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The dynamics of river confluences and their effects on the ecology of aquatic environment: A review

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Abstract: Confluences act as critical nodes in a river system. They affect hydrodynamics, sediment transport, bed morphology, and eco-hydraulics of the river system. Convergence of streams produces the complex mechanism of flow momentum and mass mixing which may affect the aquatic environment locally and even lasting for a long distance downstream. The confluence creates a hotspot for the river system's ecological change, which usually leads to changes in water temperature, suspended-sediment load, bed material, nutrient concentrations, water chemistry, and organic-matter content. Hence, the dynamics of river confluences are very complex and have critical effects on river system's water environment and ecology. For this reason, a review summarizing turbulent flow, sediment transport, morphological-dynamics, mixing processes, and their effects on the ecology of the aquatic environment at river confluences is in order. A future research agenda and opportunities pertinent to river confluence are vitally emphasized as a multidisciplinary research topic.

Key words: River confluence, hydrodynamics, sediment transport, morpho dynamics, water environment, water ecology

Introduction

Confluences are standard components of all riverine systems, and they are distinguished by converging flow streamlines, flow mixing, and a highly complex three-dimensional flow structure located in the confluence hydrodynamic zone (CHZ)[1]. Such complexity has defied researchers for years and, as a result, the interactions between flows, sediment and bed morphology at confluences have long been neglected.

With the development of measuring instruments and computer technology, it is possible to accurately capture and describe the three-dimensional flow structure, material transport, riverbed evolution and ecological and environmental effects at river confluences. After the 1980s, more and more studies on river confluences began to appear, and the research methods became more diversified, including laboratory experiments[2-16], field experiments[17-30], and numerical simulation[31-40]. It is generally believed that Mosley's research on flume experiment published in 1976 has made a pioneering contribution to the study of river confluences[2]. His laboratory experiments have laid the foundation for determining the main controlling elements (junction angle and the discharge ratio) of riverbed geomorphology related to the flow structure at the confluences. The laboratory's systematic investigation of confluence dynamics has produced idealized conceptual models of flow structure and bed morphology within the CHZ (Fig. 1)[4-5]. Flow structure at such confluences typically includes: (1) a region of reduced velocities or flow stagnation near the upstream junction corner, (2) mutual deflection of flows within the confluence, (3) a shear layer/mixing interface between the confluent flows, (4) flow separation below the downstream junction corner, (5) acceleration of flow as the flow enters the downstream channel and (6) flow recovery at the downstream end of the CHZ. CHZ morphodynamics can be related to the complex fluid dynamics of confluences, which, in

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turn, are controlled by several principal factors, including: the planform geometry of the confluence, junction angle, the ratio of discharges or momentum, bed discordance, and any differences in density between the incoming flows[6, 11, 20-21, 27, 41-46]. Although these factors significantly impact on bed morphology at channel junctions, the feedback varies between flow, sediment transport, and bedforms, because flow within a fully formed mobile bed will differ significantly from flow in sediment-free channels[5]. Thus, complete knowledge of the morphology of channel confluences necessitates a thorough understanding of the dynamic interactions between flow, sediment transport, and bed morphology at many spatiotemporal scales, ranging from flow in rill networks[47] to the dynamics of the world's largest rivers[30, 43, 48-50].

Environmental and ecological interests have lagged behind geomorphology and hydraulics, but it is clear that the interests are now growing at the fastest rate[29, 51-58]. When two streams meet at a confluence, the sediment concentrations, temperatures, and dissolved chemical and nutrient loads in each tributary might be drastically different. Because differences in the properties and transported constituents of confluent flows are common, and fluid motion at confluences may include substantial lateral and vertical components, pronounced lateral mixing of these flows sometimes occurs over a distance of a few channel widths downstream of confluences[59-60]. Furthermore, any variations in water quality parameters (temperature, conductivity, suspended sediment content) between entering tributary flows might cause stratification, which would impact on local processes in the confluence[61]. Spatial heterogeneity and dynamic hydrology of river confluences support high biodiversity and affect functional processes. The tributary can supply supplemental nutrients and energy, as well as juxtapose distinct environments, such as refugia, water quality, hydraulics, and channel morphology[62]. Some organisms may take ecological advantage of the unusual morphology and hydraulics of river confluences[63]. Therefore, environmental heterogeneity, biological diversity, and productivity should peak at river confluences[64]. These studies strongly suggest that river confluences are key nodes in river systems where tributary water and sediment flows can cause changes in the receiving channel's geomorphology, hydraulic, sedimentology, and ecology.

Confluences could be classified according to the width-to-depth ratio as small (W/H < 10), medium $(10 < W / H < 50)$, and large scale $(W / H > 50)$[30]. Understanding confluence hydrodynamics impacts at various scales is crucial for scaling-up knowledge of river processes to the drainage network scale. At small scales and flume experiments, research at river confluences examined the distinctive flows, morphologies, sedimentary assemblages and habitats that make confluence sites critical local features. Most attention has been directed towards understanding flow mixing at confluences[25, 34, 48, 59] and relations between sediment transport, and morphology[1, 18, 65-67]. Researchers have recently tested the potential of applying results from small laboratory and field experiments to large rivers, including some of the largest confluences in the world. This has led to the identification of other critical variables, such as the channel width-to-depth ratio[68]. It was proposed that the influence of secondary currents was reduced for large width-to-depth ratios due to an increase in the impact of form roughness. Therefore, extending our existing understanding of small confluences to large scale confluences is much difficult. Recent technological advancements, such as advancements in global positioning systems and the introduction of acoustic Doppler current profiling and multibeam echo sounding, have made research of large river morphodynamics

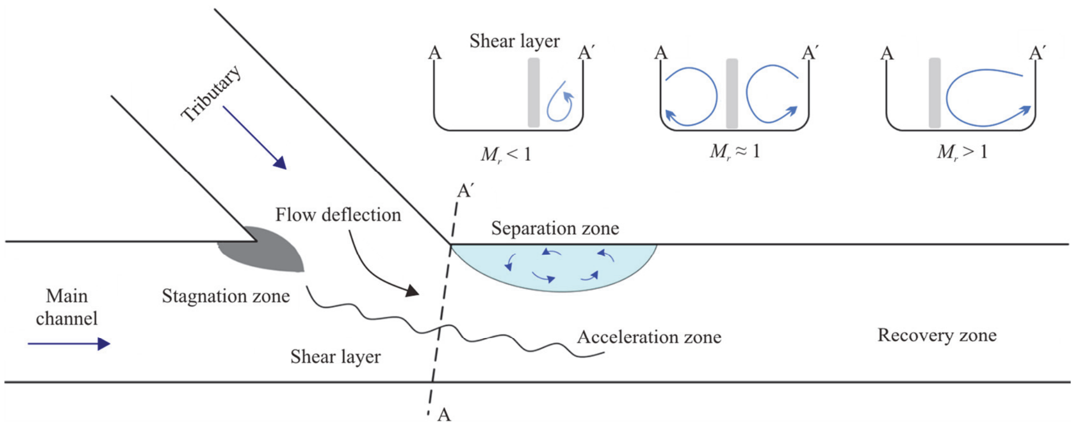

Fig. 1 (Color online) Conceptual model of flow structures at channel confluence, M_r represents the ratio of flow momentum of the tributary to that of the main channel

more accessible[30, 49-50, 65, 69-73]. These new instruments contribute to the rapid and precise mapping of flow fields and bed morphology in such large channels. Moreover, the preliminary findings from these investigations support a clear understanding of whether large-scale secondary flows are present at large confluences or not, and how high form roughness may suppress the development of such flow structures[30, 70].

Few review papers on the dynamics of channel confluence are available in the literature. Hydrodynamics, sediment transport, and morphodynamics in small river or flume confluences were systematically reviewed in the book edited by Rice et al.[68], and in the brief review in Chapter 12 in the book edited by Rhoads[74]. However, the dynamics of large river confluences and the effects of confluence dynamics on the ecology of aquatic environment at river confluences are slightly discussed. In this review paper, the recent progress on the dynamics at channel confluences, especially their effects on ecology of aquatic are discussed. Especially, the dynamics at some large river confluences, such as the Negro/ Solimões and the Yangtze/Poyang, are also detailed.

1. The dynamic mechanisms of shear layer and secondary circulation

The fundamental hydrodynamic features at the confluence have been developed in detail by Mosley[2] and Best[4]. Among these features, the shear layer and secondary circulation with complex characteristics are therefore considerable hot topics in the study of confluence flow structures.

1.1 *Shear layer*

The shear layer with horizontal vortices has been viewed as analogous to a plane that forms when two parallel flows begin to pass one another downstream[75-76]. The quasi-two-dimensional vortex occurs due to the fundamental instability of shearing especially when streamwise velocity has a large lateral gradient between the two flows. This mechanism of vortex development is known as Kelvin-Helmholtz instability, and all vortices tend to rotate around vertical axes in the same direction. However, when the discharges of the two rivers were comparable, the shear along the margins of the stagnation zone is strong, which results in quasi two-dimensional eddies with opposite senses of rotation like wake vortices[36]. Herrero et al.[77] also found that a well-developed stagnation region acts as a solid cylinder in a shallow open channel flow, which leads to the shedding of successive vortices as a von Karman vortex street. However, the effects of the wake model on the formation mechanism of the shear layer remain unclear. In some cases, KH vortices are dominant in the shear layer and do not reveal any significant difference with the discharge ratios ranging from 0.09 to 1.02[78], while, Lewis and Rhoads[79] found the vortex pairing phenomenon by the value of positive and negative vorticity. Therefore, the dynamic mechanism of the wake mode of the shear layer is still open to discussion.

The shear layer does not always have a two-dimensional coherent structure at channel confluences. The bed discordance and large lateral penetration from the tributary can distort the shear layer. Bed discordance at channel confluence is shown to obliterate flow deflection near the bed and distort the shear layer between the flows, resulting in fluid upwelling at the downstream junction corner. This upwelling is responsible for the absence of a flow separation zone near the bed[7, 80]. If the step is large, and the high-speed incoming flow has a jet-like characteristic, there is a horizontal shear layer along the margin of step and becomes disconnected from the bed[27]. On the other hand, Yuan et al.[46] showed that the shear layer was distorted when the tributary channel had a higher flow rate than the main channel, which resulted in an increase in occurrence probabilities of ejection and sweep events within the shear layer.

1.2 *Secondary circulation*

Secondary circulation is another significant hydrodynamic feature at confluences. The occurrence of helical cells at confluences has been attributed to the unbalanced between centrifugal and pressure-gradient forces in space, similar to the generation of helical motion in meander bends[22]. The planform geometry (e.g., junction angle) of confluence is a controlling factor for the pattern of secondary circulation. For example, the larger the junction angle, the greater the flow deflection at the tributary's entrance into the post-confluence channel, which could enhance the secondary circulation[81]. At symmetrical confluences, both tributaries are angled with respect to the receiving channel, and the mutual deflection of the two streams causes dual counter-rotating secondary circulations[2, 17]. On the other hand, at asymmetrical confluences, only one of the tributaries is angled, but mutual deflection of the two incoming flows can still produce opposing patterns of secondary circulation at confluences[20] or dual secondary circulations at first change into a single dominant of the downstream channel under the influence of high momentum flux ratio (Fig. 1)[21].

The dynamics of secondary circulation at river confluences have received considerable attention. The influencing factors of the secondary cells mainly include momentum ratio and bed topography [2, 6, 41, 44]. No secondary flow is detectable in runs with parallel merging flows irrespective of the momentum ratio, even though the strength and pattern of secondary circulation at confluences mainly depends on the momentum ratio[44]. Strong secondary circulation develops locally near the bed and contributes to upwelling downstream at a discordant confluence[6, 33]. At confluent meander beds, helical motion develops in the tributary flow, which curves in the opposite direction to flow in the bend, resulting in counter-rotating helical circulation on each side[82]. In addition, it is worth noting that the change of hydrologic conditions can also affect the confluence planform and the secondary circulation by changing the hyporheic fluxes[83].

2. The dynamics of bed morphology and sediment transport at confluences

The channel bed morphology at confluences is shaped by the flow structures, which cause different patterns of erosion and deposition. The hydraulic characteristics and spatial extent of the basic hydrodynamic elements are influenced by changes in controlling factors (junction angle, junction symmetry, momentum flux ratio, and discordance/concordance), and the spatial structure of bed morphology at confluences responds dynamically to these changes. The significant bed morphology features include a scour hole, tributary-mouth bars, bank-attached lateral bars, sediment accumulation, and a mid-channel bar (refer to Fig. 2)[53, 56, 84,].

At many confluences, scour holes are a prominent element of bed morphology. Convective acceleration of flow, high levels of turbulence along the shear layer, and divergent patterns of near-bed flow connected with helical motion are elements that are likely to contribute to scour at confluences[5, 9-12, 28, 56, 85]. The emergence of helical motion, particularly dual surface-convergent cells bordering the mixing interface, can situate the high-velocity core beneath the water surface at symmetrical confluences[20], thereby enhancing near-bed shear stresses[36]. Experimental studies indicate that scour increases as the junction angle increases and as the discharge of the minor tributary increases relative to the discharge of the major tributary[2,5, 86]. The same as the asymmetrical confluences, within the receiving channel, the formation of a single prominent helical cell promotes scour along the bank across from the tributary mouth and carries bed material to the opposite bank, much like flow in a meander bend (Fig. 2)[56]. If the confluences are discordant, the tributary flow moves ahead of the main-channel flow, reducing the interaction between the two flows near the bed and disrupting the development of coherent helical cells, which inhibited scour[67]. It is worth noting that the scour holes could be inhibited with the highly energetic core of the jet away from the riverbed, nevertheless the scour may promote if helical motion can develop adjacent to the jet[27].

The formation of other morphology at the confluence is also closely related to the flow structure. The sediment accumulation near the upstream junction corner may be caused by the upstream junction corner in the flow stagnation. Commonly, the bars are not that large with the fine bed material coming from upstream[18, 84]. The development of bank-attached tributary bars may be related to flow separation with sediment deposition within the region[5, 22, 85]. However, the rounded downstream corner of many natural confluences limits or prevents the development of large-scale flow separation during high-stage flows. Under this condition, the influence of helical motion inside the tributary flow entering the confluence is reflected in the bar formation, and relatively coarse-grained bars form by material transported as

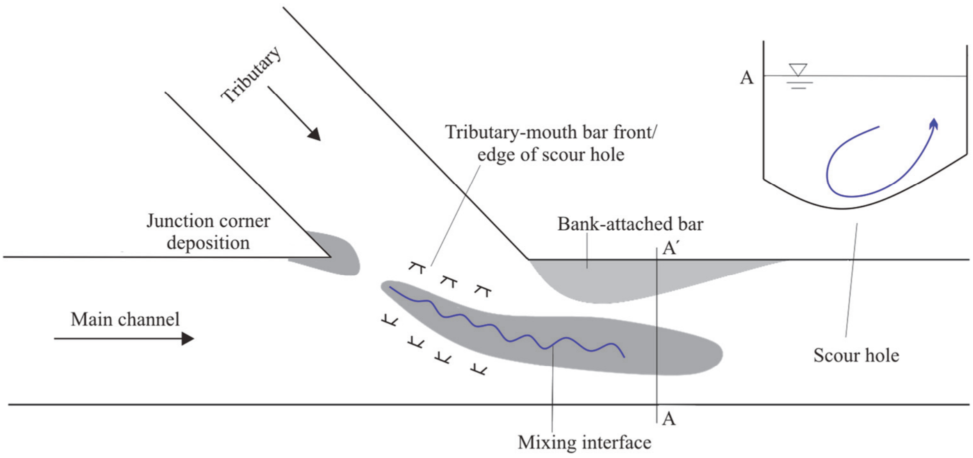

Fig. 2 (Color online) Conceptual model of bed morphology at an asymmetrical confluence

bedload[22, 87].

The confluence angle, discharge ratios and bed discordance could influence the sediment transport at river confluences[4, 7, 9, 25, 36, 67, 88]. Under conditions of equilibrium bed morphology, experimental studies of sediment movement through symmetrical and asymmetrical confluences with concordant beds show that bed material from each tributary remains segregated and travels around, rather than through, the scour hole[2, 5]. The emergence of twin surface-convergent helical cells within the scour holes, which sweep incoming bed material from each tributary along the flanks of this morphological structure, has been linked to material segregation[2, 5]. In contrast to observations by Mosley[2], particle-tracing investigations at natural confluences show that coarse bed material from the two upstream channels travels directly across the scour region following intersecting paths at low-angle confluences in the absence of a strong helical cell[89], where bed material from upstream channels travels around the scour hole and remains segregated at high-angle confluences with deep scour[90]. For small discharge ratios, fine sediment in the mainstream can be mixed with coarse tributary sediment downstream of confluence, where the dual helical cells turn into a single helical cell[20]. For large discharge ratios, fine main-channel sediment moves toward the bank-attached bar within the confluence and mixes with tributary sediment adjacent to a region of scour due to the single helical cell[21]. At a natural discordance confluence, where no apparent helical motion develops, the most active corridors of bedload transport correspond to margins of the shear layer, and bedload-transport rates correlate most closely with the root mean square of $\rho U w'$ [67]. Therefore, knowledge of the sediment transport characteristic of river confluence is far from complete, especially at a natural discordant confluence.

3. Mixing at river confluences

Understanding the transport mechanism of contaminants at a river confluence is vital for assessing of the water quality and water environment management of a river network. The tributaries carrying contaminants penetrate the main streams and the complex mixing processes between two confluent flows occur. The mixing mechanisms at rivers contain molecular diffusion, density difference, turbulent diffusion, and lateral advection. The molecular diffusion in turbulent river flows is very small compared with other mechanisms and thus can be ignored.

The density differences influence the mixing processes by causing buoyancy. The phenomenon of underflow of water with higher density beneath the water with lower density has been observed at some confluences[43, 50, 91-92]. The underflow mode with the effect of density difference can accelerate contaminants mix at confluences, which attribute to the increasing contact area between two flows[49, 93].

The lateral turbulent diffusion at confluences result from flow shear due to the differences in velocities of the flows. That is, the existence of a shear layer can promote turbulent diffusion. The Kelvin-Helmholtz vortices or vortex street in the shear layer contributes to mixing the two confluent flows[35]. The contaminants may not mix sufficiently under the effect of the flow shear since the vortices are limited in the width of the mixing interface. The mixing interface may still exist downstream of the confluence zone, although there is no shear layer[94].

The lateral advection at confluences is driven by secondary currents or even helical cells. At discordant confluences, the strong secondary flow induced by helical flow distorts the mixing interface and enhances the mixing[19, 33, 95]. The distance for complete mixing is only ten channel widths with the effect of strong lateral advection at confluences with discordant beds, while it could be hundreds of channel widths at confluences with concordant beds[59, 95]. Lane et al.[49] reported that the mixing distance at the confluence decreased from 400 km to 8 km with the formation of the channel-scale secondary flow. The degraded bed morphology consisting of the deep scour hole and the bank-attached bar can also influence the mixing processes[96-97]. Compared with the flat bed morphology, the degraded bed morphology induces stronger secondary flow which could distort the mixing interface and result in faster mixing.

4. The dynamics of surface sediment contamination at river confluences

Because the fine surface sediment (e.g., mud and clay) can adsorb/desorb or precipitate/dissolute nutrient and metal elements, sediment effects on the transport of contaminants cannot be ignored, as they are responsible for the secondary pollution in a river network. Therefore, the dynamic characteristics of contamination on surface sediment contamination at river confluences should be emphasized. In this review, we focused on the effects of the hydrodynamics and sediment processes at confluences on the dynamics of surface sediment contamination, while other influencing factors, e.g., water temperature and pH, are not considered.

It has been clarified by laboratory studies that there is a negative correlation between the contaminant uptake rate of sediment and flow velocity[98]. Therefore, the above separation zone characterized by very low flow velocity is beneficial to contamination enrichment on surface sediment, whereas the reverse is valid for the regions of the shear layer and maximum flow velocity[53, 56, 58]. The helical flow consisting of the upwelling flow and downwelling flow can form a pressure gradient on the bed surface, accelerating the contaminants exchange between the overlying water and pore water, which may induce more contamination to be absorbed onto the bed sediment in the region of the downwelling flow (Fig. 3)[54, 56].

The sorption rate of contaminants can primarily increase as the grain size of sediment decreases[99]. Hence, the zones with the deposition of fine sediment, i.e. the separation zone and stagnation zone as aforementioned, can contribute to the contamination enrichment on surface sediment. In contrast, the coarse bed sediment usually distributes within the regions of shear layer and maximum flow velocity and prevents contamination dwelling. However, Yuan et al.[29] found that finer and more contaminated sediment than ambient sediment were located in the deep scour hole than ambient sediment at the confluence of the Guohe River and the Huijihe River. They inferred that the weak turbulence in the mixing interface brought about the collision of suspended silt particles and resulted in the flocculation and settling of particles in the deep hole, and the down welling flow there also contributes to the settling of these flocs (Fig. 3). Moreover, they reported that floods had critical impact on sediment transport and its surface texture, and thus the dynamics of surface sediment contamination at the river confluence.

5. Ecological issues at river confluences

Abiotic environmental factors influence aquatic organism distribution. Confluences are significant in this context because they are locations where water, sediment, and organic matter recruitment can significantly influence on habitat in the recipient channel. In river ecosystems, confluences likely act as heterogeneity "hotspots" by creating discontinuities in longitudinal processes and influences that are propagated both up and down stream networks and provide unique habitats and important ecological functions[68, 100].

Confluences affect the local ecology by producing changes in water temperature, suspended-sediment load, bed material, nutrient concentrations, water chemistry, and organic-matter content[68, 101]. An open system with high spatial and temporal heterogeneity created by the meeting of two large rivers with different water chemistry, river confluences may have a dynamic fish assemblage[102]. Such effects can both enhance and degrade ecosystem quality. For example, it was found that wood abundance and volume, variability in median substrate size (i.e., substrate heterogeneity), concentrations of nitrogen and phosphorus in water, algal biomass, and abundance of consumers and predators peaked with a higher frequency at or downstream of tributary junctions[68]. Some tributaries have fundamental effects on the larger rivers they enter. Thus, the confluences are essential for maintaining the integrity of connections among and between ecosystems to promote habitat complexity and community structure within river networks[103]. On the other hand, a significantly increased loading of fine sediment at a river confluence affects the distribution and potential movement of benthic invertebrates in the lotic environment as sediment can act as physical barriers at the affected sites. Such increases in suspended sediment (primarily associated with anthropogenic change) may thus pose

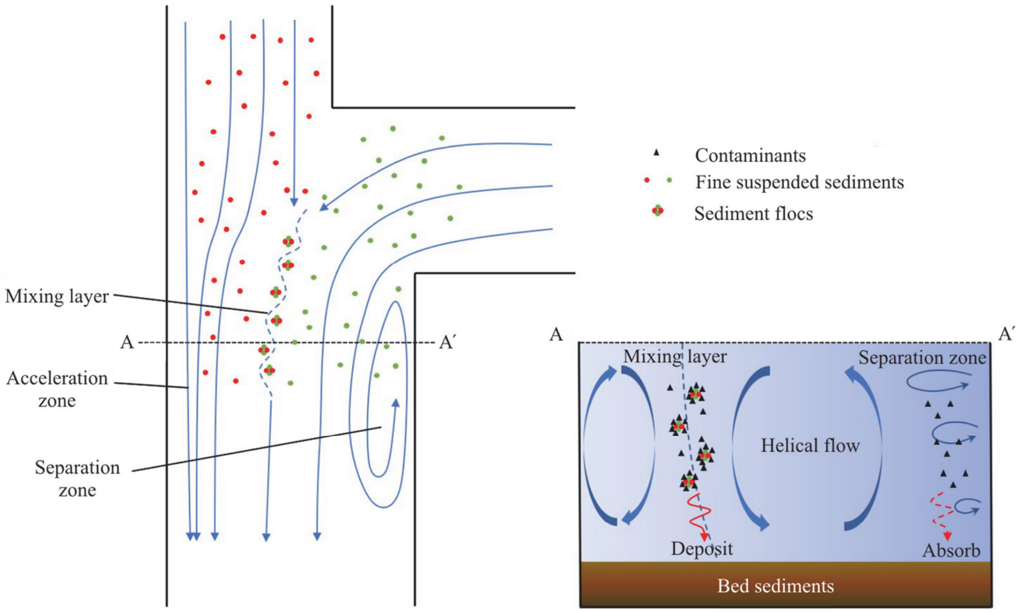

Fig. 3 (Color online) Pattern of contaminant migration at the confluence with the effect of flow and sediment

a significant threat to ecosystem integrity[104].

We currently have little understanding of how complicated hydrodynamics at river confluences affect the fish locomotion and spatial distribution in the local basin, in contrast to the extensive literature available for studies of fish swimming in steady flow or turbulence with relatively simple structures[105-115]. The flow complexity metrics which can calculate the velocity gradient, kinetic energy change and eddy intensity of local water flow were widely used to describe the different behaviors of fish and possible habitats[116-117]. Gualtieri et al.[51-52] systematically analyzed the flow complexity at the confluence of the Negro and Solimões rivers in the Amazon basin. They found that the mixing interface was a location with the highest concentration of fish larvae. In addition, they also found that the Amazon finless porpoise avoid zones with larger flow shear, while fish preferred to gather in zones with low velocity and moderate flow complexity (such as stagnation zone and nearshore areas) to facilitate preying and rest. In the Yangtze River Basin, it was found that the Yangtze finless porpoise like to stay in the separation zone, stagnation zone and flow deflection zone[118-119]. The separation zone is particularly important for fish feeding and habitat, since it has low-velocity circulation flows that benefit the concentration of zooplankton and phytoplankton[111-112, 119, 120-121]. Yet, preference alone cannot conclusively reveal mechanisms of fish locomotion or flow exploitation under the complex flow structure. When fish locomotion recordings and flow visualization techniques are employed in the laboratory (Fig. 4)[122], an interesting phenomenon is that when the fish go from the separation area to the tributary, they use the large vorticity at the boundary of the separation area as navigation information. At the same time, in order to overcome the flow velocity gradient here, their swimming strategy is adjusted to increase the tail-beat frequency and reduce the tail-beat amplitude. These findings will help in the prediction of fish performance and the enhancement of fish habitats at river confluences. Further research is needed to establish how fish movement is affected by the complicated turbulence structures around channel confluences.

6. Scale effects of hydro-morphodynamics of river confluences

Scale effect is a crucial factor that cannot be ignored if confluence conceptual models developed on small-scale confluences are applied to the large river confluences. On the one hand, the scale effect includes that the large river confluences with large width-depth ratios can make form roughness effectively suppress the development of flow structures. On the other hand, the increased likelihood of spatial differences in bed morphology (bars and dunes) within large confluences cause the topographic forcing of flow fields. Moreover, the confluence of two larger channels may drain significantly different areas in terms of geology and climate, and can thus have a greater range of inflow conditions, such as water chemistry and sediment, as compared to smaller confluences. Therefore, understanding the influence of such scale effects on the process dynamics of large river confluences is vital since they adopt a pivotal role in controlling, and regulating the local water security.

Knowledge of the hydro-morpho-sedimentary processes at large river confluences is sparse. Although major hydrodynamics features associated with small confluences such as stagnation zone, deflection zone, maximum velocity region, separation region with recirculation, and flow recovery region, were also observed at some larger river confluences[30, 50, 85, 123], current understanding of small confluences cannot be straightforward extended to large confluences. Therefore, observational studies of large river confluences have been carried out to investigate how scale-related changes in confluence geometry affect the flow structure during the last decade[30, 48-50, 70, 73, 85, 123-125].

For large river confluences, empirical evidence and theoretical analysis suggest that the high width-to-depth ratio in wide rivers may impede the formation of coherent channel-size secondary flow cells[126]. For example, at the large braid-bar confluences at Paranà River, the helical motion was restricted in the spatial extent to portions of the flow near the mixing interface[73], or even these channel-scale secondary circulation cells were absent[70]. They attributed this to the large channel width-to-depth ratio that allowed the effects of form roughness to become dominant, but the effects may be localized and not extend across the entire channel width. In the large river confluence between Paranà and Paraguay Rivers, it was observed that rapid and slow mixing between the confluent flows was related to a channel-scale circulation pattern being present or absent[49]. Such channel-scale circulation should be related to the interaction between bed discordance, downstream topographic forcing and the momentum ratio between the confluent channels.

Nevertheless, channel-size secondary flows, i.e., the dual counter-rotating cells in high flow conditions and a single secondary cell during low flow conditions, were observed at the confluence of the Yangtze River (the largest river in China) and the outflow channel of the Poyang Lake (the largest freshwater lake in China, Figs. 5, 6)[30]. The helical cells were mainly attributed to the curvature of the mainstream and the penetration

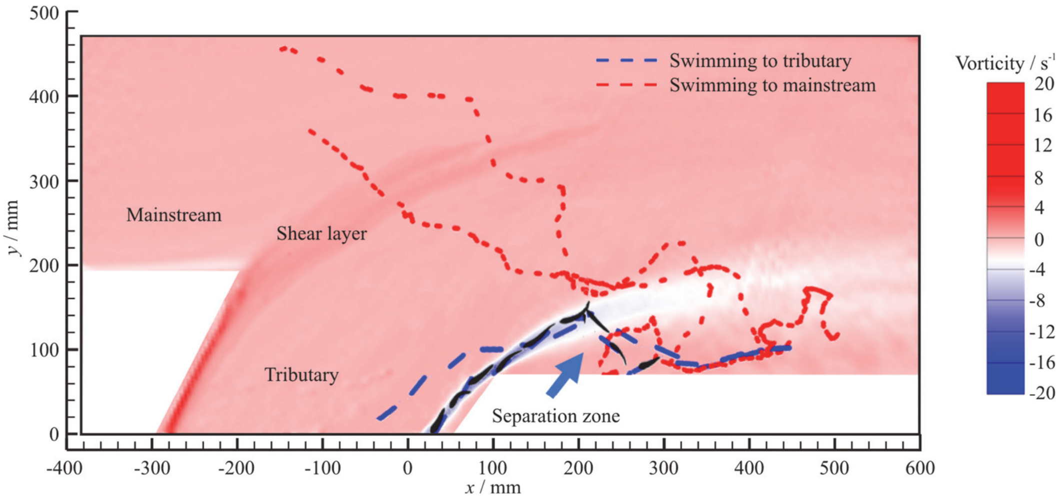

Fig. 4(a) (Color online) Representative trajectories of juvenile silver carp near the separation zone at the channel confluence. The background is a contour of average horizontal vorticity (s^{-1}) in the horizontal plane near the flume bottom. The red and blue dash lines represent the typical trajectories of juvenile silver carp swimming in the mainstream and getting into the tributary, respectively. The black shading represented the movement pattern of one carp when it was swimming to the tributary. According to the flow field and movement pattern of carp, the locomotion of carp while escaping from the separation zone to the tributary can be divided into three phases. Phase I: The carp stayed within the separation zone, Phase II: It moved along the boundary of the separation zone, and Phase III: It escaped across the boundary and was swimming within the tributary

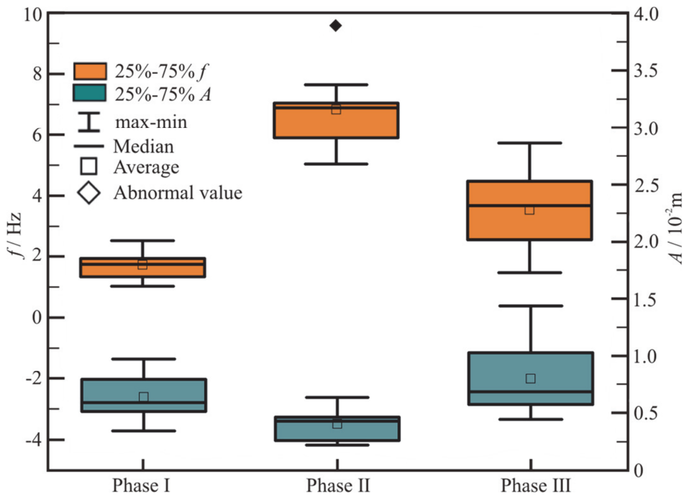

Fig. 4(b) (Color online) Swimming behavior parameters of juvenile silver carp during three phases, including average tail-beat frequency (orange box) and average tail-beat amplitude (green box) of all 24 carp that swam to the tributary

of the main flow into the tributary flow. In summary, the generation or inhibition of the channel-size secondary flow cells at larger river confluences is not governed by scale alone, and its dynamic mechanisms need further study.

Common morphological features observed at large confluences associated with laboratory studies include: a scour hole, avalanche faces at the mouth of each tributary, sediment deposition within the stagnation zone, and bars formed within possible flow separation zones or mid-stream in the downstream channel[73, 85, 127]. Scour hole occurrence and development at large confluences was generally related to the momentum/discharge ratio, bed material texture, sediment load and secondary currents[30, 73, 85, 123, 127]. Szupiany et al.[73] suggested that the cores of maximum velocity in large confluence might have the most significant influence on the scour hole by increasing the shear stress. Ianniruberto et al.[85] reported that at the Negro/Solimões confluence, there was no correspondence between the development of the scour hole with the observed hydrodynamic features, and this could probably be attributed to the peculiar geologic and hydrologic setting of this confluence, with one channel bed being alluvial, and the other bedrock. Zhang et al.[123] reported that a long scour hole at the confluence of the Yellow River (the world-famous high sediment-load river) and the Fen River was observed to be positioned near the side of the tributary and shifted toward the opposite side as the momentum ratio increased. Yuan et al.[30] suggested that at the Yangtze/Poyang confluence, the observed large scour hole in high flow conditions or the deep channel in low flow conditions are likely related to the downwelling and upwelling flows caused by helical motions. More investigations are necessary to expand the current database and knowledge on the morpho-dynamics of large river confluences.

Fig. 5 (Color online) Pictures of the large confluence of Yangtze River and Poyang Lake

More attention shall be paid to the dune bedforms, since they are the critical elements of bed roughness affecting the flow structures, especially for large river confluences. Dune features are expected to show a great complexity at river confluences, as the interaction mainly decide them among the flow, sediment transport and geological setting[70, 128-130]. Gualtieri et al.[124] found that large and very large dunes[131] with an observed maximum wavelength and wave height of 350 and 12 m, at the Negro/Solimões confluence. Those dunes were characterized by a lee side angle which was consistently below 10° without flow separation, as observed in large rivers. For large river confluences, the effects of hysteresis in the response of dunes to the changing flow stage may be more significant[70, 85, 124].

The transport of suspended sediment at large river confluences mainly relates to the local flow structures[30, 70, 73, 123]. Zhang et al.[95] reported that at the Yellow/Fen confluence, sediment near the bed surface at the mixing interface was found to be re-suspended due to the high turbulence levels of flows, and the reduction of upstream discharges decreased the sediment-carrying capacity of flows as well as the median particle size of the suspended sediment at the confluence. Szupiany et al.[73] reported that the highest concentrations of suspended sediment at large braid-bar confluences in the Paranà River were found along the flank of the scour hole, which was similar to the small-scale channel confluences as aforementioned. They also suggested that the phenomenon should be related to the high turbulence levels of the shear layer, which in turn helped to maintain the scour hole at the confluences. The effects of helical motions on sediment transport at large confluences have been mentioned by some studies[70, 73]. In a common belief, the secondary currents may be too weak (and/or spatially restricted) to significantly influence on the cores of high sediment concentration. Nonetheless, Lane et al.[49] observed that the large-size secondary circulation was likely beneficial to the rapid

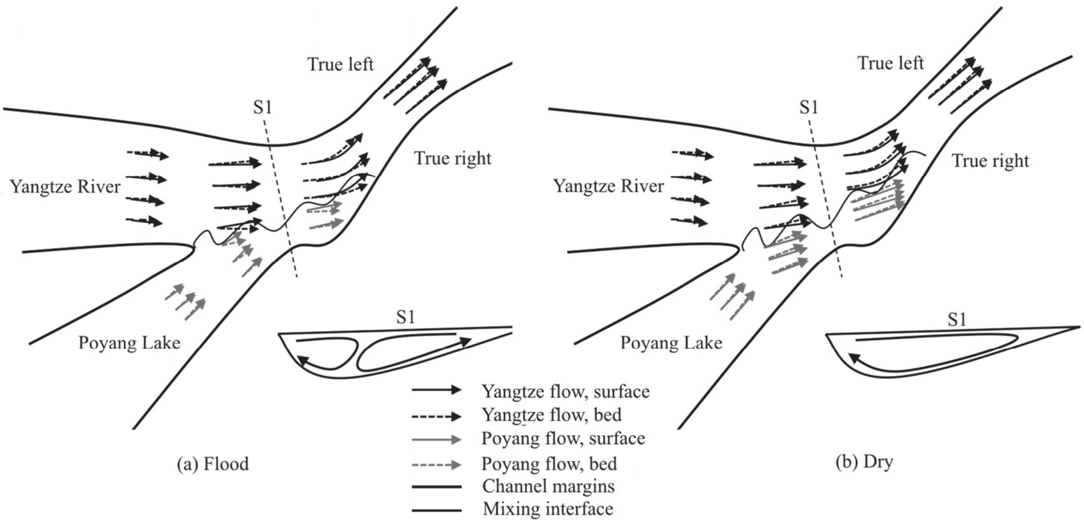

Fig. 6 Conceptual model of flow structure at the Yangtze/Poyang confluence in high flow conditions (a) and low flow conditions (b)

mixing of two large confluent rivers. Furthermore, Yuan et al.[30] reported that at the Yangtze/Poyang confluence, large-size secondary cells were found to restrict the core size of high sediment concentration originated from the Yangtze River flow, and downwelling flows acted as a barrier hindering the exchange of sediment between the two rivers.

7. Discussions and perspective

River confluences are ubiquitous features of the river network and are essential in several theoretical and applied research areas, encompassing river dynamics and flood and ecological management. This paper has outlined some areas of ongoing research and debate. Meanwhile, more studies for integrated, and most importantly interdisciplinary to fully understand the hydrodynamics, sediment transport, and morphological dynamics of river confluences and their effects on water environment and ecology are needed in the future. After completing our review of the literature, we suggest that the following topics require further attention.

(1) Although several conceptual models have been proposed to describe flow structure at channel confluences by experimental and numerical studies including six zones, helical cells and vortices within the mixing interface, there is no clear consensus on the exact role of the complex coherent structures at confluences (e.g., SOV, helical cells, KH vortices or wakes). There is also a lack of field or even laboratory studies that have measured and analysed the detailed three-dimensional coherent flow structures (e.g., eddies sizes, vortex pairing, the thickness of the mixing interface) at channel confluences.

(2) Knowledge of morphology and sediment-transport characteristics of river channel confluences is far to be complete. The interactions between complex flow structure, bed material texture, channel planform, and the development of bed morphology are complex, which can change over various spatial and temporal scales. Two challenging themes emerge for future research. First, there are few studies on the effects of the tributary inflows on the longitudinal evolution of bed forms of the main stream. Second, further research on the effects of the flood plain in one tributary or the bed discordance (especially that can produce the jet-like flows) on the sediment transport and bed morphology is needed.

(3) The importance of density difference between two confluent flows on the mixing processes have been highlighted by numerical simulations in previous studies[132-133]. More field and laboratory data are required to explore the mixing dynamics. Moreover, the flow density difference's role in the mixing processes shall be clarified and quantified among all the influencing factors, like momentum flux ratio, turbulent mixing by flow shear, bed friction, local morphological steering and channel-scale secondary currents.

(4) The confluence as the critical nodes in a river network affects the transport and transform of contaminations, and thus the water environment of the whole network. The previous studies mainly focused on traditional contaminations, e.g., phosphorus, while emerging contaminants, e.g., micro-plastic, shall be emphasized at confluences as they possess different interactions with water flow and sediment from traditional ones. How do they migrate with the complex flows and maybe transform onto or off the sediment at confluences? To cope with a new challenge on the water environment, further research on the effects of the river confluences on transporting of these emerging contaminants is necessary. In addition, the studies on ecological effects of the confluences mainly focus on the spatial heterogeneity of its habitat and the preference of aquatic organisms for habitat selection. There is a lack of understanding of dynamic behavior of aquatic organisms, especially fish, to the complex flow structures at a confluence.

(5) Despite the abundance of research on confluence hydrodynamics, some critical issues concerned with the large river confluences have yet to be resolved. For example, can the large-scale circulation cells be produced in large confluences with the strong steering effects of bedform roughness? Moreover, why were they missing in some field surveys[49, 70]? What are precisely the causes and criteria of the occurrence of large-scale circulation cells? The dynamical processes related to these secondary currents, such as mixing of suspended sediment and water chemistry and the evolution of local bed morphology, also need further research.

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