Influence of junction angle on three-dimensional flow structure and bed morphology at confluent meander bends during different hydrological conditions

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ABSTRACT: Recent field and modeling investigations have examined the fluvial dynamics of confluent meander bends where a straight tributary channel enters a meandering river at the apex of a bend with a 90° junction angle. Past work on confluences with asymmetrical and symmetrical planforms has shown that the angle of tributary entry has a strong influence on mutual deflection of confluent flows and the spatial extent of confluence hydrodynamic and morphodynamic features. This paper examines three-dimensional flow structure and bed morphology for incoming flows with high and low momentum-flux ratios at two large, natural confluent meander bends that have different tributary entry angles. At the high-angle (90°) confluent meander bend, mutual deflection of converging flows abruptly turns fluid from the lateral tributary into the downstream channel and flow in the main river is deflected away from the outer bank of the bend by a bar that extends downstream of the junction corner along 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. A large influx of sediment to the confluence from a meander cutoff immediately upstream has produced substantial morphological change during large, tributary-dominant discharge events, resulting in displacement of the pool inward and substantial erosion of the point bar in the main channel. In contrast, flow deflection is less pronounced at the low-angle (36°) confluent meander bend, where the converging flows are nearly parallel to one another upon entering the confluence. A large helical cell imparted from 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. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: confluent meander bends; confluences; flow structure; bed morphology; junction angle

Introduction

The convergence of separate flows at river confluences produces a complex hydrodynamic 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; Bristow et al., 1993; Biron et al., 1993a, 1993b; 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., 2004, 2005; 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; McLelland et al., 1996; Biron et al., 1996a, 1996b), 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 (M), junction angle, and equal (concordant) or unequal (discordant) bed elevations of the confluent channels as the primary factors influencing patterns of three-dimensional (3D) fluid motion and bed morphology at junctions.
Confluence research has focused mainly on angular junction platoons with straight approach channels and 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, 1984b), forming confluent meander bends. Experimental work and numerical modeling of the hydrodynamics of this type of confluence platoons (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. Recent work has also shown that inherited flow conditions from upstream channel curvature can influence the structure of flow within confluences (Dordevic, 2013) and at bifurcations (Kleinhans et al., 2013).

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 (e.g. Mosley, 1976; Best, 1987). However, research is needed to evaluate how differences in the location of the tributary mouth around the bend and the angle of tributary influence patterns of fluid motion in confluuent meander bends, to relate these patterns of fluid motion to bed morphology, and to explore the influence of upstream channel curvature on flow structure at natural confluences.

This paper examines the response of flow structure and bed morphology to hydrological events with different momentum-flux ratios at two large confluent meander bends with different tributary entry angles. Cross-sectional measurements of 3D velocity components are obtained for high ($M_1 > 1$) and low ($M_1 < 1$) 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 ($M_1 > 1$) 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). The results provide critical insight into the response of flow and morphological features to variation in geometric and hydrological controlling factors, and contribute to the advancement of a comprehensive model of confluent meander bend dynamics.

**Field Sites**

Two confluent meander bends with different junction angles along the Wabash River, USA were selected as study sites for the research (Figure 1). 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 km²) is over three times greater than the drainage area of the Wabash River (85 237 km²). 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 about 675 m downstream of the confluence. The Wabash River bends sharply as it joins the Ohio River. Channel width increases from 300 m upstream of the junction to 475 m at the mouth of the river. Maximum channel depth at the mouth of the Wabash River is approximately 10.5 m, whereas maximum depths in the Ohio River are as great as 15 m.

The John T. Myers Locks and Dam is 3.2 km upstream of the junction on the Ohio River, but does not disrupt patterns of flow at 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 (0.00010) is steeper than the gradient of the Ohio River (0.00006) below the John T. Myers Locks and Dam. Bed material at the site is comprised primarily of coarse sand with a minor amount (<10%) of fine gravel.

The second study site, the confluence of the Wabash River and Vermilion River (WRVR), is located 375 km upstream of ORWR in west central Indiana. The Vermilion River enters the Wabash River downstream of the apex of a meander bend on the Wabash River at an angle of 36°. At the confluence, the drainage area of the Wabash River (21 481 km²) is nearly six times larger than the drainage area of the Vermilion River (3714 km²). The Vermilion River upstream of the confluence is relatively straight and aligned with the downstream channel of the Wabash River, whereas the Wabash River curves both upstream and downstream of the confluence. The Vermilion River is about 60 m wide at its mouth and the Wabash River is approximately 140 m wide. Bankfull channel depth is about 6 m in the Vermilion River and 6–8 m in the Wabash River. Average channel gradients upstream of the confluence are 0.00007 for the Wabash River and 0.00028 for the Vermilion River. Bed material at the junction consists of a mixture of coarse sand and gravel.

**Field Methods and Data Analysis**

Field data for the two study sites include measurements of incoming flow, 3D velocities, near-surface temperatures, and bed morphology. Measurements of discharge and mean velocity obtained at two cross-sections of the confluent rivers immediately upstream of each junction were used to compute the momentum-flux ratio ($M_1$) of the incoming flows:

$$M_1 = \frac{\rho Q_2 U_2}{\rho Q_1 U_1}$$  \hspace{1cm} (1)

where $\rho$ is fluid density (in kg m$^{-3}$), $Q$ is discharge (in m$^3$ s$^{-1}$), $U$ is mean cross-sectional velocity (in m s$^{-1}$), and the subscripts 1 and 2 refer to the main river and tributary (upstream river with the smallest drainage area), respectively. To assess change in hydraulic conditions, water-surface elevations during periods of field measurements at ORWR were determined from stage data for the John T. Myers L/D lower gage on the Ohio River (Figure 1A), whereas at WRVR, water-surface elevations were surveyed near the upstream junction corner at the beginning and end of each measurement campaign.

Three-dimensional velocity, water temperature, and bathymetry data were obtained at several cross-sections distributed throughout each confluence. Cross-sections were located...
upstream of the confluence on each river to characterize inherited flow structure, within the central region of the junction, and across the downstream channel (Figures 1C and 1D). Cross-sections at both sites were oriented orthogonally to the direction of the local centerline of either the main channel, which includes cross-sections within the confluence, or the tributary.

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 manufactured by Teledyne RD Instruments (TDRI, Poway, CA) 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; Parsons et al., 2005; Dinehart and Burau, 2005a, 2005b; 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 0.25 m below the transducers. Also, the bottom ~6% of the measured flow depth was removed due to acoustic

Figure 1. Aerial photographs and maps of field sites. National Agriculture Imagery Program photographs of (A) ORWR and (B) WRVR in August 2008, and measurement cross-sections at (C) ORWR and (D) WRVR confluences. Inset map shows location of field sites and drainage basin in gray. This figure is available in colour online at wileyonlinelibrary.com/journal/espl
side-lobe interference in the near-bed returns. The sampling interval of the ADCP ranged between 1.3–1.7 seconds 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 ($M_1 < 1$), whereas a 600 kHz ADCP was used to survey high-momentum flux ratio conditions ($M_1 > 1$) to prevent signal loss associated with elevated acoustic backscatter caused by high suspended sediment concentrations.

Boat position and velocity were determined using a differential global positioning system (DGPS) receiver. The DGPS-receiver provides time-stamped geographic coordinates at 10 Hz with up to sub-meter accuracy and was integrated with the ADCP to fully 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 using software developed by HYPACK, Inc. (Middletown, CT). The DGPS-antenna was affixed to the port side mount directly above the ADCP.

Following recommendations from Szupiany et al. (2007), 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. Wide channels 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.

The Velocity Mapping Toolbox (VMT), an ADCP post-processing software package, was used to compute spatially and temporally averaged 3D velocity data for each cross-section from repeat transect measurements (Parsons et al., 2013). Besides yielding averaged values of downstream ($U_2$), cross-stream ($V$), and vertical ($W$) velocities, VMT also computes lateral velocity components oriented perpendicular to the local depth-averaged velocity vector (Rozovskii, 1957). Previous studies of confluence hydrodynamics have used the Rozovskii rotation method to detect helical motion in strongly converging flows (Rhoads and Kenworthy, 1998; Lane et al., 2000).

Near-surface water temperatures were measured by a sensor in the transducer head of the ADCP. To examine patterns of thermal mixing, 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. The normalized data were spatially interpolated by kriging to produce contour plots of near-surface temperature patterns on each measurement date. The mixing interface was defined by the location where temperature deviation from the cross-sectional mean equals 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 four-beam depths at each ensemble and converting depths to elevations based on flow stage data. Besides data from the cross-section surveys, four to six longitudinal transects throughout each confluence with approximately equal spacing across the width of flow 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.

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Results

Hydrologic and hydraulic conditions

Field data on 3D 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 normalized flow dominance ratio (Zinger et al., 2013), a modified discharge ratio of the converging flows scaled by a formative discharge event for the tributary channel, from mean daily discharge data recorded at upstream river gages. The normalized flow dominance ratio is calculated as:

$$F_d = \left( \frac{Q_2}{Q_1} \right) \left( \frac{Q_3}{Q_2} \right)$$

where $Q$ is discharge (in m$^3$ s$^{-1}$), 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, and the subscript ‘2 yr’ refers to the two-year flood. Plots of $F_d$ against time provide a hydrological context for the ADCP measurement campaigns, and duration curves of index values derived for the periods of record from the upstream river gages show the frequency of the events measured in this study (Figure 2).

At ORWR, low momentum-flux ratio conditions ($M_1 < 1$) prevailed on May 15, 2008 (Table I) 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 John T. Myers L/D lower gage during 7.5 hours of data collection. A series of tributary-dominant discharge events ($M_1 > 1$) followed during the late spring and summer of 2008 (Figure 2A). A second set of field data was collected on January 6, 2009 during high momentum-flux ratio conditions resulting from 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 five hour period during which stage decreased by 0.11 m.

Tributary-dominant flow conditions are infrequent and short-lived at WRVR (Figures 2B and 2D). A period of sustained low discharge-ratio conditions preceded the survey on January 9, 2007 (Figure 2B). 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 $M_1 > 1$ at the confluence on February 6, 2008 (Table I). Data were collected over six hours during the rising stages of this event, in which water levels increased by 0.5 m.

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 3A). The pool turns inward at the upstream junction corner from a position...
against the outer bank, resulting in relatively symmetrical channel cross-section profiles through the center of the confluence and upstream end of the downstream channel (Figure 4, cross-sections L, N, and O). The pool shifts back toward the outer bank farther downstream (Figure 3A, 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 asymmetry of the channel cross-sectional profiles (Figure 4, 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. The USACE surveyed the bathymetry 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 3B, 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 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 3B, cross-sections K and L). The downstream portion of the pool within the bend is still located near the outer bank (cross-sections O–Q).

Dredging of the navigation channel occurred during summer 2008, but the bathymetric data for January 6, 2009 show that the influx of sediment from the Wabash River persisted. For the most part, the pool has the same general alignment through the junction as on June 23, 2008, but the thalweg is wider and located closer to the outer bank in January 2009 than in June 2008 (Figures 3B and 3C). The point bar remains truncated by the pool toward the inner bank of the bend. Across the channel, the distinctiveness of the sediment wedge has diminished;

Table 1. Hydraulic conditions of measured flows at ORWR and WRVR

|              | May 15, 2008 | January 6, 2009 | January 9, 2007 | February 6, 2008 |
|--------------|--------------|-----------------|-----------------|------------------|
|              | OR WR WR/OR  | OR WR WR/OR     | OR WR WR/OR     | OR WR WR/OR      |
| Q            | 4882         | 2193            | 0.45            | 2333             |
| U            | 0.94         | 0.68            | 0.72            | 0.62             |
| M            | 4 589 080    | 1 491 240       | 0.32            | 1 446 460        |
|              |              | 1 890 000       | 1.31            | 1 890 000        |
|              |              |                 |                 | 1.31             |
| Note:        | Q, discharge (in m³ s⁻¹); U, mean cross-sectional velocity (in m s⁻¹); M, momentum flux (in kg m s⁻¹). |
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 3B and 3C). Patterns of bed morphology in the Wabash River remain comparatively unchanged since June 2008, although aggradation is evident along the inner bank at cross-section A (Figure 4).

In contrast, morphological features at WRVR are similar on both measurement dates (Figure 5). 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 5). 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 6, 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 5, 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 6, 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).

**Depth-averaged velocity**

The degree of convergence between depth-averaged velocity vectors and corresponding flow deflection along the mixing interface differs between the field sites. At ORWR, curvature of both rivers immediately upstream of the junction, along with curvature of the downstream channel, produces complex spatial patterns of velocity vectors (Figure 7). 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 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 turns 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).

Low momentum-flux ratio conditions on May 15, 2008 ($M_r < 1$) result in a distinct mixing interface on the tributary side of the confluence characterized by abrupt lateral change in vector magnitudes, rapid change in the orientation of velocity vectors representing incoming flow from the Wabash River, and minimal outward deflection of vectors in the Ohio River (Figure 7A, 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 highest velocities in the Wabash River from the outer bank (cross-section A) to the inner (west) bank (cross-section D) as flow from this river 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 highest 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 7B) 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

Figure 4. 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.
Wabash River between the survey dates in response to a meander cutoff immediately upstream produces strong flow convergence downstream of this feature (cross-section A). High 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 D). 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 within the Wabash River is absent. 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 highest velocities 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 nearly parallel to each other upon entering the confluence (Figure 8). 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 highest velocities 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.

Flow from the Wabash River occupies most of the confluence when $M_r < 1$ on January 9, 2007 (Figure 8A). 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 low velocities 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 6, 2008 (Figure 8B). 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).

### Downstream and secondary velocities

Spatial patterns of downstream and secondary velocities 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 extends upstream along the outer (east) bank of the Wabash River when $M_r < 1$ (May 15, 2008) (Figure 9A, cross-section D). This region of superelavated water 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), 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 (Figure 9B, cross-section J).

The channels of both rivers curve immediately upstream of the junction, resulting in curvature-induced secondary circulation on both measurement dates. Secondary velocity vectors, derived using the Rozovskii method, reveal the presence of a helical cell with clockwise circulation in the Wabash River spanning most of the channel cross-section on May 15, 2008 (Figure 9A, cross-sections 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 9B, 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 Wabash River and patterns of secondary circulation become less coherent (Figure 9B, 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 9A, cross-section I; Figure 9B, cross-section J).

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 9A and 9B, 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 Wabash River, especially when $M_t > 1$ (Figures 9A and B, cross-sections L and N). The helical cell

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**Figure 6.** 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.
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 9A, cross-sections L and N) than for $M_r > 1$, when flow from the Wabash River penetrates far into the confluence (Figure 9B, 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 in 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 10).

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 seemingly 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 9A, 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. Along the flanks of the mixing interface, fluid plummets toward the bed. Confinement of the mixing interface near the outer (north) bank (Figure 10A) restricts the smaller helical cell within flow from the Wabash River to the outer 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

Figure 7. Depth-averaged velocity vectors at ORWR on (A) May 15, 2008 and (B) January 6, 2009.
downstream junction corner develops adjacent to this cell along the outer bank (cross-sections O and P).

When $\mathcal{M}_r > 1$, increased penetration of tributary flow into the confluence and subsequent shifting of the mixing interface to the center of the channel (Figure 10B) enhances flow separation along the outer (north) bank downstream from the tributary entrance (Figure 9B, cross-sections O and P). The helical cell within flow from the Wabash River extends inward from the separation zone across more than half of the downstream channel (cross-section P). The opposing helical cell within flow from the Ohio River is confined to the inner (south) portion of the downstream channel and is clearly smaller than for $\mathcal{M}_r < 1$. The counter-rotating cells are similar in size at the entrance to the downstream channel (cross-section N) and transfer downstream momentum laterally to the center of the channel cross-section where the combined flows accelerate. Farther downstream (cross-section P), coherent patterns of secondary circulation are difficult to discern as the effects of flow curvature within the confluence begin to wane.

The comparatively low junction angle at WRVR results in less direct flow deflection between the converging rivers and thus simpler patterns of flow structure than at ORVR (Figure 11). 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 11A and 11B, cross-sections F and I). For $\mathcal{M}_r < 1$ (January 9, 2007), a core of high downstream velocity in the Wabash River upstream of the confluence expands from the center and inner (east) portion of the channel (Figure 11A, 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 $\mathcal{M}_r > 1$ (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 11B, cross-sections F and I). Downstream velocities exceed 1.5 m s$^{-1}$ across most of the flow width of the Wabash River (cross-section B).

Contrasts in both downstream velocity and surficial water temperature between the converging flows define the surficial position of the mixing interface through the central region of the confluence on both measurement dates (Figures 11A and 12A, cross-section J; Figures 11B and 12B, 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 $\mathcal{M}_r < 1$ (Figure 11A, cross-sections J–K). Downstream, the velocity differential between the flows diminishes (cross-sections K–N), even though the contrast in surficial water temperature persists (Figure 12A), indicating that the mixing interface remains well-defined 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 $\mathcal{M}_r < 1$ (Figure 11A, 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 within 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 12A).

Flow deflection by the Vermilion River is enhanced when $\mathcal{M}_r > 1$ and shifts the mixing interface more than 25 m toward the inner (east) bank in the downstream channel compared to its location when $\mathcal{M}_r < 1$ (Figure 12B, cross-sections M and N). The mixing interface aligns with the inner margin of the

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Figure 8. Depth-averaged velocity vectors at WRVR on (A) January 9, 2007 and (B) February 6, 2008.

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high-velocity core from the tributary, which persists through the confluence (Figure 11B, cross-sections J and K) and over the outer portion of the downstream channel (cross-sections M and N). Low-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 downstream (cross-sections M and N), yet surficial water temperature patterns indicate a lack of mixing as the temperature differential between the two confluent flows remains well-defined (Figure 12B).

Two counter-rotating, surface-convergent helical cells are apparent within the central region of the confluent meander bend when \( M_r > 1 \) (Figure 11B, cross-sections J and K). The clockwise-rotating cell over the outer (west) portion of the confluenace presumably forms when high-momentum fluid from the Vermilion River 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).

Discussion

Analysis of patterns of 3D fluid motion at the two sites investigated in this study reveal both similarities and differences in the response of flow structure between high angle and low angle confluent meander bends to changes in \( M_r \). At both high and low angle confluent meander bends, a zone of flow stagnation develops near the upstream junction corner—a phenomenon observed at other confluences and confluent meander bends (Best, 1987; Rhoads and Kenworthy, 1998;
Rhoads and Sukhodolov, 2001; Roberts, 2004; Riley and Rhoads, 2012) and caused by the development of an adverse pressure gradient at this location. The position of this stagnation zone responds to changes in $M_r$ by shifting around the junction corner into the upstream channel of the incoming river with the lower momentum flux. For $M_r < 1$, the zone of stagnation extends into the tributary channel (i.e. the river with the smallest upstream drainage area) (Figure 9A, cross-section D; Figure 11A, cross-sections B, K–N), whereas for $M_r > 1$ the stagnation zone extends upstream into the main river (Figure 9B, cross-section J; Figure 11B, cross-sections F and I).

Both the location and angle at which the tributary enters the curving main river largely control the extent of flow deflection in the central region of each confluence. 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 incoming flows of the rivers are nearly orthogonal to one another. 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, which confines flow from the tributary to a narrow path between the interface and outer bank of the bend (Figure 13A). Increased penetration of tributary flow into the confluence when $M_r > 1$ deflects flow from the main river inward (Figure 13B), although the presence of an inflowing tributary at the bend apex deflects main river flow away from the outer bank even for $M_r < 0.5$ (Riley and Rhoads, 2012) and is comparable to deflection of main river flow away from the mouth of the lateral tributary at asymmetrical junctions (Best, 1987; Rhoads and Sukhodolov, 2001).

Figure 10. 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. This figure is available in colour online at wileyonlinelibrary.com/journal/espl
Figure 11. Downstream velocities with Rozovskii secondary 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. Dashed line indicates approximate location of mixing interface determined by measurements of near-surface water temperature. This figure is available in colour online at wileyonlinelibrary.com/journal/espl
At WRVR, the small angle of tributary entry leads to incoming flows that are nearly parallel to one another. Consequently, the position of the mixing interface at the upstream end of the confluence, where the flows initially meet, does not change substantially as momentum-flux ratio varies (Figures 11A and 11B, cross-section J). Because penetration of tributary flow into the confluence is greatly reduced compared to ORWR, the Vermilion River is ineffective at deflecting flow from the Wabash River away from the outer bank of the meander bend in the downstream channel when $M_r < 1$ (Figure 14A). The low frequency of channel-formative tributary-dominant flows at WRVR (Figure 2D) indicates that momentum from the main river may routinely be transferred outward across most of the downstream channel, thereby deflecting tributary flow against the outer bank in much the same way as flow is deflected toward the bank opposite the dominant tributary at symmetrical confluences (Mosley, 1976). The planform geometry of the confluence limits penetration of tributary flow into the center of the junction and downstream portion of the bend, even when $M_r > 1$ (Figure 14B). During these infrequent conditions, the high-velocity core of the tributary persists over the outer portion of the downstream channel and confines flow in the main river to the center and inner portions of the bend.

Large-scale helical motion at these two confluent meander bends 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 9A and 9B, 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 (Figure 13). Both helical cells persist in the downstream channel, although the size of the cells depends strongly on $M_r$.

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 14A). 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 14A). 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 14B). 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.

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 10 and 12). The mixing interface at the high-angle confluent meander bend (ORWR) is flanked by dual counter-rotating helical cells on each measurement date (Figure 9), 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 boundary...
between the high velocity core of the high-momentum incoming flow and the adjacent low velocities of the low-momentum incoming flow (Figure 11). Downstream momentum is advected laterally into 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). Apparently the strength of secondary flow relative to the streamwise flow is less at these large confluences than that at small confluences, but further work is needed to explain these differences.

Previous field work at a high-angle confluent meander bend showed that tributary flow accelerated over the outer portion of the downstream channel, thereby preventing flow separation (Riley and Rhoads, 2012). This finding contrasts with the development of flow separation at the angular downstream junction corner of experimental channels (Best and Reid, 1984; Best, 1987), including experimental confluent meander bends (Roberts, 2004). Studies of natural confluences indicate that flow separation may or may not occur, depending on how rounded the channel bank is at the downstream junction corner (Roy et al., 1988; Roy and Bergeron, 1990; Ashmore et al., 1992; Rhoads and Sukhodolov, 2001). The results of this study indicate that flow separation is also variable at natural confluent meander bends. 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 alignment 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 11B), whereas advection of downstream momentum from the Wabash River across the channel when $M_r < 1$ confines flow from the tributary along the bank below the downstream junction corner (Figure 11A). In contrast, flow separation develops for both high and low momentum-flux ratio conditions at the high-angle ORWR, although the zone of separation is more

Figure 13. Conceptual model of flow structure and bed morphology at high-angle confluent meander bends when (A) $M_r < 1$ and (B) $M_r > 1$. This figure is available in colour online at wileyonlinelibrary.com/journal/espl
extensive when $M_r > 1$ (Figure 9B). Topographic steering by a well-developed bar at the downstream junction corner deflects flow toward the adjacent thalweg, enhancing separation — a mechanism documented at a small symmetrical confluence (Rhoads and Kenworthy, 1995).

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. At ORWR, the path of the pool in the Ohio River through the confluence (Figure 3A) generally coincides with the position of the high-velocity core and curvature-induced helical cell for low $M_r$ (Figure 9A). Near-bed fluid directed inward by this cell presumably sweeps sediment inward over the face of the point bar in this bend. A large influx of sediment from the Wabash River associated with a meander cutoff immediately upstream of the confluence (Zinger et al., 2011) shifted the pool laterally to a position near the inner bank (Figure 3C). 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 conditions documented at a small natural confluent meander bend when flows with $M_r = 1$ lead to a strong influence of the lateral tributary on bed morphology (Riley and Rhoads, 2012).

The comparative uniformity of the channel bed over time and lack of substantial bed scour ($< 0.5 \text{ m}$) at the low-angle WRVR differ from the morphodynamics of the high-angle ORWR. Although central bed scour is a common feature at many confluences, it can be shallow or even absent at junctions with discordant beds (Biron et al., 1993b), coarse bed material (Roy et al., 1988), or low junction angle. At WRVR, the low angle of tributary entry limits mutual deflection of the confluent flows, which constrains the depth of scour (e.g. Mosley, 1976; Best, 1988). Furthermore, tributary-dominant flows that can generate a helical cell with rotation counter to that of the cell in the curving main channel are rare and too short-lived to substantially alter bed morphology (Figures 2B and 2D).

The dominance of bed morphology by flow in the curving Wabash River at this low-angle confluent meander bend results in persistence of an inner bank point bar through the downstream channel. The persistence of this bar contrasts with periodic erosion of the point bar at ORWR and at the small confluent meander bend studied by Riley and Rhoads (2012), both high-angle confluences, but conforms with

Figure 14. Conceptual model of flow structure and bed morphology at low-angle confluent meander bends when (A) $M_r < 1$ and (B) $M_r > 1$. This figure is available in colour online at wileyonlinelibrary.com/journal/espl
patterns of bed morphology typically found in meander bends (Dietrich, 1987).

Finally, the development of a bar at the downstream junction corner, which was documented previously at a high-angle confluent meander bend (Riley and Rhoads, 2012), also occurs at the high-angle confluent meander bend in this study, but not at the low-angle confluent meander bend. 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 and continues around the junction corner into the downstream channel (Figure 3). The bar enlarges below the downstream junction corner for increasing M₄ (Figure 4, 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 size of the bar is greater than the overlying zone of separated flow (Figure 9), 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 (Rhoads and Kenworthy, 1995; Best and Rhoads, 2008). Deposition along the outer bank of the curving main channel downstream of the mouth of the lateral tributary protects this bank from erosion (Riley and Rhoads, 2012). The lack of a well-defined bar at the downstream junction corner at WRVR can be attributed to the relatively straight alignment between the upstream channel of the Vermilion River and the downstream channel of the Wabash River, which limits flow separation and sediment flux convergence at this location.

Conclusion

This research contributes to emerging knowledge of the hydrodynamics and morphodynamics of confluent meander bends by investigating the response of 3D flow structure and bed morphology to changes in M₄ 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), and show that flow conditions inherited from upstream channel curvature are reflected in the structure of flow within confluent meander bends on large rivers — confirming results of experimental work (Dordević, 2013) and of field studies at a small natural confluent meander bend (Riley and Rhoads, 2012). Strong flow deflection at the high-angle confluent meander bend 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 through the downstream channel that vary in relative size with changes in M₄. At the low-angle junction, 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 M₄ 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 M₄.

The mixing interface at each site extends through the downstream channel, suggesting 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 mixing at small confluences with strong helical motion (Rhoads and Kenworthy, 1995; Rhoads and Sukhodolov, 2001). Complete mixing often does not occur for tens or even hundreds of channel widths downstream of large river confluences (Mackay, 1970; Stallard, 1987), but local conditions, such as density contrasts and topographic forcing, can lead to rapid mixing (Lane et al., 2008). Further work is needed to resolve the causes and rates of mixing at large river junctions.

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, the outer bank of the curving main river, is the downstream extension of a depositional body that develops along the inner bank of the curving tributary channel upstream of the confluence. Thus, flow from the high-angle lateral tributary induces bar development downstream of the bend apex of the main river where bank erosion typically occurs (Dietrich, 1987). A broad inner bank point bar on the main river persists through the downstream channel for low M₄, but inward displacement of the pool by a large influx of sediment into the confluence from the lateral tributary resulted in scour of this bar. Bed morphology is comparatively stable at the low-angle confluence, where the low angle of the confluence and the infrequency of short-duration tributary-dominant flows limit bed scour and erosion of the point bar on the main river.

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 of these factors has on confluent meander bend hydrodynamics 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 planform stability and protection of the outer bank from erosion may not be related solely to the development of a bar along the downstream junction corner (Riley and Rhoads, 2012), but also to the capacity of tributary flow to deflect main river flow away from the outer bank and to the degree of channel curvature immediately upstream of the junction.

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