Field investigation of flow and bed erosion/deposition at the confluence of the Yellow River and Fen River

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Abstract: In order to study the characteristics of flow structure and bed erosion/deposition at the confluence of the Yellow River and the Fen River, the three-dimensional velocity components, water depth, water level, and suspended sediment particle sizes of the typical sections were measured in field to analyze the bed morphology, the flow field structure, suspended sediment distribution, and the variation of the bed erosion or deposition. The results showed that the pattern of the flow field at the confluence essentially conforms to the conceptual model, but represented a relatively complex structure, owing to the dual influence of the convergent flows and the tanglesome bed topography. The spatial distribution of suspended sediment was affected by the flow velocity and eddy turbulence. The particle size of suspended sediment was approximately normal distribution. The median particle size range from 17.19μm to 140μm. The suspended sediment at the confluence center was mainly composed of upstream transfer sediment and resuspended local sediment near the bed surface. The riverbed morphology was highly complex with frequent changes in erosion and deposition. And there was a strip-shaped sand ridges at the center of the channel and a long-narrow scouring belt near the tributary side. In addition, the bed configuration was similar in the dry and normal season. Due to the sediment deposition, the bed elevation was higher in dry season than that in normal season. During the flood season, the washed bed was stated in a dynamic flattening period, as well as the sand ridge disappeared and the scour belt became shallow.

1. Introduction

The river confluences are ubiquitous geomorphic units in the natural riverine system, representing a region where converging tributary flows determine changes in hydrodynamics, geochemistry, channel geometry, and bed morphology. Presently, the studies on confluence mainly focus on the hydrodynamic zone or the area near the confluence. A large number of experimental and simulation studies have investigated the hydrodynamics and morphological dynamics at the confluence with simple geometric configurations, such as asymmetric confluence with sharp connection angle[1]. Best[2] established the conceptual model of hydrodynamics zone at the confluence with this geometric plane, including the regions as follows: i) a zone of flow stagnation near upstream junction corner; ii) an area of flow deflection as tributary flows enter confluence; iii) a shear layer and/or a mixing interface
between the two converging flows; iv) a possible zone of separated flow about the downstream junction corner(s); v) flow acceleration within the downstream channel; vi) flow recovery at the downstream end of the Confluence Hydrodynamic Zone as illustrated in Figure 1.

Figure 1. Conceptual model of river confluence

In recent years, numerous scholars have conducted extensive studies on the influences of intersection conditions (connection angle, discharge ratio, width-depth ratio, and bed elevation concordance etc.) on hydrodynamic characteristics and bed morphology at the confluence, including hydrodynamic zone, water surface morphology, turbulence intensity and shear stress. Zeyu Mao et al. [3] conducted theoretical analysis and experimental study on the shape and size of flow separation zone at the confluence of equal-width open channel, and proposed the calculation formula of contraction and energy loss coefficient of separation zone. Through a series of flume experiments, Xiekang Wang et al. [4] studied the effects of flow discharge and sediment concentration inherited from tributaries on the sediment transport characteristics at main channel when the connection angle was 30°, obtaining the evolution process of sediment transport rate and cumulative sediment transport amount of the main river with and without inflow and sediment in different discharge ratios over time. Tonghuan Liu et al. [5] measured the variation of water surface slope and distribution characteristics of time-mean velocity at a 90° connection angle confluence with Acoustic Doppler Velocimetry (ADV). The study showed that the water surface slope and the depth-time average velocity were significantly affected by the flow patterns and the discharge ratio of two confluent flows. Additionally, there were distinct high and low velocity zones and separation zones within the immediately downstream cross-section of the confluence. Yang Xiao [6] revealed the influence of flow structure at a 90° confluence on phosphorus distribution in bed sediment. Abolfazl et al. [7] investigated the effect of the Froude number, connection angle, discharge ratio, width-depth ratio, and bed material properties on sediment transport at the confluence through multi-group flume experiments, laying a foundation for confluence research on bed morphology and sediment transport mechanism. Saiyu Yuan et al. [8] examined the distribution of flow velocity, turbulence intensity and shear stress at the 90° confluence with ADV. The result showed that a helical motion formed at the center of confluence and extended to the downstream for a long distance, when the velocity of tributary was higher than that of mainstream. With studies of the hydraulic characteristics and sediment distribution at the confluence of curved rivers, Roberts [9] exposed that the flow structure and sediment distribution characteristics at the curving river confluence were quite different from those in the straight open channel. Riley et al. [10] surveyed the water depth and three-dimensional velocity at the confluence of Little Wabash River and Big Muddy Creek with acoustic Doppler current profiler (ADCP). And drawing a conclusion as the flow pattern and channel morphology were completely different from the typical model in most curved rivers, but consistent with the curved-confluence conceptual model obtained from previous laboratory experiments and numerical simulations.
The Yellow River has the representativeness and particularity of typical northern China rivers with high sediments content. Yuanfeng Zhang et al. [11] discussed the bed evolution of the confluence of asymmetric high-sediment tributaries and the Yellow River through prototype scaling experiment, and found that there was a linear relationship between sediment deposition and sediment transport volume in the stagnation zone, and the sediment thickness was approximately normal distribution. Wang ping et al. [12] studied the influence of connection angle on siltation scale of sand dam at the confluence of Kongdui and Yellow River, and the results showed that connection angle has great influence on separation zone, backwater zone, water depth and siltation of main channel, concluding that 30° is helpful to reduce siltation at the confluence from the analysis of siltation scale and riverbank stability. Xinjuan He [13] calculated the amount of erosion or deposition at the main channel and the confluence of the Yellow River and tributaries in Ningxia China, and analyzed the change in bed morphology at the confluence during 1993 and 2015, as well as the influence of the different flow discharge and sediment concentration combinations on the erosion or deposition at the confluence. The results showed that the larger the annual inflow sediment coefficient of the Yellow River was, the more serious the sediment deposition was at the main channel, and the increase in sediment concentration of tributaries had little effect on the erosion and deposition of the main channel bed; There was no significant correlation between the annual average volume of erosion and deposition at the confluence and the annual average sediment transport coefficient of the main channel; The larger the annual average sediment transport coefficient was, the more serious the erosion was at the confluence.

There is no unified and scientific understanding of the flow structure and bed morphology at the confluence of the sandy Yellow River, needing the further field investigation. Such as the statistical analysis on the multi-year historical data is not the same as the laboratory test results, the flow discharge and sediment transport of the tributaries is different within a year, the natural boundary conditions are complicated and changeable. Therefore, this study selects the confluence of the hyperconcentrated Yellow River and its clear tributary, Fen River, obtains the three-dimensional flow velocity, water depth, water level, and suspended sediment particle size of the nine monitoring cross-section with acoustic Doppler current profiler (ADCP), and investigates the vertical average flow velocity, flow field distribution, distribution characteristics of suspended sediment particle size and bed erosion and deposition. The research results can provide important scientific basis for the study on the flow and sediment movement, flood control, and silt reduction and sad-dam control projects at the confluence of high-sediment rivers in the north China.

2 Study site
The reach of the Yellow River from Longmen to Tongguan hydrological station is a typical wandering river, which has characteristics of wide and shallow water surface, frequent oscillation planform, easy erosion/deposition channel, developable sandbank, and extremely unbalanced water and sand [14]. The average annual runoff and sediment transport volume is 33.55 billion m³ and as high as 978 million tons respectively, that ranks first among the world's most sandy rivers. Fen river is the second largest tributary of the Yellow River, with much smaller runoff than the Yellow River. The average annual flow discharge is only 990.7 million m³, and the annual sediment transport volume is only 20.2 million tons. The Fen River joins the Yellow River from its left bank in Wanrong county, Shanxi Province, China, and the drainage map of the confluence is shown in Figure 2. In the past decades, there have been some problems at the confluence, such as the main flow of the Yellow River in the junction area was uncertain, and usually flowed backward to the east, seriously beheading the Fen River and resulting in the reduction of the Fen River flood carrying capacity. Meanwhile, the flow of the Fen
River significantly silts up, forming a large area of beach and stagnating the pollutants and sediment in the water. The study site is a typical confluence of the low sediment concentration rivers and the wandering hyperconcentrated rivers of northern in China.

3 Measuring instruments and monitoring cross-sections

In this study, three field measurements on November 27, 2016, August 5, 2017 and March 31, 2018, which corresponded to the flat water period, the wet season and the dry season respectively, were conducted at the confluence. Due to the article length limitations, except for the riverbed elevation comparison, the rest of the research content is based on the November 27, 2016, flat water period measurement results. The monitoring cross-sections were all set essentially perpendicular to the direction of the water flow. Two monitoring cross-sections, namely the F1-F2 section, were arranged longitudinally along the channel in the Fen River reach of the confluence. In the Yellow River reach, there were 7 sections of H1-H7 along the longitudinal direction of the flow. A total of 9 typical monitoring sections were set up, as shown in Figure 3. Before the field measurement, the high-precision real-time kinematics (RTK, Chinese South S86T, horizontal accuracy ±1 cm+1 ppm, vertical accuracy ±2 cm+1 ppm) was used to measure the section shore coordinates and set the station number for subsequent field measurement. During the measurement process, the water level of the section was monitored by the RTK, and the water depth, three-dimensional velocity components of each cross-section were collected with the ADCP (SonTek, ADP-1500Hz, ±1% accuracy). The water and sediment samples were collected by a deep-water sampler near the left bank, right bank, and center at cross-sections H1 to H7 of the Yellow River. During the measurement, the organic matter was first removed from the sediment samples, dispersant was added next, and the particle size was analyzed by the laser particle size analyzer (Coulter, ls-100q) after an ultrasonic shock treatment.

The data of the elevation of water surface, maximum water-depth, channel width, and mean velocity on the left and right bank of 9 monitoring sections on November 27, 2016 are showed as Table 1. It can be seen from Table 1 and Figure 3 that the study area is mainly of a wide and shallow channel. The cross-section F1 immediately upstream of the confluence has a shallow water depth, the maximum water-depth is only 1.87m, the channel width is 148.784m, the water flow is slow, and the average velocity of flow is 0.232 m·s⁻¹. The water depths of the cross-section H1-H2 are larger than those of the Fen River. The maximum water depth is about 2.5m, the channel width is 240-283m, and the water flow velocity is uniform, about 0.9 m·s⁻¹. Entering the junction corner, a deep thalweg has formed by the turbulence of flow, the kinetic energy consumes severely, the flow velocity is reduced,
and the river width is gradually increased, due to the convergence of the two flows. The mainstream is close to the left bank of the confluence, forming a long and narrow scouring zone between the H3-H6 sections. The maximum depth of the scouring zone is 6.16m and the flow velocity is about 0.5-0.9 m·s⁻¹. The flow develops downstream and gradually recovers to stability, the river channel widens, and the water depth decreases. The maximum water depth of the H6-H7 section is about 2.09m to 2.90m respectively.

Figure 3. Measurement cross-sections and subaqueous terrain map

Table 1. Field experimental data of the 9 cross-sections

| Section | Elevation of surface(L)/m | Elevation of surface(R)/m | Maximum depth of the water/m | Water surface width/m | Average flow velocity/(m·s⁻¹) |
|---------|---------------------------|---------------------------|-----------------------------|-----------------------|-------------------------------|
| F1      | 356.11                    | 356.11                    | 1.87                        | 148.78                | 0.23                          |
| F2      | 355.81                    | 356.13                    | 3.98                        | 96.61                 | 0.17                          |
| H1      | 356.12                    | 356.12                    | 2.49                        | 241.10                | 0.86                          |
| H2      | 356.17                    | 356.01                    | 2.57                        | 283.02                | 0.99                          |
| H3      | 355.96                    | 355.91                    | 4.68                        | 244.52                | 0.69                          |
| H4      | 355.83                    | 355.84                    | 6.16                        | 306.42                | 0.52                          |
| H5      | 355.82                    | 355.83                    | 4.64                        | 134.78                | 0.86                          |
| H6      | 355.66                    | 355.66                    | 2.90                        | 269.97                | 1.19                          |
| H7      | 355.51                    | 355.51                    | 2.09                        | 767.75                | 0.75                          |

4. Results and discussions
4.1 Bed topography, flow pattern and depth-average velocity

Figure 4 shows the bed elevation and the depth-average velocity of each cross-section. The solid line in the figure indicates the bed elevation, the pentacle represents the depth-average velocity, and the dotted line indicates the water surface. It can be seen from the figure that, the maximum depth-average velocity of cross-section F1 at Fen River reach is 0.7 m·s⁻¹. Compared with the cross-section F1, the velocity of the section F2 is reduced to 0.28 m·s⁻¹. The reason is that the strong turbulent shear and the mixed layer of the two streams from the Fen River and the Yellow River have contributed to the riverbed erosion near the location 18m from the left bank, resulting the bed elevation reduction and the flow energy consumption.

For the Yellow River reach of the upstream junction corner, the depth-average velocity distributions of the cross-sections H1 and H2 are that the flow velocity near the mainstream zone is large, but the flow velocity away from the mainstream zone is small. As the flow of Fen River joins the Yellow River, it exerts a jacking effect on the flow of Yellow River, producing a flow stagnation zone at the channel of Yellow River near the tributary. The flow in the stagnation zone squeezes the
main flow of the Yellow River, deflecting the flow towards the right bank (cross-section H2). And the mainstream gradually shifts to the right bank, forming a flow deflection zone; The low flow velocity in the stagnation zone reduces the sediment carrying capacity of the flow, resulting in the deposition of coarse particle sediment and the rise of bed elevation. The range 0-50m from the left bank of cross-section H3 is the mixing zone of the confluence, with a low flow velocity of about 0.4 m·s⁻¹ and poor flood discharge capacity, where flow turbulence shear is relatively strong and scours the bed surface seriously, forming a deep scour hole. At a distance of 100m from the left bank of cross-section H3, the flow velocity decreases and the bed elevation increases, forming a sand bar. The bar divides the mainstream of the Yellow River into left and right flanks, and the flow velocity near the right bank is about 1.5 m·s⁻¹. A region 0-50m from the left bank of cross-sections H4 and H5 is located in the flow separation zone, where the flow velocity is relatively low, about 0.65 m·s⁻¹. The flow pattern within the region represents a large vortex, and the bed topography shows a strip-shaped scour belt. The measured results show that the maximum velocity zone at the confluence is formed within the region of that 125-225 m from the left bank of cross-section H3, 110-200m from the left bank of cross-section H4, and 80-130m from the left bank of cross-section H5. And the depth-average velocity in the zone is between 1.0m and 2.0 m·s⁻¹. Far away from the junction corner, a flow recovery zone locates between the cross-section H6 and H7, where the mixing and jacking effect has been basically eliminated, the flow has been fully developed, the mainstream has been recovered to the left bank, and the velocity distribution is within the range of 0.8-1.5 m·s⁻¹.

The change in bed elevation at the confluence of the Yellow River and Fen river is closely related to the flow pattern and the depth-average velocity. Within the stagnation zone, the low flow velocity causes the sediment deposition and the raise of the bed elevation. At the center of the junction corner, the flow turbulence is tempestuous, and the momentum of convergent flows is continuously exchanged and influenced each other, making a great bed scour belt. At the shear layer and the maximum velocity zone, the large water depth and depth-average velocity result the bed surface erosion and the elevation decline.
4.2 Velocity field

The contour map of flow velocity field of 9 typical cross-sections at the confluence shows as the Figure 5. In the figure, thick solid lines represent bed elevation boundary, thin solid lines indicate velocity contour lines, and dashed lines represent water surface. The Figure 5 shows that the flow velocity field distribution of the cross-section is affected by the bed boundary. The flow velocity near the boundary of bed is small, and the flow velocity increases gradually along the vertical upward.

The flow of the cross-section F1 upstream of the confluence is mainly distributed on the left and right flanks, the velocity near the right bank is larger. Affected by the flow of the Yellow River, the mainstream of the cross-section F2 is close to the left bank, and the right bank represents a stagnation zone, where the flow velocity is reduced. The flow in cross-section H1 of the Yellow River is relatively stable, and the high-velocity flow is located on the position between the left bank and the center of the channel, with a higher velocity than that of the Fen river. At the left side of the cross-section H2 within the stagnation zone, the flow velocity near the water surface is reduced, and the high-velocity flow shifts toward the right bank, forming a deflection zone. And there are two distinct helical motions with different sizes. The flow near left bank of cross-section H3 is mainly dominated by eddy current, while the right bank forms the maximum velocity zone. The flow pattern
of cross-section H4 has the characteristics of that the vertical gradient of the velocity is small, the lateral velocity distribution is uneven, and the velocity near the left bank is higher than that near the left bank of cross-section H3. The flow of cross-section H5 is still affected by the convergence of two tributaries, the transverse distribution of flow velocity is low near the left bank but high near the right bank, and the maximum flow velocity is within the region of 65-140 m from the left bank. To the downstream cross-section H6, the water flow develops over a longer distance, and the main stream recovers to the left bank of the channel, and the flow velocity distribution has gradually become uniform. Until the last section H7, the distribution of flow field is uniform and stable, and the influence of the convergent flows has essentially disappeared.
4.3 Particle size of suspended sediment

The measured values and variation laws of the median diameter of suspended sediment in each section at the confluence are shown in Figure 6. It can be seen from the figure that the median particle size of suspended sediment in each cross-section of the field measurement region varies in a large range. Along the direction of flow, the median particle size near the left bank and within the center of the channel presents a "large-small-large" change rule, while the value near the right bank of channel presents a "small-large-small" change rule. The particle size distribution of suspended sediment is closely related to the velocity distribution of the section. The median diameter of the suspended sediment is larger when the flow velocity is larger. Otherwise, the median diameter is smaller. For example, the position near the left bank of cross-section H2 and cross-section H4 is located in the stagnation zone and separation zone respectively, where the flow velocity is smaller than that at the center and near the right bank of the channel. Therefore, the proportion of coarse sediment carried in the flow and the median particle size of suspended sediment are small. The flow velocity near the left bank of cross-section H3, where is located in the mixing layer at the confluence, is small. The suspended sediment median particle size transported from the upstream cross-section H2 is only 17.19 μm. However, the value of the particle size within the mixing layer increases to 35.21 μm, this is attributed to that the turbulent flow pattern scours the bed severely, and the surface sediment re-suspend up. Near the right bank of the cross-sections H3, H4, and H5, and the left bank of the cross-section H6, where are positioned in the maximum velocity zone, the median particle size of sediment is much larger than the average level of all sections.

In order to further examine the law of sediment distribution at the confluence, the sediment
grading curves of the suspended sediment at the upstream cross-section H2 and the downstream cross-section H6 are shown in Figure 7. The sediment particle size distribution at each sampling point in the section is approximately normal. The distribution range of sediment particle size near the left bank of cross-section H2 is narrow, ranging between 0.345μm and 188.5μm, and d80≈44μm. However, the particle size range of suspended sediment at other sampling points was wide, ranging between 0.440μm and 240.0μm.

![Grading Curves of Suspended Sediment](image)

**Figure 6.** Median particle size of the suspended sediment in each section

![Cumulative Frequency](image)

**Figure 7.** Grade curve of suspended sediment at section

### 4.4 Bed erosion or deposition

The bed elevation measured in field on November 27, 2016, August 5, 2017, and March 31, 2018 are shown as Figure 8. The bed morphology of the cross-section F1 on the Fen River reach at the upstream confluence is relatively stable compared with that of the Yellow River, maintaining a relatively steady channel-bed shape for a long time, which is attributed to the low sediment content in the flow. However, under the influence of the convergent flows, cross-section F1 presents a gradual scouring trend. The results of three measurements show that the annual scour depth is about 1.5m. The position near the left bank of cross-section F2 is located at the center of the confluence, and there is a scour hole, which is 1.5-3m deeper than the bed elevation at cross-section H2 of the Yellow River. In
addition, on March 31, 2018, during the dry season of the Yellow River basin, the width of the scour hole increased, but the depth of that decreased, resulting in the deposition of bed. This is because that the discharge of flow in Fen River is too small in the dry season, the more strong dominant flow of the Yellow River pour backward into the Fen River, and a vortex formed in this region, resulting the widening of the scour hole.

The bed elevation is in a state of gradual siltation at the center of the confluence(cross-section H3), and the effective water conveyance section gradually shrinks. In the dry season of 2018, the channel of cross-section H3 silted seriously, with a channel width of only 45m, indicating from another perspective that the Yellow River flows backwards into the Fen river. During the flat and dry seasons, the morphology of the bed sections, within the range of 2–3 river channels widths adjacent to downstream of the junction corner, was essentially similar (such as cross-section H3–H6), but only the bed elevation changed, resembling a scaling pattern. Compared with the flat water period, the bed is in a silt state in the dry season. There is a narrow scour zone on the side of the channel near the tributaries, the length of which is about 2 channel width. During the wet season, the strip-shaped sand ridges at the channel center of the cross-section H3-H5 downstream of the confluence gradually disappeared due to washing effect of the shear layer, and the channel developed to the dynamic flattening period, and the channel shape gradually change to flat. In general, influenced by the convergence of two flows at the confluence of the hyperconcentrated Yellow River and the Fen River, the discordant distribution of velocity caused the uneven spatial distribution of suspended sediment transport capacity, which led to the highly complex bed morphology and the frequently evolution of erosion/deposition at the Confluence Hydrodynamic Zone.

Figure 8. Bed profile and elevation changes

5 Conclusion

In this paper, the bed elevation, water level, flow velocity and suspended sediment particle size at the
confluence of Yellow River and the Fen River were measured in field with the acoustic Doppler current profiler and high-precision real-time kinematics. The variations in bed morphology, flow structure, and suspended sediment particle size distribution at the confluence were studied in detail. The results are of great significance for further understanding hydrodynamics and morphodynamics at the confluence with complex confluent conditions. The following conclusions are obtained according to the field data:

(1) The hydrodynamic zone at the confluence of Yellow River and Fen river can be divided into stagnation, mixing, deflection, separation, maximum velocity, and flow recovery zones, which conformed to the previous study results. The formation of each hydrodynamic zone is mainly related to the flow pattern and bed morphology at the junction corner. Meanwhile, the flow structure of each zone affects the spatial distribution of bed morphology.

(2) The flow velocity distribution is relatively uniform at the upstream cross-section H1 and the downstream cross-section H7 of the confluence; The convergent flows produce the jacking effect at the center of the confluence, representing a complicated flow structure, which is affected by both the flow pattern and the riverbed morphology; It essentially conforms to the flow velocity characteristics in each hydrodynamic zone.

(3) The spatial distribution of suspended sediment is affected by the flow velocity and eddy turbulence. The particle size of suspended sediment is approximately normal distribution, and the median particle size ranges from 17.19μm to 140μm. The suspended sediment at the confluence center is mainly composed of upstream transfer sediment and resuspended local sediment near the bed surface.

(4) The bed configuration of tributary with extremely small sediment concentration is relatively stable, but exhibits a gradual scouring state. During the flat and dry seasons, at the 2-3 channel widths region immediately downstream of the confluence, a strip-shaped sand ridge locates at the center of the channel, while a long and narrow scour belt locates within an area close to the tributary, with a downstream distance of 2 channel widths. However, the bed is stated in the period of dynamic flattening during the wet season, and the sand ridge disappeared and the scouring belt became shallow.

Acknowledgements

The research presented in this paper was supported by the National Natural Science Foundation of China (Grant No. 51679191) and the Science and Technology Plan for Water Conservancy of Shaanxi Province (No. 2017 slkj-9). The authors are grateful to the Key Laboratory Research Project of the Education Department of Shaanxi Province (Project No. 17JS102).

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