORWR is largely due to
curvature of the Wabash River immediately upstream of the confluence. The bar forms within a broad region of deposition that begins along the inner bank of the tributary in the upstream channel, where a point bar develops through sediment flux convergence (Nelson and Smith, 1989), and continues around the junction corner into the downstream channel (Figure 4.4). The bar enlarges below the downstream junction corner for increasing $M_r$ (Figure 4.5, cross-sections L-O), presumably due to diminished sediment transport capacity along the outer bank as the high-velocity core and helical cell of the tributary penetrate far into the confluence. The bar stores some of the sediment from the meander cutoff and its size is greater than the overlying zone of detached flow (Figure 4.10), suggesting that deposition of bedload related to patterns of decreasing bed shear stress downstream of the junction corner is primarily responsible for development of the bar, as opposed to flow separation. The absence of flow separation at WRVR and the comparatively linear alignment of the tributary with the downstream channel prevent the development of a junction corner bar.

The mobilization and transport of large amounts of sediment through ORWR following tributary-dominant discharge events that produced a meander cutoff on the Wabash River (Zinger et al., 2011) confirms that rapid rearrangement of bed morphology can occur in response to changing $M_r$ at large confluences in a manner similar to the dramatic changes in bed morphology documented at small confluences (Best, 1988; Biron et al., 1993b; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads et al., 2009). The large influx of sediment into the confluence at ORWR and contrasting response of bed morphology at ORWR and WRVR to different $M_r$ brings into question factors that may control long-term stability of the confluent meander bend planform. Previous work at a small natural confluent meander bend with a 90° junction angle revealed minimal change of the bed during the course of a field campaign
spanning more than 1 year (Riley and Rhoads, 2012), similar to WRVR, and analysis of aerial photographs of the confluence over many decades supports the hypothesis that this type of junction planform is a quasi-stable channel configuration in meandering river networks (Parker, 1996). Similar airphoto analysis for ORWR and WRVR illustrates differences between these confluences in the evolution of their planforms over the long-term. A comparison of the position of channel centerlines at ORWR from aerial photographs between August 22, 1940 and April 15, 2005 show that the mouth of the Wabash River has migrated over 500 m upstream along the outer bank of the meander bend of the Ohio River due to strong curvature of Wabash River.


immediately upstream of the confluence. This curvature has promoted outer bank erosion and growth of the point bar along the inner bank of the tributary (Figure 4.18). Conversely, assessment of WRVR between July 9, 1939 and April 8, 2005 reveals nominal change in the spatial relationship between the confluent channels and indicates prevailing outward flow from the main river is unable to erode the channel bank downstream of the mouth of the tributary (Figure 4.19). These differences in planform stability suggest that tributary curvature immediately upstream of the junction can effect significant long-term planform change in confluent meander bends.
4.6 Conclusion

This research contributes to emerging knowledge of the hydro- and morphodynamics of confluent meander bends by investigating the response of 3-D flow structure and bed morphology to changes in $M_r$ at two large confluent meander bends with different tributary entry angles and locations around bends. The results show the importance of junction angle and tributary entry location on flow structure and bed morphology, providing the basis for elaboration of a conceptual model of the dynamics of confluent meander bends based on previous experimental, field, and numerical modeling studies (Roberts, 2004; Riley and Rhoads, 2012). The findings are also consistent with relationships between junction angle and hydrodynamic conditions for asymmetrical and symmetrical confluences (Mosley, 1976; Best, 1987). Strong flow deflection at the high-angle confluent meander bend (ORWR) augments helical motion inherited from flow curvature through meander bends in the main and tributary channels upstream of the junction, producing twin surface-convergent, counter-rotating helical cells that vary in relative size with changes in $M_r$. This dual cell structure persists through the downstream channel and laterally transfers downstream momentum from the confluent flows toward the mixing interface at the surface. At the low-angle junction (WRVR), the nearly linear configuration of the straight tributary channel with the downstream channel limits the extent of turning of tributary flow at the confluence and inhibits helical motion for prevailing low $M_r$ conditions. Instead, a single large helical cell inherited from flow curvature in the main river upstream of the confluence extends across most of the downstream channel. A weak counter-rotating helical cell forms over the outer portion of the bend for large $M_r$, when high-velocity fluid from the tributary confines flow from the main river to the center and inner portions of the downstream channel.
The mixing interface at each site is defined by a near-surface water temperature differential between the confluent rivers that extends through the downstream channel. The mixing interface is generally positioned between the helical cells at the high-angle confluence, whereas the interface aligns with the margin of the high-velocity core of the dominant tributary and adjacent low-velocity flow from the subordinate tributary at the low-angle confluence. The persistent temperature differential between flows at both sites suggests that mixing is limited and not greatly enhanced by lateral advection of momentum from helical motion within the confluence and downstream channel – a finding that contrasts with patterns of thermal mixing at small confluences with strong helical motion (Rhoads and Kenworthy, 1995; Rhoads and Sukhodolov, 2001). Complete mixing may not occur for a substantial distance downstream of these large river confluences (Mackay, 1970; Stallard, 1987).

Channel and hydrological properties of the tributary largely affect patterns of bed morphology at both sites. A lateral bar at the downstream junction corner of the high-angle confluence is the downstream extension of a larger depositional area that begins with the development of a point bar along the inner bank or the curving tributary channel upstream of the confluence. Tributary flow deflects flow and helical motion in the curving main river away from the outer bank of the bend. A helical cell inherited from curvature of tributary flow upstream of the junction sweeps sediment from the pool over the bar platform, and collectively with flow separation from the downstream junction corner, induces bar development where bank erosion typically occurs downstream of the bend apex (Dietrich, 1987). Long-term planform change is attributable to growth of this bar structure and outer bank erosion that forces the mouth of the tributary to shift upstream along the outer bank of the main channel meander bend. A broad inner bank point bar on the main river persists through the downstream channel for low $M_r$, but the
inward displacement of the pool by a large influx of sediment into the confluence from the formation of a meander cutoff on the tributary resulted in scour of this bar across from the mouth of the tributary. Enhanced penetration of tributary flow into the confluence for large $M_r$ shifts the mixing interface inward and confines flow and the helical cell of the main river to the inner portion of the bend overlying this region of increased shear stress.

Bed morphology is comparatively stable at the low-angle confluence, where the infrequency and flashiness of tributary-dominant flows prevents substantial adjustment of the bed. The low-angle of tributary entry at the downstream end of a meander bend on the main river limits the extent of flow deflection and produces little bed scour. The inability of tributary flow to penetrate the center and inner portion of the bend, even during large $M_r$, results in minimal change to the large inner bank point bar on the main river. Negligible change in the bed morphology at WRVR is consistent with long-term planform stability.

Additional studies that document the influence of 1) different configurations between the tributary and main channel, such as the dynamics of a confluent meander bend where the tributary curves in the same direction as the main channel, and 2) different physical and hydrological channel characteristics, including the impact of upstream tributary curvature at confluent meander bends with low junction angles, are needed to more fully ascertain the control each has on confluent meander bend hydro- and morphodynamics. Continued work at the high-angle confluence is of critical importance to document the long-term response of bed morphology at a large confluent meander bend to influxes of sediment from upstream channel change on the tributary and may provide insight into the factors that influence the evolution of this type of confluence planform. The results of this study indicate long-term planform stability may not be related to the development of a bar along the downstream junction corner (Riley and
Rhoads, 2012), but rather to the ability of tributary flow to deflect main river flow away from the outer bank and the extent of channel curvature immediately upstream of the junction.
CHAPTER 5. CONCLUSIONS

5.1 Summary of findings related to research objectives

This research has documented the response of patterns of flow and bed morphology at three natural confluent meander bends with different geometric properties to hydrological variability. The results supplement findings from previous experimental and numerical research of confluent meander bends (Roberts, 2004) with field data to evaluate flow structure in erodible channels and how flow processes are related to bed morphology. The research assesses the influence of controlling factors on flow and bed morphology at natural confluent meander bends, including momentum-flux ratio ($M_r$), junction angle, and tributary entrance location. A general conceptual model of the hydro- and morphodynamics of confluent meander bends is proposed based on this field research, the modeling work of Roberts (2004), and current knowledge of confluence and meander bend dynamics. The conclusions of the research suggest that patterns of flow and channel morphology at confluent meander bends are quite different from typical patterns in meander bends, but are not dissimilar to those found at asymmetrical confluences.

The research was guided by objectives described in Chapter 1 and restated below with an evaluation of the findings relevant to each. This discussion begins with objective 6 because the development of a conceptual model provided the overarching framework from which field results were evaluated and compared to improve understanding of confluent meander bend dynamics.

6) integrate collected field data with results from laboratory experiments and numerical modeling to develop a conceptual model of confluent meander bend dynamics
A conceptual framework based on the modeling work of Roberts (2004) and current knowledge of confluence and meander bend flow dynamics is introduced in Chapter 3 and served as the basis from which to evaluate the field results. The model includes hydrodynamic zones that are commonly observed at confluences (Best, 1987), including 1) flow stagnation near the junction apex, 2) mutual deflection of converging flows in the central region of the confluence, 3) turbulence along a shear layer generated between the flows, 4) flow separation at the downstream junction corner, 5) flow acceleration through the junction, and 6) flow recovery in the downstream channel where flow structure returns to patterns associated with a meandering channel. Deflection-induced curvature of tributary flow initiates helical motion over the outer portion of the downstream channel. The tributary deflects the high-velocity core and helical motion inherited from channel curvature of the main river upstream of the confluence to the inner portion of the bend. Twin helical cells develop on either side of the mixing interface and respond to fluctuations in $M_r$.

The model is expanded upon in Chapter 4 to integrate findings on three-dimensional (3-D) flow structure and bed morphology at the junction of the Little Wabash River and Big Muddy Creek (LWRBMC), a small natural confluent meander bend with a junction angle of 90°. The morphologic components of the model include a broad scour hole that corresponds with the position of the high-velocity core of the main river, extending from the center of the junction to the inner portion of the bend where it impedes point-bar development in the receiving channel. Channel cross-sectional area is constricted by bar development along the downstream junction corner, causing the combined flows to accelerate through the receiving channel and precluding flow separation from the rounded junction corner. Deviations from the model at confluent meander bends with different tributary entry angles and locations around bends are also
discussed in Chapter 4. Findings of these field studies are summarized in review of objectives 1, 2, and 3 below.

1) obtain field data on 3-D flow structure at a 90° confluent meander bend with erodible channel boundaries for different $M_r$ to evaluate the findings of previous experimental and numerical research

Flow structure at LWRBMC was derived from measurements of 3-D velocity components for flow conditions when $M_r \approx 1$ and $M_r < 1$. Patterns of flow are comprised of many of the hydrodynamic features identified in the conceptual model. A zone of flow stagnation initially segregates the high-velocity cores of the converging streams near the upstream junction corner. Maximum velocities of the main river are confined to the inner portion of the channel cross section within and immediately downstream of the confluence due to the development of the stagnation zone and flow deflection by the tributary, resulting in the inward displacement of the thalweg. On the opposite side of the mixing interface, the high junction angle forces the tributary flow to abruptly turn into the downstream channel, producing a counter-rotating helical cell along the outer bank of the bend. The size and intensity of the twin helical cells in the downstream channel are largely controlled by $M_r$. The high-velocity cores of each stream coalesce in the receiving channel, where cross sectional area is reduced by a bar along the downstream junction corner. Shoaling of flow over the face of the bar causes acceleration of the combined flows and inhibits flow separation. This finding is the main discrepancy with the conceptual model, but is consistent with previously identified differences between the geometry of the downstream junction corner at experimental and natural junctions (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Rhoads and Sukhodolov, 2001).
2) ascertain patterns of bed morphology at natural confluent meander bends, as the design of previous modeling work used fixed boundaries with rectangular channel cross sections, and document the effect of variation in $M$, on the configuration of the bed.

Patterns of bed morphology at LWRBMC are similar to those of an asymmetrical confluence (Rhoads et al., 2009), but differ from typical patterns of erosion and deposition observed at most meander bends without inflowing tributaries (Dietrich, 1987). A broad scour hole within the central region of the junction generally underlies the high-velocity core and helical cell of the main river that is deflected inward by the tributary flow. Inner bank erosion and scouring of the bank toe limits point-bar development across from the mouth of the tributary and into the downstream channel. Confinement of high-velocity flow from the main river to the inner part of the bend and the formation of a bar at the downstream junction corner protects the outer bank from erosion. The formation of this bar is likely related to deposition of bedload due to decreased bed shear stresses around the junction corner during formative flows. Further study of the development of this bar is needed, especially for channel-shaping flow events, as it may be critical to the long-term stability of confluent meander bends. Channel morphology remains largely unchanged in response to fluctuations in $M$, although data were not collected for $M > 1$. Minor adjustments in bed morphology include slight scouring of the inner bank toe and bar-building at the downstream junction corner when $M$ increases.

3) examine the influence of variation in planform geometric characteristics, such as differences in junction angle and the location of tributary entry around bends, on 3-D flow structure and bed morphology.
The impact that junction angle and tributary entrance location have on 3-D flow structure and bed morphology were compared between two large confluent meander bends for high and low $M_r$. Patterns of flow and bed morphology at the high-angle junction of the Ohio River and Wabash River (ORWR), where the tributary enters the main channel near the apex of a bend, generally resemble patterns at the smaller LWRBMC junction for $M_r < 1$. Curvature of the tributary channel immediately upstream of the junction supports a large depositional region that begins at the point bar along the inner bank of the tributary upstream of the confluence and extends around the junction corner into the downstream channel. A helical cell inherited from upstream channel curvature sweeps sediment from the centrally positioned pool over the face of the lateral corner bar. Enhanced penetration of tributary flow into the confluence for $M_r > 1$ shifts the mixing interface toward the inner bank of the bend of the main channel and increases flow separation at the downstream junction corner. The size of the lateral bar increases as well, although much of the growth is in response to large, tributary-dominant discharge events that delivered a large amount of sediment to the junction as the result of the development of a meander cut-off upstream of the confluence on the tributary. Flow in the main river is deflected toward the inner bank, where the point bar was substantially eroded during the aforementioned tributary-dominant flows.

The low angle of tributary entry at the downstream end of a meander bend at the confluence of the Wabash and Vermilion Rivers (WRVR) limits the extent of flow deflection such that the converging flows almost parallel each other at the entrance of the junction. A large helical cell imparted from upstream flow curvature in the main river occupies most of the downstream channel for prevailing $M_r < 1$ conditions. A weak counter-rotating cell forms during infrequent tributary-dominant flow events. The near linear alignment of the tributary with the receiving
channel precludes flow separation and bar-development at the downstream junction corner. Bed morphology remains relatively stable and lacks significant scouring that usually occurs at confluences with concordant beds, but is consistent with reduced scour depths at confluences with low junction angles (Mosley, 1976; Best, 1988).

4) determine if hydro- and morphodynamic features at confluent meander bends translate across spatial scales

Generally, many hydro- and morphodynamic features identified at a small natural confluent meander bend (LWRBMC) also develop at a large natural confluent meander bend (ORWR) with a similar junction configuration (i.e., 90° junction angle, location of tributary entrance near bend apex). The spatial arrangement of these features is similar between the junctions for $M_r < 1$, when two surface-convergent helical cells overlie a broad zone of central bed scour, downstream of a flow stagnation zone at the upstream junction corner, and adjacent to a bar at the downstream junction corner where bank erosion typically occurs below the bend apex (Dietrich, 1987). A notable difference between the confluences is the extent of point-bar development along the inner bank of the main river. A broad bar persists into the downstream channel at ORWR, whereas the point bar is truncated across the confluence from the mouth of the tributary at LWRBMC. Scouring of the bar at ORWR during large tributary-dominant discharge events produces similar erosional patterns as those observed at the inner bank of the bend at LWRBMC, suggesting differences in bar morphology at the two sites for $M_r < 1$ may not be scale-related, but may reflect differences in the frequency of $M_r > 1$ events between the junctions that are capable of scouring the point bar. Differences in the origin of helicity within the tributary flow between the confluences also do not appear to be associated with scaling relations, but with differences in
upstream curvature of the tributary channel. Accurate comparison of features for $M_r > 1$ is limited by the lack of data for such flows at LWRBMC and dramatic rearrangement of bed morphology at ORWR between surveys. Further work is needed to measure flows with comparable $M_r$ between field sites and isolate the impacts of upstream channel curvature to provide a more thorough comparison of flow and morphologic features based on junction size.

5) compare repeat aerial photographs to determine if the meander bends at each site are migrating over time or if the confluent channels remain relatively stable

The analysis of repeat aerial photographs over a period of many decades at LWRBMC and WRVR indicate that the planforms of these junctions are stable, whereas the mouth of the tributary at ORWR has migrated upstream along the outer bank of the main river. The assessment of the relative stability of channel morphology at this type of confluence planform was driven by 1) the hypothesis that tributary-deflection of the high-velocity core of the main river away from the outer bank of the bend and development of a flow separation zone at the downstream junction corner of experimental confluent meander bends (Roberts, 2004) may prompt deposition rather than outer bank erosion at natural confluent meander bends, similar to lateral-bar formation at some asymmetrical junctions (Best and Reid, 1984; Best, 1987; Rhoads and Kenworthy, 1995; Rhoads, 1996), thereby limiting bend migration, and 2) speculation that confluent meander bends may represent a quasi-stable channel configuration in meandering river networks (Parker, 1996). The results indicate that the stability of this planform may not be related to bar-development at the downstream junction corner. While long-term planform stability at LWRBMC conforms to this premise, nominal change in the spatial relationship between the confluent channels or the position of the meander bend also occurred at WRVR,
where nearly linear alignment of the tributary with the downstream channel prevents lateral-bar development at the junction corner. At ORWR, growth of the point bar within a broad depositional region that encompasses the inner bank of the curving tributary and downstream junction corner and outer bank erosion have actually led to migration of the mouth of the tributary along the outer bank of the meander bend on the main river. Differences in planform stability between these sites suggest that the extent of tributary curvature and related point-bar building and cut bank erosion upstream of the junction can effect long-term planform change in confluent meander bends. Additional work is needed beyond this small sample to identify factors that control the long-term stability of this confluence planform.

5.2 Future work

This research examined 3-D flow structure and bed morphology at natural confluent meander bends with different junction angles and tributary entrance locations. The arrangement of the tributaries at each of the field sites are such that the tributary either does not curve appreciably upstream of the confluence (LWRBMC and WRVR) or curves in the opposite direction of the main channel (ORWR). These configurations produce or enhance helical motion of the tributary flow, except for $M_r < 1$ at WRVR, which is opposite to the rotation of the helical cell in the main river originating from upstream channel curvature. Additional work is needed to document patterns of flow and bed morphology at confluent meander bends where the tributary curves in the same direction as the main channel (Figure 5.1), hypothetically producing twin helical cells with the same sense of rotation upon entering the junction. The results of the research also demonstrate that junction angle and the extent of upstream tributary curvature are factors that control confluent meander bend dynamics. Further research on planform geometric
Figure 5.1. Aerial photograph of the confluence of the West Fork and East Fork of the White River in southwestern Indiana on June 7, 2012. Generally, the West Fork flows north to south and the East Fork flows east to west. Note the tributary and main channel curve in a similar direction near the junction.

characteristics, such as the effect of upstream tributary curvature at low-angle confluent meander bends and variation in junction angle at different locations around a bend (e.g., low angle of tributary entry near a bend apex, high angle of tributary entry near the downstream end of a bend), is necessary to advance a comprehensive model of confluent meander bend dynamics.

A limitation of confluence research has been the paucity of data to link morphologic change to flow patterns and sediment transport during formative events. Measured flows at each of the field sites in this study were not highly effective at reshaping the channel bed. Bed morphology remained relatively stable at two of the confluent meander bends for different $M_r$ (LWRBMC and WRVR). Substantial morphologic change occurred between measurement dates at the large high-angle junction (ORWR) due to large, tributary-dominant discharge events that produced a
meander cut-off upstream of the confluence. Research is needed to not only link bed morphology change to flow structure during formative flows, but to document the long-term response of confluent meander bend morphology to upstream channel disturbances, which may provide further insight into how these types of junctions regulate the longitudinal distribution of sediment in meandering river systems (Ashmore and Parker, 1983).

The persistence of the mixing interface through the downstream channel of large confluent meander bends (ORWR and WRVR), based on differences in near-surface water temperature between the converging flows, suggests that helical motion induces little mixing of these flows within the vicinity of the confluence. However, further work is needed to document 3-D patterns of mixing over the entire flow depth to determine the extent of mixing below the surface. Thorough investigation of the spatial evolution of the mixing interface within and downstream of the junction and the extent of turbulence generated along the shear layer between the flows should reveal patterns of mixing at confluent meander bends. Additionally, this research did not document the development of a helical cell near the outer bank of the meander bend on the main river upstream of the junction of the field sites. The evolution of this cell and its impact on confluent meander bend dynamics at bends where it does form needs to be established.

Further work is needed to more fully elucidate the prevalence and spatial distribution of different tributary configurations at confluences in meandering river systems. Previous investigations of tributary development and arrangement (Flint, 1980; Abrahams, 1984) and inventories of tributary junction locations along bends of a few selected meandering rivers in Minnesota (Hills, 1983) have noted the preferential entry of tributaries on the outside of meander bends. A systematic inventory of tributary entrance locations in meandering river systems based on measures of planform geometric parameters (e.g., position of tributary entrance, radius of
channel curvature, junction angle) would provide a more definitive assessment of the prevalence of confluent meander bends compared to other junction planforms. Additional study of the evolution of confluent meander bends is necessary to evaluate the long-term stability of the planform and better identify factors that may control this stability. Comparison of historical and modern aerial photographs provides an effective means of planform change assessment, and may also provide insight into events that lead to the formation of these fluvial features.
REFERENCES


