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Distribution of phosphorus in bed sediment at confluences responding to hydrodynamics

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Knowledge of the distribution of contaminants at channel confluences is critical for understanding their transport and dwelling at river networks where flow confluences constitute the key nodes. Flume experiments were conducted to study the distribution of phosphorus adsorption in surface sediment under complex hydrodynamics at channel confluences. The influence of the discharge ratio of the tributary discharge to the main stream discharge was also investigated. The results showed that the horizontal velocity and vertical velocity of flow are the dominant factors affecting the distribution of phosphorus adsorption. Flows with a larger horizontal velocity are not beneficial to phosphorus adsorption on sediment and thus low- and high-adsorption strips of phosphorus occur in the maximum velocity zone and the flow separation zone, respectively. Downwelling flows are beneficial to phosphorus adsorption on sediment as they can enhance phosphorus exchange between overlying water and the bed sediment. A small flow penetration with a small discharge ratio causes a decrease in vertical velocity in the separation zone as well as the strong intrusion of a helical cell into the bottom of this zone, which results in an increase in horizontal velocity near the bed and consequently the phosphorus adsorption is largely restricted.

Notation

Fr	Froude number
g	acceleration due to gravity
h	water depth
k	kinetic energy of turbulence
Q	discharge
R	hydraulic radius
Re	Reynolds number
U	mean velocity of flow
u	streamwise velocity
v	lateral velocity
w	vertical velocity
v_h	horizontal velocity
ρ	water density
$-\rho\langle v'w' \rangle$	Reynolds shear stress
ν	kinematic viscosity

1. Introduction

Huaihe River, one of the most important rivers in east China, suffers from severe point pollution (e.g. sanitary and factory sewage) and non-point pollution (e.g. from farming operations) with a high concentration of phosphorus and ammonia

nitrogen, which has caused serious damage to the downstream fishery. In February 2013, a severe ammonia nitrogen pollution event occurred in Huiji River, one of the tributaries of Huaihe River originating from Henan province to Anhui province, which raised government and public concerns about the water environment of Huaihe River. One of the most significant concerns is the distribution of phosphorus in surface sediment in river networks. Pollutants from municipal and industrial effluents transported in river networks may linger and dwell on fine sediment, waiting to be conveyed again. In such cases, polluted sediment becomes a secondary source of pollution that affects water quality (Ahiablame *et al.*, 2010; Förstner and Westrich, 2005). Flow confluences are critical nodes in river networks and how pollutants are transported or remain at channel confluences is important for the prediction of pollution. However, there is little available literature concerning the distribution of pollutant adsorption on surface sediment at channel confluences where the flow structure is very complex. Many factors can affect pollutant adsorption on sediment, including sediment characteristics (e.g. particle size and aggregation of sediment) (Meng *et al.*, 2014; Tang *et al.*, 2016), pollutant characteristics, the external environment (e.g. pH and temperature) and flow velocity (House *et al.*, 1995; Zhang *et al.*,

2011), but the influence of complex flow structures such as those that occur at channel confluences is not well studied. Related research on hydrodynamics at river confluences and the influencing factors of phosphorus adsorption are now briefly reviewed.

Time-averaged flow structures at river confluences have been investigated over the past 30 years (Best, 1987, 1988; Best and Reid, 1984; Best and Roy, 1991; Boyer *et al.*, 2006; Constantinescu *et al.*, 2011, 2012; Mosley, 1976; Rhoads and Sukhodolov, 2001, 2004, 2008). A conceptual model consisting of six distinct hydrodynamic zones (flow stagnation, flow deflection, flow separation, maximum velocity, gradual flow recovery and shear layer associated with vortex generation) at river confluences was proposed by Best (1987). Among these six zones, the flow separation zone (Best and Reid, 1984; Yang *et al.*, 2009) and the shear layer (Rhoads and Sukhodolov, 2004, 2008) are particularly important for the transport of pollutants and sediment, and have received a lot of investigation. It has been found that the three-dimensional (3D) characteristics of the separation zone are significantly affected by the discharge ratio/momentum flux and the confluence angle (Best and Reid, 1984; Yang *et al.*, 2009). Furthermore, hydrodynamics and morphodynamics at a channel confluence are also influenced by the level of the concordance between channel beds at the confluence entrance and differences in the water characteristics between the incoming tributary flows (Gualtieri *et al.*, 2017). Penetration of a large tributary discharge at channel confluences can distort the shear layer (Yuan *et al.*, 2016) and result in a large variation in Reynolds shear stress and vorticity magnitude.

House *et al.* (1995) measured the net influx of soluble reactive phosphorus (SRP) to riverbed sediment and observed the change in the adsorption amount with time for different flow velocities. They found a systematic increase in the net influx of SRP as the water velocity increased. The results also suggested that the thickness of the boundary layer for diffusion should decrease with an increase in water velocity, which indicated that SRP in the overlying water and interstitial water could spread more easily. Zhang *et al.* (2011) studied phosphorus retention responding to hydrology by means of a static column and a steady-flow flume experiment. They found that an increase in flow velocity could accelerate the adsorption of phosphorus and also increase the phosphorus adsorption amount. Using a recirculating flume and sediment cores, Barlow (2004) found that velocity and water depth did not have a considerable influence on the rate of phosphorus adsorption. In that study, the adsorption rate decreased significantly with an increase in the original phosphorus content. After conducting a field survey in a series of ditches and measuring the adsorption amount of phosphorus in bed sediment in each season, Smith (2009) proposed that the adsorption amount decreased as the water velocity increased. D'Angelo and Benfield (1991) also came to the same

conclusion according to a long period of field observations and reported that increased velocity resulted in a loss of retention ability for bed sediment. They suggested that increased velocity led to more opportunities for contact between the water and sediment, which caused more nutrient uptake during periods of slow velocity. However, in general, the influence of hydrodynamics on phosphorus adsorption is still disputable.

A few studies have focused on the spatial adsorption of phosphorus in bed sediment, particularly in estuaries (Ping *et al.*, 2009; Strom and Biggs, 1982). The fractions of different phosphorus compounds were analysed and the relation between them and the contents of metallic elements were established. Chomicki *et al.* (2016) mentioned that along-shore currents could affect the spatial distribution of phosphorus near the mouth of the Grand River. However, the effects of hydrodynamics have rarely been considered in studies of phosphorus distribution.

The principal objective of the present study was thus to investigate the distribution of phosphorus adsorption in surface sediments at channel confluences considering the influence of hydrodynamics. It is important to note that this study differs from previous work conducted by others in the following three important aspects.

- The flow structure of the confluence zone was more complex than that considered in previous studies and includes the separation zone, the maximum velocity zone and so on.
- Hydrodynamic indicators for the distribution of phosphorus adsorption in surface sediment were explored.
- The experimental setup and procedure were well-designed in order to obtain accurate results.

The remainder of this paper is structured as follows. The experimental setup and procedure are introduced in Section 2. The results of flow measurements and the distribution of phosphorus in surface sediment at a channel confluence in the laboratory experiment are presented in Section 3, along with a discussion on how hydrodynamics influence the distribution of phosphorus at a channel confluence. The main conclusions from the study are given in Section 4.

2. Experimental method

Laboratory experiments for two cases were conducted in an acrylic glass circulating flume confluence, as shown in Figure 1. The configuration consisted of three tanks, PVC pipes (inner diameter of 110 mm), two ultrasonic flowmeters, pump–valve systems, honeycombs and a tailgate. Water was discharged from the two upstream tanks to the two downstream channels. The flow rate was controlled by the ultrasonic flowmeters and pump–valve systems. Honeycombs and sufficiently long channels were used to ensure fully developed flows entering the junction point. The water level was controlled by

	Case 1			Case 2		
	Main	Tributary	Post confluence	Main	Tributary	Post confluence
Fr	0.063	0.094	0.118	0.094	0.063	0.118
Re	7045	10 568	15 050	10 568	7045	15 050
Discharge ratio		1.5			0.67	

- In case 1, the discharge of the main stream (Q_1) was 4.0 l/s and the discharge of the tributary (Q_2) was 6.0 l/s. The water depth (h) was 16.5 cm. The discharge ratio (Q_2/Q_1) was thus 1.5 and the momentum flux ratio ($\rho Q_2 U_2 / \rho Q_1 U_1$) was 2.25, where ρ is the water density and U the mean velocity.
- In case 2, Q_1 was 6.0 l/s and Q_2 was 4.0 l/s. Thus, the discharge ratio and the momentum flux ratio were 0.67 and 0.44, respectively.

A mass of 10.7 g of monopotassium phosphate (KH_2PO_4) powder was added to the water in the downstream tank and mixed well. The flow was continued for 2 h to minimise the

Figure 2. Particle size gradation curve of sediment used in the experiments

Figure 3. Time series of phosphorus concentration during the experiment

potential influence of the flume system on phosphorus adsorption onto the clay sediment. After that, a plate (100 cm × 40 cm) together with a 1 cm thick layer of sediment was placed in the confluence hydrodynamic zone, and flows of constant discharge were generated in the flume. Water samples were collected every 15 min at first, then every hour for the next 2 h and then every 2 h for the next 44 h (Li *et al.* (2016) showed that the adsorption of phosphorus onto sediment in the Huaihe River reached equilibrium in 47 h). The phosphorus concentration in the overlying water, measured by means of the ultraviolet spectrophotometric method throughout the experiment, was around 1.25 mg/l (Figure 3).

To collect sediment samples, six sampling cross-sections (S1–S6) at intervals of 10 cm were used. As shown in Figure 1, there were 17 measurement points in each cross-section with a horizontal interval of 2 cm. Sediment cylinder cores (of diameter 1 cm) at these measurement points were taken using a 1 cm dia. round plastic tubing and air dried in a ventilated environment (Figure 4). The upper layer, of about 1 mm thick (0.2 g) thickness, was cut off and used for the measurement of IP content based on the EC standard measurement and testing programme (González, 2005). The phosphorus fractions in one original and eight randomly selected post-test samples were analysed according to this programme. The majority of phosphorus in the sediment was IP, including non-apatite phosphorus (associated with oxides and hydroxides of aluminium (Al), iron (Fe) and Manganese (Mn)) and apatite phosphorus (associated with calcium (Ca)), which accounted for 83% of the total weight. The amount of IP varied by about 10–18.5% during the experiment, while the amount of organic phosphorus rarely changed. Thus, only the adsorption of IP onto sediment was measured. The concentration of IP was

Figure 4. Sediment layer (a) and sediment core (b)

determined using the molybdenum blue method on an ultraviolet–visible spectrophotometer (TU-1810PC, Persee Co., Beijing, China).

To avoid disturbing the adsorption process, velocity measurements were conducted during an experiment without pollutant but with a plate with a 1 cm thick layer of sediment in the confluence zone. Three-dimensional velocities were measured above each sediment core with an interval between two adjacent points of 1 cm. The 3D velocities at these points were measured with an acoustic Doppler velocimeter (ADV) at a sampling frequency of 100 Hz over a duration of 120 s, which was sufficient to capture turbulence information at the channel confluence (Yuan *et al.*, 2016). Seeding materials consisting of neutrally buoyant hollow glass spheres (Potter Industries Sphericle) were added to provide acoustic scattering signals for the ADV during the measurement process. The raw streamwise

velocity, cross-stream velocity and vertical velocity were processed by removing weak signals (signal-to-noise ratio <30) and poorly correlated signals (<90% correlation) and de-spiking using WinADV software.

3. Results and discussion

3.1 3D velocity and turbulent kinetic energy

To analyse the potential influencing factors of the distribution of phosphorus, the flow field, including the 3D velocities and kinetic energy of turbulence, is analysed first. The 3D velocities are shown in Figures 5–7. The streamwise velocity, u , is the horizontal velocity component perpendicular to the cross-section; the lateral velocity, v , is the horizontal velocity component parallel to the cross-section; w is the vertical velocity along the z -axis, which is perpendicular to the bottom of the flume, as shown in Figure 1. Figure 8 shows the spatial distribution of the kinetic energy of turbulence, k .

In case 1, the region with low values of u near the inner wall indicates the flow separation zone, a characteristic region at channel confluences (Best, 1987), which is caused by flow detachment from the inner wall in the post-confluence channel and its reattachment further downstream. Its width decreased as it approached the bed surface. Due to compression of the separation zone, the velocity of the main stream increased from 10 cm/s to 21 cm/s, which indicates the maximum velocity zone. This region occupied about half of the whole cross-section. Adjacent to the separation zone was a helical cell rotating counter clockwise, with a width of about two thirds of the cross-section. It is interesting to observe the significant downwelling flow (induced by the helical motions) at the outer side of S2. Two strips with large values of k indicate the location of the shear layer (Sukhodolov and Rhoads, 2001) and the boundary of the separation zone, respectively. Large flow shear occurred in these two locations. The shear layer was distorted significantly at all cross-sections. The intensity of flow shear in this layer decreased with distance from the junction corner. More details about the distorted shear layer are available in previous work by the authors (Yuan *et al.*, 2016).

In case 2, the width of the separation zone was much smaller than in case 1 due to the smaller discharge ratio. It also decreased as it approached the bed and disappeared near the bed surface. The values of maximum velocity were smaller, ranging from 16 cm/s to 20 cm/s, and the maximum velocity zone was enlarged to about two thirds of the cross-section. Interestingly, due to the low intensity of flow separation, the helical cell evidently intruded into the bottom of the separation zone and constricted the size of the separation zone near the bed. The position of the downwelling flow was closer to the inner side of the channel than in case 1. The helical cell was much smaller than that in case 1, which was caused by the stronger main flow. The shear layer, which was not distorted, can be distinguished by the vertical strip with high k values.

3.2 Reynolds shear stress

The pattern of Reynolds shear stress ($-\rho\langle v'w' \rangle$, where $\langle \cdot \rangle$ denotes time averaging) illustrates vertical vortices or eddy motion, which can cause flow shear on the sediment bed and probably affect the adsorption of phosphorus on sediment. For simplicity, $\langle v'w' \rangle$ is used here to represent the Reynolds shear stress, which is calculated by the covariance of velocities v and w , as $\langle v'w' \rangle = \text{cov}(v, w)$. Figure 9 shows the spatial evolution of $\langle v'w' \rangle$ in the two cases. Strong secondary flow is associated with large values of $\langle v'w' \rangle$ (Yuan *et al.*, 2017). In case 1, the large values of $\langle v'w' \rangle$ in the middle of all cross-sections were due to distortion of the shear layer caused by the entry of a tributary flow. In the inner portion, large values of $\langle v'w' \rangle$ occurred at the boundary of the separation zone, and values decreased from the bed to the water surface.

In case 2, the Reynolds shear stress within the shear layer was much smaller than in case 1 due to the almost vertical shear layer. The maximum value of $\langle v'w' \rangle$ occurred at the boundary of the separation zone and decreased from the bed to the water surface, which is similar to case 1. However, this region was closer to the inner portion at cross-sections S4 to S6, which also reflects the penetration of helical cells into the bottom of the separation zone resulting from the decayed flow separation mentioned above.

Figure 10 shows the vertical profile of the average Reynolds shear stress inside the separation zone ($y = 34.5\text{--}36.5\text{ cm}$) at cross-section S5. In case 1, $\langle v'w' \rangle$ was in the range $0.2\text{--}0.6\text{ cm}^2/\text{s}^2$, with no significant change from the water surface to the bed. In case 2, the values of $\langle v'w' \rangle$ were lower near the water surface (about $0.3\text{ cm}^2/\text{s}^2$) than in case 1 due to the lower intensity of the flow separation, but the shear stress increased dramatically from the water surface to the bed ($0.9\text{ cm}^2/\text{s}^2$), illustrating the intrusion of helical cells in the bottom of the separation zone.

3.3 Distribution of phosphorus in bed sediment

Figure 11 shows the distribution of phosphorus adsorption on bed sediment for the two cases considered in this work. The adsorption amount of phosphorus in the separation zone differed significantly in two cases. In case 1, the adsorption amount of phosphorus in the separation zone was high (about 0.7 mg/g) and occupied half of the channel width. In case 2, the adsorption amount in the separation zone was about 0.53 mg/g and occupied about a third of the channel width. Outside the separation zone, both cases showed an enrichment region and a low-adsorption strip but the positions of these two regions were different in the two cases. In case 1, the low-adsorption strip with an adsorption amount of about 0.55 mg/g was close to the separation zone. Outside this strip was an enrichment region, about 20 cm long and 5 cm wide, with an adsorption amount of about 0.73 mg/g . In case 2, the enrichment strip (about 30 cm long and 5 cm wide) was next

Figure 5. Contours (upstream oriented) of the spatial distribution of the streamwise velocity, u : (a) case 1; (b) case 2

Figure 6. Contours (upstream oriented) of the spatial distribution of the lateral velocity, v : (a) case 1; (b) case 2

Figure 7. Contours (upstream oriented) of the spatial distribution of the vertical velocity, w : (a) case 1; (b) case 2

Figure 8. Contours (upstream oriented) of the spatial distribution of the turbulent kinetic energy, k : (a) case 1; (b) case 2

Figure 9. Contours (upstream oriented) of the spatial values of Reynolds shear stress ($\langle v'w' \rangle$) from cross-sections S1 to S6: (a) case 1; (b) case 2

to the separation zone, with an adsorption amount of about 0.68 mg/g. The low-adsorption strip, with an adsorption amount of about 0.54 mg/g, was close to the outer bank and occupied about half of the channel width.

3.4 The effects of hydrodynamics on phosphorus adsorption

Observations of the flow structure and phosphorus distribution in the surface sediment were presented in Sections 3.1–3.3.

Figure 10. Vertical distribution of Reynolds shear stress $\langle v'w' \rangle$ inside the separation zone

These observations are now comprehensively analysed and the relation between the complex hydrodynamics at confluences and the distribution of phosphorus adsorption is discussed.

In order to determine their influence on the phosphorus distribution, the 3D velocity, kinetic energy of turbulence and Reynold shear stress of the flow were measured and calculated to illustrate different hydrodynamic zones at the flume confluence. A distorted shear layer between two combining flows was found. The causes of this shear layer and its effects on confluent flows are discussed in detail by Yuan *et al.* (2016). Moreover, its effects on sediment transport and bed morphology at the confluence hydrodynamic zone were studied by Yuan *et al.* (2017). Strong downwelling flow was found to occur at the outer side of the main channel, which was involved in helical motions. Yuan *et al.* (2017) suggested that this downwelling flow could be the main contributor to mid-channel scour holes. Yuan *et al.* (2016, 2017) did not focus on the flow separation zone, which was found to vary with different discharge ratios in the current work. In particular, for a small discharge ratio, it was found that a helical cell can penetrate the bottom of the separation zone and constrict the size of the separation zone near the bed.

The separation zone is an important region for the distribution of phosphorus adsorption at channel confluences. Its size is determined by the discharge ratio (Best and Reid, 1984; Yang *et al.*, 2009). Here, the zero-velocity isoline method proposed by Yang *et al.* (2009) is used to define the separation zone. Comparing the two cases, the horizontal dimension of the separation zone was found to increase with an increase in the discharge ratio; this was also observed by Feng *et al.* (2009) and Yang *et al.* (2009). In the current study, the separation zone

Figure 11. Distribution of phosphorus adsorption amount in the bed sediment at confluences: (a) case 1; (b) case 2

occupied a third of the cross-section in case 1 and a sixth of the cross-section in case 2. There was a strong helical cell next to the bottom of the separation zone (Yang *et al.*, 2009), which was characterised by large values of the Reynolds shear stress $\langle v'w' \rangle$. In the near-bed portion, the velocity in the separation zone became smaller due to the bed resistance, and thus the scale of the separation zone decreased and helical cells tended to intrude into the inner portion. The existence of helical cells, which may affect the distribution of phosphorus in the separation zone, can change the horizontal velocity near the bed surface significantly. The helical cell intruded into the separation zone near the bed and caused different horizontal velocity fields in the two cases considered in this work. The horizontal velocity is defined as $v_h = (u^2 + v^2)^{1/2}$. The experimental results reveal that the average horizontal velocity below the separation zone was 7.67 cm/s in case 2 while it was only 3.47 cm/s in case 1. Contamination enrichment is difficult in the case of

high-velocity flow according to the observations of Smith (2009) and D'Angelo and Benfield (1991). The reason for this is probably because there is less contact opportunity between water and sediment when the flow velocity is high. Bencala (1983) also found that the interactions of solutes with a stream bed were more intense at low flow than they would be at high flow. The higher horizontal velocity may thus reduce the adsorption amount of phosphorus in the separation zone in case 2 (Figure 11(b)). Figure 7 shows that the size and intensity of downwelling flow were much larger in case 1 than in case 2 due to the large separation zone. Downwelling flow could significantly increase the pressure at the bed surface and variation of pressure at the bed surface can cause hyporheic exchange (Elliott and Brooks, 1997), which can enhance phosphorus exchange between the overlying water and the bed sediment. Thus, a stronger downwelling flow will also make a contribution to the enrichment of phosphorus in the separation zone when the discharge ratio is larger. In general, low horizontal velocity near the bed and significant downwelling flow in the case of a larger discharge ratio result in the enrichment of phosphorus, while the adsorption amount is

lower in the case of a smaller discharge ratio and a small separation zone.

Both cases showed a low-adsorption strip outside the separation zone, which can be attributed to the high-velocity flow. Figure 12 shows the distribution of horizontal velocity near the bed at confluences. When the discharge ratio was 1.5 (case 1), the maximum velocity zone occurred at the entry point of the tributary and extended to the outer bank downstream, mainly as a result of the inflow of high tributary flows. In particular, the maximum velocity zone was coincident with the low-adsorption strip. When the discharge ratio was 0.67 (case 2), the maximum velocity zone developed almost along the outer bank and originated from the main stream. Due to the smaller scale of the separation zone, the maximum velocity zone was larger than that in case 1 and hence a wider low-adsorption strip developed along the outer bank in case 2. In case 1, there was an obvious enrichment zone (average adsorption amount of 0.73 mg/g) outside the maximum velocity zone, which may be attributed to strong downwelling flow due to the blockage of the large tributary flow by the main channel flow (Figure 7). In case 2, downwelling flow appeared closer to the tributary entrance point for the smaller tributary discharge. Thus, the enrichment zone (average adsorption amount of 0.64 mg/g) occurred at $y = 20\text{--}25\text{ cm}$ inside the maximum velocity zone. The average adsorption amount was lower than that in case 1 due to the effects of the maximum velocity zone.

4. Conclusions

The following important conclusions can be drawn from this study.

- Horizontal velocity and vertical velocity are the important factors influencing the distribution of phosphorus at a channel confluence. A higher horizontal velocity can result in a lower adsorption amount while downwelling flow can promote the adsorption of phosphorus.
- Low-adsorption strips were located in the maximum velocity zone in both the cases considered in this work. The maximum velocity zone moved to the outer bank with a decrease in the discharge ratio and the size of this zone increased.
- The enrichment of phosphorus mainly resulted from the downwelling flow pointing towards the bed. This is because downwelling flow can cause hyporheic exchange and enhance phosphorus exchange between overlying water and bed sediment.
- The adsorption amount of phosphorus in the separation zone varied significantly with a change in the discharge ratio. The separation zone was large when the discharge ratio was high, which resulted in low horizontal velocity near the bed and significant downwelling flow in this zone. The adsorption amount of phosphorus is thus high

Figure 12. Distribution of horizontal velocity, v_h , 2 cm above bed surface at the confluences: (a) case 1; (b) case 2

in this case. However, the size of the separation zone became smaller with a decrease in the discharge ratio, resulting in higher horizontal velocity near the bed and weaker downwelling flow in this zone. The adsorption amount of phosphorus thus decreased with a decrease in the discharge ratio.

This study was based on laboratory experiments, and it is acknowledged that conditions would be more complex in the field. Bed morphology and bathymetry can affect the 3D characteristics (e.g. horizontal velocity and upwelling/downwelling) of the flow in the confluence hydrodynamic zone and, consequently, the adsorption of phosphorus. Further study is needed to explore the distribution of phosphorus in surface sediment at a natural channel confluence by means of a long-term field investigation.

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