Flow and sediment behaviours and morpho-dynamics of a diffluence—Confluence unit

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Abstract
A diffluence-confluence unit is an elementary component within a river system and presents a complex yet linked pattern of both flow and sediment transport in between. This study deals, by means of field investigations and numerical modelling, with morpho-dynamics of such a unit on the lower Yangtze River reaches. The unit comprises, looking downstream, a secondary (left) course and a main (right) course. Field surveys are performed for measurements of flow discharge, sediment loads at selected locations and river bathymetry at certain intervals. The field data show that the reach is mainly composed of suspended load, whose amount exhibits a declining trend with the elapse of time. Simulations in 3D are made to complement the field data and clarify the basic features of the unit, especially the partitioning of flow and suspended sediment in the diffluence and their subsequent reciprocal adjustment in the confluence. The results indicate that approach flow variations have a bearing on the diffluence flow partition. To augment flow discharge in the left branch, a training wall is devised in the diffluence to modify the intake flow. Secondary flow structures are found to be more influenced by the thalweg curvature than the flow division. The “inlet step” or differential topography contributes to the unequal flow division. In the confluence, a two-cell flow structure coexists, which may diminish along with the dynamical adjustment of the two waters. The classical bed discordance is also observed. With the typical flow and sediment features, the main course is prone to slight erosion, while the secondary branch faces up with gradual siltation. These findings contribute to the understanding of the alluvial behaviours of such units, and provide reference for studies in similar situations and river management.

Keywords
3D modelling, diffluence-confluence unit, field measurements, flow pattern, fluvial processes

1 INTRODUCTION
In a natural alluvial stream, a combination of diffluence and confluence, though not frequently encountered as meandering loops, is a basic planimetric feature. A river course bifurcates into two branches that unite farther downstream, forming thus a diffluence-confluence unit. It is common that the distance in between is a few km. Usually, the branches are relatively stable in bedform. The differences in geometry within the unit generate complex flow patterns at each end (Le et al., 2018). With economic development, the river morphological...
changes and riverine human activities affect each other; their relationship is reciprocal.

A diffluence is a node in braided channels, controlling the routing of flow and sediment and platform stability of the diffluence-confluence unit (Hackney et al., 2018). As the flow bifurcates into two branches, the upstream river curvature (Kleinhans, Ferguson, Lane, & Hardy, 2013) and each branch’s local along-channel slope (Hardy, Lane, & Yu, 2011) create helical flows in each branch. The splitting angle (Hardy et al., 2011) affects the formation of separation zones near the apex of the junction. This causes sediment deposition and in turn accelerates the flow divergence (Bristow & Best, 1993). In addition to the diffluence asymmetry, the unequal partitioning of sediment carried by the flow is also of concern, which plays a role in the bed evolution within the unit.

As for confluence, Mosley (1976) and Best (1986) develop the theory of six distinct confluent flow zones. As elaborated by time-averaged velocity data (Rhoads & Kenworthy, 1998), the classical viewpoint is the coexistence of two secondary flow cells, rotating counter-clockwise, at the cross-section downstream of the confluence (Riley, Rhoads, Parsons, & Johnson, 2014). Further studies by Lane, Bradbrook, Richards, Biron, and Roy (2000) and Constantinescu, Miyawaki, Rhoads, Sukhodolov, and Kirkil (2011) show that, by analysing instantaneous flow data, a 3D streamwise coherent structure exists in the confluence. Its existence enhances the mixing in the interface between the two tributaries (Bouchez et al., 2010; Lane et al., 2008). The confluence mixing results in highly active sediment transport (Mosley, 1976). The presence of a scour-hole features typically the morphology pattern (Ashmore & Parker, 1983; Mosley, 1976). The tributary flow conditions, inclusive of incoming angle, discharge ratio and bed discordance, play an essential role in the max. Scour depth (Best & Roy, 1991; Biron, Roy, & Best, 1996; Mosley, 1976).

The diffluence-confluence unit is a key geo-morphological element and exhibits a coupled behaviour of flow and sediment in between. Many studies focus mostly on separate examinations of diffluence or confluence; more attention should be paid to their interplay (Hackney et al., 2018; Le et al., 2018). Within the unit, the adjustment of flow, sediment and morphology goes reciprocal with changes in flow discharge. Thus it follows that, to understand the morphodynamics of a diffluence-confluence unit, the knowledge of flow discharge range and corresponding sediment rate is necessary (Hackney et al., 2018). Hence, a renowned diffluence-confluence unit on the Yangtze River is chosen in the study. The focus is laid on examinations of its flow and sediment variations and the impacts thereof on the morpho-dynamics.

The study area is a part of the lower Yangtze River, China. It is situated ~350 km up estuary from the river mouth in Shanghai (Figure 1a). An island, called Baguazhou, splits the river into two

**FIGURE 1** Study site: (a) Location of study area; (b) layout of measurement stations and (c) flow and sediment variations at Datong station, 2011 [Colour figure can be viewed at wileyonlinelibrary.com]
branches; the right one is the main course (Figure 1b). The left and right branches are 21.6 and 10.5 km long, respectively. Measured at the normal water level, the average river width is \( \sim 800 \) and \( \sim 1,200 \) m; the average depth is 11.0 and 23.0 m (Yu et al., 2014). At the diffuence, the splitting angle is \( \sim 55^\circ \); at the confluence, the merging angle is \( \sim 90^\circ \).

The flow and sediment into the area are significantly influenced by the Three Gorges Project (TGP) beginning its impoundment in 2003. The Datong station, located \( \sim 1,250 \) km downstream of the TGP and \( \sim 250 \) km upstream of the study site, is the most seaward hydrological station of the river. In terms of flow and sediment data, the gauging station is representative of its downstream reaches, upon which the majority of the studies dealing with the lower Yangtze River are based.

The average annual runoff of the reach is \( \sim 28,000 \) m\(^3\)/s, with an uneven monthly distribution. To exemplify, the May–October flow volume accounts for \( \sim 70\% \) of the annual runoff, which is influenced by the East Asian monsoon. The reach is characterized by suspended load, with a 0.332 kg/m\(^3\) sediment concentration and a 11.68 t/s annually averaged rate. The river-bed material is dominated by fine-grained sand and clay.

Depending on flood magnitude, the left branch passes between 12 and 18% of the total flow rate in the river. Perennially over the years, constructions of wading structures along the reach have changed in an unfavourable manner the flow conditions and increased the hydraulic resistance, also leading to local sediment deposits. As a result, the flow rate of the left branch undergoes a decline, which has become an issue of concern. The riverain area is densely populated and plays an essential role in the regional economic development. Along the branch, the industrial output accounts for \( \sim 40\% \) of the city’s production capacity (Yu et al., 2014). Stable flow partition offers a sustainable environment for shipping and water intake for industry. To counteract the declining trend and even reduce sediment accumulation in the left branch, engineering measures should be undertaken.

The research aims to look into the flow and sediment characteristics and the morpho-dynamic responses of the unit, especially during medium and low flows. Both field measurements and numerical simulations are performed, which complement each other to help understand the alluvial behaviours. As a concept, an application of a training wall in the diffuence area is examined, which is motivated by the need to improve the flow diversion ratio. The combination of the field and numerical results reveals features with respect to both flow and sediment within the large diffuence–confluence unit, providing thereby reference to similar river situations.

## METHODS

Field surveys are conducted of water flow, sediment and bathymetry; three-dimensional numerical simulations are performed to capture detailed flow structures and predict future bedform changes.

### 2.1 Field measurements

To record the hydrological data and map the river topography, field surveys were undertaken at three flow discharges during the May–September 2011 period. The measured parameters included water level \( Z \) (m), flow velocity \( V \) (m/s), flow discharge \( Q \) (m\(^3\)/s), sediment concentration \( S \) (kg/m\(^3\)) and grain-size distribution.

Also marked in Figure 1b is the layout of the measurement stations for water levels at seven locations (denoted as WL1–7) and flow velocities at seven locations (denoted as FV1–7, three along the left branch). At FV1–3, sediment concentrations were also monitored (denoted as SC1–3). At each FV, five and six plumb lines were arranged in the left and right branches. Along each line, sampling was made at five depths, that is, the distance from the water surface \( h_i = 0, 20, 60, 80, \) and \( 100\% \) of water depth \( H_i \) (\( i = 1–5 \)). All data were recorded at one-hour intervals. At one cross-section (BM1) at the diffuence, bed materials were sampled at three cross-channel positions.

The river bathymetry used for the study was achieved with a HY1600 bathymetric profiler. RDI Workhorse Acoustic Doppler Current Profilers (ADCPs) of 4-beam 600/1200-kHz measured flow depth and velocity, using the bottom tracking mode at each cross-section. The ADCP was attached to a customized motorboat, with GPS positioning. The four beams were at 20° from each other. YJD-1 type pressure sensors measured water-levels, with \( \pm 1 \) cm accuracy. The relative error of the flow discharges was estimated at below \( \pm 5\% \). Suspended load was sampled with point-integrative water samplers.

Figure 1c shows the field data of flow and sediment variations acquired at Datong station during 2011. To examine the variations in flow and sediment and their impacts on the morpho-dynamics, three dates, May 13, June 22 and Sept. 27, were chosen, indicated by red dots. June 22 corresponded to the peak flood of the year. Challenges did exist during the measurements, which was mainly due to difficulties in navigating the boat to follow the predetermined transects and maintaining constant boat speed (preferably 1 m/s). The large flow velocity, local eddies and strong turbulence were the contributing factors. That was the reason why only flow velocity and water level were recorded at selected stations. Despite this, measurements were repeated several times to guarantee accuracy.

Between the two branches, the partitioning varies as a function of flow discharge. For a given discharge, let \( R_l \) and \( R_r \) denote the flow and sediment split ratio

\[
R_l = \frac{Q_l}{Q_l + Q_r}, \quad (1)
\]

\[
R_s = \frac{q_l}{q_l + q_r}, \quad (2)
\]

where \( Q \) (m\(^3\)/s) = flow discharge and \( q \) (kg/s) = sediment transport rate. Subscripts \( l \) and \( r \) denote the left and right branch.
2.2 | Numerical simulations

The Delft3D program package, version 4.04, (Deltares, 2014) is used to explore the flow behaviours and morphology changes. In consideration of the unit’s complex geometry, three-dimensional modelling is a realistic approach, which enables the modeller to capture the main cross-sectional features.

2.2.1 | Mathematical formulation

The model is based on the finite-difference method to solve the Navier-Stokes equations. Bed-form changes are simulated with specification of the bed stability coefficient and bed resistance. The governing equations include flow continuity, flow momentum, sediment transport and bed deformation. Only the latter two equations are given here to save space. For a more detailed description of all the equations, one refers to the Delft3D website (https://oss.deltares.nl/web/delft3d) and recently published results such as Xie, Yang, Lundström, and Dai (2018) and Xie, Yang, and Lundström (2019).

On account of the sediment trapping at the TGP, the bed-load amount is negligibly small; the suspended load dominates in the transport. For mass balance and advection–diffusion, the suspended load equation in 3D reads as

\[
\frac{\partial S}{\partial t} + \frac{\partial}{\partial x}(ux) + \frac{\partial}{\partial y}(vy) + \frac{\partial}{\partial \sigma}(\omega - \omega_s)s = -F_s, \tag{3}
\]

where \(x, y, \sigma = \) coordinates, \(u, v, \omega (m/s) = \) longitudinal, transversal and vertical velocity components, \(t (s) = \) time, \(\omega_s (m/s) = \) sediment settling velocity, \(\varepsilon_{s,x}, \varepsilon_{s,y}, \varepsilon_{s,\sigma} (m^2/s) = \) eddy diffusivity of sediment fraction and \(F_s = \) function of river-bed deformation. \(F_s\) is dependent on sediment erosion and deposition, given by

\[
\frac{\partial Z_b}{\partial t} = F_s \tag{4}
\]

\[
F_s = D_b - E_b \tag{5}
\]

\[
D_b = \begin{cases} 
\omega_s S_b \left(1 - \frac{\tau}{\tau_d}\right) & \tau \leq \tau_d \\
0 & \tau_d < \tau
\end{cases} \tag{6}
\]

\[
E_b = \begin{cases} 
M \left(\frac{\tau}{\tau_e} - 1\right) & \tau \geq \tau_e \\
0 & \tau < \tau_e
\end{cases} \tag{7}
\]

where \(Z_b (m) = \) change in bed elevation, \(\gamma_0 (N/m) = \) dry weight of bed material, \(D_b (kg/(m^2s)) = \) sediment flux of deposition from suspended load, \(E_b (kg/(m^2s)) = \) sediment flux of erosion resulting in suspended load, \(S_b (kg/m^3) = \) sediment concentration near bottom, \(\tau (N/m) = \) bed shear stress, \(\tau_d\) and \(\tau_e (N/m) = \) critical stresses of deposition and erosion and \(M (kg/m^2s) = \) bed scurbing rate.

2.2.2 | Grid and bathymetry

The river bathymetry is based on the field data in June 2011 (Figure 2a). The computational domain is 25.00 km long (measured along the main river). To reduce boundary effects, 1,000 m upstream of WL1 and 1,200 m downstream of WL5 are included. Based on a coarse mesh, global and local refinements are made to achieve a fine

**FIGURE 2** Model set up: (a) Bathymetry measured in June 2011 and (b) numerical grid with local enlargements at the diffuence and confluence [Colour figure can be viewed at wileyonlinelibrary.com]
mesh. Several meshes of varied cell sizes are evaluated to ensure grid independence, which is checked through steady-state calculations. Figure 2b shows the adopted refined mesh, with enlarged views of the diffuseness and confluence.

In plan, the domain is covered by 105,000 cells, comprising 350 streamwise and 30 transverse. The grid size varies between 10 and 20 m, typical for most simulations. Smaller cells, with a min. Size of 5 m, are used in the diffuseness and confluence to account for large velocity gradients. In the vertical direction, as recommended by Deltares (2014), 10 layers are specified. From riverbed to water surface, the thickness of each layer is 2, 3, 4, 6, 8, 10, 12, 15, 20, and 20% of \( H_0 \). The total thickness is equal to \( H_0 \). The difference between two neighbouring layers should not exceed the thickness of its lower layer. The whole domain is thus divided into 105,000 hexahedral elements.

### 2.2.3 Boundary conditions

Boundary conditions are defined in terms of both flow and sediment, which are based on the in-situ measurements. At the upstream boundary, \( Q \) and \( S \) are given; at the downstream, \( Z \) is specified. For the river bed and banks, a non-entry condition specifies a zero normal gradient of sediment content. The wetting and drying function of cells is activated to account for water-level fluctuations. For three flow cases, Table 1 summarizes the boundary conditions. Cases 1 and 3 correspond to the low and medium flow discharges, while Case 2 to the peak discharge.

#### Table 1

| Case | \( Q \) (m\(^3\)/s) | \( S \) (kg/m\(^3\)) | \( Z \) (m) | Date        |
|------|---------------------|-------------------|-----------|-------------|
| 1    | 15,290              | 0.053             | 1.616     | May 13th   |
| 2    | 46,100              | 0.254             | 5.973     | June 22th  |
| 3    | 27,310              | 0.189             | 3.581     | Sept. 27th |

#### Table 2

Parameter values adopted in the model

| Parameter | Data range          | Source                      |
|-----------|---------------------|-----------------------------|
| \( \omega_s \) (m/s) | 0.0004              | Field measurements          |
| \( \tau_n \) (N/m\(^2\)) | 0.06–0.10           | Equation (6) (Partheniades, 1965) |
| \( \tau_e \) (N/m\(^2\)) | 0.10–0.20           | Equation (7) (Emmanuel, 1986) |
| \( M \) (kg/m\(^3\)/s) | 0.0002–0.02         | Equation (7) (Emmanuel, 1986) |
| \( \gamma_0 \) (kg/m\(^3\)) | 1.600               | Field measurements          |

#### Table 3

\( R_f \) comparison between measurements and calculations, 2011

| Date        | \( Q \) (m\(^3\)/s) | \( R_f \) (%) | 1 – \( R_f \) (%) |
|-------------|---------------------|--------------|------------------|
|             | Measured            | Calculated   | Difference       | Measured   | Calculated   | Difference   |
| May 13th    | 15,290              | 12.36        | 12.52            | −0.16      | 87.64        | 87.48        | 0.16           |
| June 22th   | 46,100              | 18.54        | 18.24            | 0.30       | 81.46        | 81.16        | −0.30          |
| Sept. 27th  | 27,310              | 13.58        | 13.47            | 0.11       | 86.42        | 86.53        | −0.11          |

The river-bed resistance (\( n \)), represented by Manning’s roughness, is a parameter dependent on factors such as bed form, flow patterns including water depth, etc. Based on the field investigations, the \( n \) range corresponds to 0.025–0.30 for the left branch and 0.020–0.025 for the right one. For a given position, linear interpolation is made in light of water depth. Table 2 summarizes, in the model setup, other parameters, that is, \( \omega_s \), \( \tau_n \), \( \tau_e \), \( M \) and \( \gamma_0 \).

To achieve numerical stability, the time step chosen is \( \Delta t = 0.1 \) s. In a coupled process, the flow, sediment and morphology are updated from one time step to another. The simulation terminates when the solution becomes independent of iterations. For each steady-state case, the wall-clock time is \( \sim 12 \) hrs.

#### 2.2.4 Comparisons with measurements

To assess the model accuracy, Table 3 compares the calculated values of \( R_f \) with the field data. The analysis shows, for the three cases, that the relative differences are all below \( \pm 1\% \). In addition, \( V \) at FV2, FV3, FV5 and FV7 at \( Q = 15,290 \) m\(^3\)/s and \( S \) at SC2 and SC3 at \( Q = 27,310 \) m\(^3\)/s, are also checked. Figure 3 shows the comparisons of their cross-channel \( V \) and \( S \) profiles. The results indicate good model performance for both flow and sediment calculations.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Flow and sediment features

The TGP impoundment starting from year 2003 modifies the discharge pattern and sediment delivery to the downstream inclusive of the study area. To analyze the variations, annual historical data between 1998–2015 at the Datong station are used. Figure 4a exemplifies the flow-sediment relationship before and after the impoundment, where \( Q_n \) (m\(^3\)/s) and \( W \) (t) denote annual flow discharge and sediment flux. The dam effectively smoothes out the flood discharge peaks and modifies the inflow downstream. The changes in \( Q_n \) are not significant, but the decrease in \( W \) is drastic. This indicates that sediment bypassing the dam exhibits a declining trend, leading to release of relatively clear water and augment in erosion potential downstream.

Based on the 2011 field measurements, Table 4 summarizes cross-sectionally averaged flow and sediment parameters at FV1, FV2 and FV5. The following features are observed:

#### Table 3

| Date        | \( Q \) (m\(^3\)/s) | \( R_f \) (%) | 1 – \( R_f \) (%) |
|-------------|---------------------|--------------|------------------|
|             | Measured            | Calculated   | Difference       | Measured   | Calculated   | Difference   |
| May 13th    | 15,290              | 12.36        | 12.52            | −0.16      | 87.64        | 87.48        | 0.16           |
| June 22th   | 46,100              | 18.54        | 18.24            | 0.30       | 81.46        | 81.16        | −0.30          |
| Sept. 27th  | 27,310              | 13.58        | 13.47            | 0.11       | 86.42        | 86.53        | −0.11          |
1. With the right branch as the main watercourse, the left branch passes between 12.36 and 13.58% of the total flow rate and 14.96% of the sediment flux. It implies that diffuence almost always attain a highly asymmetrical partition of flow and sediment, and their partitionings are the similar. The finding is consistent with that of Kleinhans, Jagers, Mosselman, and Sloff (2008).

**FIGURE 3** V comparison with measurements at 15,290 m³/s: (a) FV2; (b) FV3; (c) FV5; (d) FV7. S comparison with measurements at 27,310 m³/s: (e) SC2; (f) SC3 [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 4** Historical data (a) Qa–M relationship before and after the TGP impoundment in 2003 and (b) historical Rf changes with water levels [Colour figure can be viewed at wileyonlinelibrary.com]
2. At $Q = 15,290$ m$^3$/s, corresponding to the dry season of the year, $R_f = 12.36\%$, which is critical for both navigation and water intake in the left branch. The low partitioned portion is an issue of concern.

3. For both dates of measurement, $Z$ at FV2 is lower than that at FV5, which is related to the local flow velocity and acceleration. The flow accelerates into the right branch and decelerates into the left one.

4. For a given discharge, $V$ at FV2 is almost twice as high as that at FV5.

Previous studies show that the split of flow and sediment between the two branches is mainly controlled by the cross-stream water-surface slope (Szupiany et al., 2012), bed slope (Hardy et al., 2011) and geometrical aspects (Marra, Parsons, Kleinhans, Keevil, & Thomas, 2014). To further illustrate the sensitivity of flow partitioning to discharge, Figure 4b shows the 60-year historical data of $R_f$, grouped in the light of $Z \geq 4.00$ m and $Z < 4.00$ m. The $R_f$ values for $Z < 4.00$ m are smaller than those for $Z \geq 4.00$ m. It indicates an obvious declining trend. The descending in water level (flow discharge) leads to unfavourable hydraulic conditions for the left branch and potential sediment deposition. In recent years, it passes only 12–15% of the total flow rate, significantly less than 18–26% in the 1950’s. The riverine economic development requires that the discharge should be maintained or increased. In case of low flow discharge, it is essential that the flow impacts be well understood and proper countermeasures be taken.

Based on the field measurements, the reach comprises mainly suspended load; the bed material consists predominantly of fine to medium sand, a common feature of many fluvial rivers. Figure 5a,b shows their particle size distributions and median grain size ($D_{50}$) at SC1 and BM1. The results indicate that the suspended load falls in the range 0.001–0.10 mm in diameter, with $D_{50} = 0.007$ mm. For the bed material, its range is 0.10–1.00 mm, with $D_{50} = 0.20$ mm. These data form the basis for the numerical modelling.

Let $S_i$ (kg/m$^3$) denote point sediment concentration at $h_i$. To display its feature along the vertical lines of measurement, Figure 5c,d presents, at SC2 and SC3, the $S_i$ distributions as function of $h_i/H_0$. The lines are numbered from the left to right bank. The results show that, from water surface to bed, $S_i$ exhibits an increasing trend. For a given line, the $S_i$ value at $h_i = 0.6H_0$ is near to the line-averaged value. At each cross-section, the $S_i$ values along lines 2 and 3 are larger.

### TABLE 4  Measured flow and sediment parameters, 2011

| Date    | Location | $Z$ (m) | $V$ (m/s) | $Q$ (m$^3$/s) | $R_f$ (%) | $S$ (kg/m$^3$) | $q$ (kg/s) | $R_s$ (%) |
|---------|----------|---------|-----------|---------------|-----------|---------------|------------|-----------|
| May 13  | FV1      | 1.78    | 0.58      | 15,290        | —         | —             | —          | —         |
|         | FV2      | 1.72    | 0.60      | 13,400        | 87.64     | —             | —          | —         |
|         | FV5      | 1.76    | 0.30      | 1890          | 12.36     | —             | —          | —         |
| Sept. 27| FV1(SC1) | 3.81    | 0.91      | 27,310        | —         | 0.189         | 5,173      | —         |
|         | FV2(SC2) | 3.71    | 0.93      | 23,600        | 86.42     | 0.186         | 4,399      | 85.04     |
|         | FV5(SC3) | 3.78    | 0.47      | 3,710         | 13.58     | 0.209         | 774        | 14.96     |

**FIGURE 5** Sediment features: (a) Suspended load size distributions at SC1; (b) bed material size distributions at BM1; Suspended load distributions along each line at (c) SC2 and (d) SC3 [Colour figure can be viewed at wileyonlinelibrary.com]
implying that the cross-channel distribution is not uniform, and the main stream carries more sediment. Despite the significant difference in $Q$ between the two branches, $S_i$ exhibits a comparable magnitude.

### 3.2 Planform of flow patterns

Shown in Figure 6a,b, the depth-averaged velocity field is used to illustrate the planform of flow patterns, corresponding to Cases 2 and 3. The velocity field is visualized by contours of velocity magnitude. The flow features are similar although the magnitudes differ significantly.

Upstream of the diffluence, $V$ amounts to 0.70–1.00 m/s in Case 2 and 0.60–0.90 m/s in Case 3. Higher velocity occurs at its upper part where the water passage area is smaller. In the left branch, $V$ amounts to 0.30–0.50 m/s in Case 2 and 0.25–0.40 m/s in Case 3. For the right branch, the corresponding values are 0.75–1.00 m/s and 0.50–0.85 m/s. Obviously, the left branch exhibits much lower flow velocity, approximately 50% of the right one. From the diffluence, the flow decelerates into the left branch and accelerates into the right. At the confluence, the left branch flow is not sufficiently strong to press the right one. As a result, the main stream is close to the left bank downstream of the merging location. These results are consistent with the measured ones.

To further examine the flow patterns in the unit, Figure 6c,d showcases the enlarged flow fields for Case 1. It is noticed that the other cases have similar qualitative features. There is a large zone of flow circulations, in counter-clockwise direction, in the beginning of the left branch, which is mainly due to the bank curvature changes on its left side (Figure 6c). A smaller vortex also exists in the right branch. In the confluence, there exists a vortex zone around its upstream corner (Figure 6d). The difference in cross-sectional area between the branches is large. Another factor is that the merging angle of the flows is $\sim 80^\circ$. As a result, the left branch flow is not strong enough to suppress the right one and the main stream is close to the left bank. Downstream of the wake of the island, a shear layer appears between the two flows, caused by their velocity gradients. To conserve the flowrate, the fast stream decelerates and expands laterally, thus suppressing the slow one that gradually accelerates. Thus, the demarcation line migrates in cross-section towards the left bank. The streamwise development ceases until both the currents reach equal speed. Measured from the wake of the island, the shear layer extends $\sim 2,100$ m downstream.

**FIGURE 6** 2D planform of flow structures: (a) 46,100 m$^3$/s; (b) 27,310 m$^3$/s; local enlargements of (c) diffluence and (d) confluence at 15,290 m$^3$/s [Colour figure can be viewed at wileyonlinelibrary.com]
3.3 | 3D diffluence flow structures

To elaborate diffluence flow features in 3D, six cross-sections, D1–D6, are defined (Figure 2a). D1 and D2 reside upstream of the diffluence, D3 and D4 along the left branch and D5 and D6 along the right one. Their velocity profiles are plotted in Figure 7. The horizontal distance is counted from the left river bank. Upstream of the diffluence, a distinctive feature is the non-uniform distribution of the cross-sectional velocities (Figure 7a). At D1, the core of high velocities is to the left of the channel centreline. Downstream of D2, it shifts to the right and follows the thalweg line. Typical of rivers with a large ratio of width to depth, this behaviour has an impact on the flow split (Federici & Paola, 2003; Pittaluga, Repetto, & Tubino, 2003). There is also a transverse gradient in the area and $R_f$ is somewhat affected.

At D3 and D4, an obvious flow deceleration is noticed (Figure 7b). The high velocity core follows the deep part of the channel, suggesting the centrifugal effects on the flow. This phenomenon is accentuated at high-flow stages (Szupiany et al., 2012), leading to appreciable morphological modifications. Secondary flows are also evidenced, circulating clockwise, which is mainly due to the thalweg curvature.

On the contrary to the left branch, the flow at either D5 or D6 exhibits acceleration behaviours (Figure 7c). Morell, Tassi, and Vionnet (2014) also confirm the presence of a central core of convectively accelerated flow bounded by curved streamlines in the diffluence. Secondary flows, though with low intensity, are also observed along the right bank. This is mainly attributable to the influence from the sharp topographic forcing (large thalweg curvature). It is also affected by the curvature of bifurcation and flow division (Miori, Hardy, & Lane, 2012). However, the former plays a dominant role. Parsons et al. (2007) investigates a diffluence in Paraná River, Argentina, and no evidence of channel-scale secondary flow is detected. In a wide and shallow river, it is regarded that other than the above factors, the secondary flow is also influenced by bedform roughness.

**FIGURE 7** Diffluence flow structures at 15290 m³/s: (a) D1 & D2; (b) D3 & D4 and (c) D5 & D6 [Colour figure can be viewed at wileyonlinelibrary.com]
3.4 | Construction of a training wall

Long-term field records show that the flow discharge in the left branch demonstrates a declining trend. This becomes a concern at medium and low discharges; engineering measures are necessary to counter this. To increase its flow ($R_f$), construction of a training wall in the diffuence is, as a concept, proposed. This is also a topic of discussions during the past years. The wall is erected with cylindrical piles, thus forming vertical sides and limiting the sideward intrusion in the flow. Principles for its layout are as follows. (a) It is oriented in such a way that its interference to the flow is minimized. (b) The resulting increment in local water level is acceptable. (c) The erosion risk at its upstream end is controlled. (d) The extent of resulting flow circulations is limited in the right channel. (5) Its length is practically feasible.

Based on preliminary simulations, the wall length is set at 550 m, its crest elevation being the same as the water level. With reference to the planform of the existing flow patterns, two layouts are proposed to assess their effects. The wall follows the waterline of the right channel's left bank. Let $\alpha$ denote the angle between the wall and the Y-axis. Layouts A and B refer to $\alpha = 45^\circ$ and $75^\circ$, respectively. In combination with tracer trajectories of the surface water motion, Figure 8a,b showcases the results of flow field for Case 1. In relation to the existing situation, Figure 8c plots, for the three cases, the values of $R_f$ of the two layouts.

The results show that $R_f$ ranges between 19.50 and 25.20% in layout A and between 16.13 and 21.15% for layout B, with an increase from the exiting level 12.40–19.27%. The improvement is considerable at low and medium discharges. The training wall diverts part of the inflow to the left branch; layout A is more effective than layout B. However, the former intrudes more in the flow and generates a large zone of flow circulations. Layout B gains by comparison, featuring preferable flow patterns with a smaller vortex zone. Previous studies show the left branch is sustainable as long as $R_f$ is not below 20% (Yan, Xu, & Hou, 2010). It is a trade-off to achieve an acceptable flow pattern in the diffuence and to increase the left branch flow. The wall layout should be optimized at a prescribed flow rate or water stage. If needed, a curved wall is an option.

3.5 | Confluence flow features

To examine 3D confluence flow features, six cross-sections, C1–C6, are chosen (Figure 2a), with C1 and C2 residing on the left branch, C3 and C4 on the right branch and C5 and C6 downstream of the confluence. The velocity profiles are plotted in Figure 9, in which the horizontal distance is, at each cross-section, measured from the left river bank.

The cross-sectional velocity shows a pattern of flow convergence within the confluence. The transverse flow runs towards the right bank.
at C1 and C2 (Figure 9a) and towards the left bank at C3 and C4 (Figure 9b). The merging of the two transverse flows opposite in direction is abrupt, giving rise to large velocity gradients and strong mixing with an obvious shear interface. The pattern implies that the two cells of transverse flow with opposite motions develop a confluence convergence. There is significant asymmetry in the flow field at the junction corner. The right main branch has a larger velocity core than that of the left one. The largest core with streamwise velocity >1 m/s, though with an uneven distribution in the vertical direction, occupies almost the right half of the main channel. As seen in Figure 9c, there exists, at C5, a classical two-cell flow structure. The cells are indicated by the high-velocity cores in both the right and left sides. The interface between two flows is close to the left, an indication of the flow dominance of the right branch. In the confluent area, secondary flow structures are also observed, with cells in clockwise rotation. Downstream of the confluence, the flow convergence pattern diminishes as the transverse velocity on the left side decreases, indicating that the flow becomes aligned with each other. Further downstream, with the dynamical adjustment of the two flows, secondary flows disappear and a cross-sectional equilibrium is achieved.

3.6 Morphology characteristics

A diffluence-confluence unit is usually characterized by distinct thalweg behaviours and reciprocal adjustment between the flow and
bathymetry. Upstream of the diffluence (Figure 10a), the thalweg is close to the left side and a considerable thalweg curvature is evidenced. An increase in bed elevation is observed along the thalweg as it approaches the diffluence. Once the flow is divided, the channel depth increases downstream, especially in the main river course. Zolezzi, Bertoldi, and Turbino (2006) arrived at similar findings. Figure 10b presents, along two cross-sections of the diffluence, the cross-channel profiles of bed elevation. The diffluence is obviously characterized by a larger transverse bed slope than the longitudinal one.

Downstream of the diffluence, the so-called “inlet step” is observed in each branch, referring to the significant difference in thalweg water depth in the flow direction. A similar situation is shown by Zolezzi et al. (2006). A larger inlet step features the right branch. Field data indicate that the measured thalweg depths correspond to \( \sim 10 \) and \( \sim 25 \) m in the left and right branches, respectively. Besides other topographic forcing effects (Pittaluga et al., 2003; Thomas et al., 2011), this inlet step contributes to the flow partitioning.

In the confluence, the classical bed discordance is observed. As shown in Figure 10c, the cross-channel difference in river-bed elevation is pronounced. Immediately upstream of the confluent area, the lowest river-bed elevation is \( -5 \) and \( -15 \) m a.s.l. in the left and right branches. The confluence morphology is characterized by a prominent scour hole, a typical bathymetric feature found in high-angle asymmetrical confluences (Best, 1988; Ginsberg, Aliotta, & Lizasoain, 2009; Parsons et al., 2007). Towards the scour hole, the along-channel slopes of the two branches differ substantially, however at a much larger gradient in the left branch. The hole formation is attributable to

![FIGURE 10](figure.png)

**FIGURE 10**  (a) Bathymetry of diffluence; (b) cross-sectional bed elevation at the diffluence; (c) bathymetry of confluence; the erosion and deposition patterns at (d) 27,310 m\(^3\)/s; (e) 46,100 m\(^3\)/s; (f) 15,290 m\(^3\)/s [Colour figure can be viewed at wileyonlinelibrary.com]
in Figure 10e,f. Similar patterns of erosion and deposition are found: the ranges of bed-level changes differ however in magnitude.

4 CONCLUSIONS

A diffuence followed by a confluence forms a basic unit in many fluvial rivers, imposing an impact on the routing of both flow and sediment and eventually on the river bedform changes. Through field surveys and numerical modelling, the study addresses the flow, sediment and morphological features of such a unit on the Lower Yangtze River. There is obviously reciprocity between the unit and the increasing riverain activities. A matter of especial importance is the descending trend of flow discharge in the left branch, which has practical implications for economic development. The main conclusions are summarized as follows.

In the diffuence, the flow partition is affected by variations in the incoming flows. At medium and low flowsrates, the flow in the left branch accounts for approximately 12% of the total discharge and exhibits a decline in magnitude. The decrease in discharge leads to unfavourable flow conditions and reduction in sediment transport capacity. To counterbalance this, a training wall is devised, as a concept, to modify the flow intake to the left branch.

In connection with the Three Gorge Dam impoundment, the sediment amount in the reach exhibits an obvious declination. Field surveys show that the overwhelming part is suspended load; the bedload is limited in amount and consists mainly of fine to medium sand. The sediment transport is influenced by the diffuence geometry and channel curvature. Despite the large difference in flow rate, the two branches exhibit comparable suspended load concentrations.

The flow patterns are similar at three examined flows rates. Changes in the riverbank geometry give rise to the vortex zones in both the diffuence and confluence. For the latter, a shear layer is also observed, generated by velocity gradients of the two waters. Secondary flow structures are also evident, with major influence from the channel thalweg curvature. With dynamical adjustments of the two flows, the classical two-cell flow structure coexists in the confluence and disappears further downstream.

In the diffuence, there is a reciprocal adjustment between the flow and bathymetry. The difference in the two inlet steps contributes to the unequal flow division. The classical bed discordance features the confluence, with significant flow asymmetry at the junction corner. A scour hole exists in the confluent area, with a max. Depth of 28 m below the main river bed level. With the typical flow and sediment features, the right branch is subjected to slight erosion, while the left branch is encountered with gradual siltation.

ACKNOWLEDGEMENTS

The authors are members of a 111 Project entitled Discipline Innovation & Research Base on River Network Hydrodynamics System and Safety (Grant No. B17015), from Ministry of Education and State Administration of Foreign Experts Affairs, China, with Hohai University as executive organization. The field data is based on the measurements by Hydrology and Water Resources Survey Bureau of the Lower Yangtze River. James Yang acknowledges the assistance with diverse issues from Ander Ansell of KTH Concrete Structures.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Xie QC, Yang J, Lundström TS. Flow and sediment behaviours and morpho-dynamics of a diffuence–Confluence unit. *River Res Applic*. 2020;36:1515–1528. https://doi.org/10.1002/rra.3697