Study on hydrodynamic and sediment transport characteristics considering implement of the Fuhe River Diversion Project in China

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Abstract. A movable-bed physical model is presented to investigate characteristics of hydrodynamic and sediment transport (ST) in a planned excavating channel downstream the Fuhe River (FHR) and the Qinglan Lake (QLL), Jiangxi Province, China. The model is validated by the observed water level and velocity data during the low water period in May 13 and high water period in June 21 2014, respectively, which shows well agreements between simulated and observed data. With repeating 6-years cycle of the runoff discharge and suspended sediment concentration condition from the Lijiadu hydrological station downstream the FHR during 2006 and 2008~2012, experiments are conducted to predict bed evolution process in the excavated channel and QLL after the implement. The hydrodynamic results indicate that the cross-section averaged velocity generally increases both in the QLL and upstream of the excavated channel during a 20-year return period flood. The ST results show that erosion develops mainly in the left side of the channel and deposition occurs slightly upstream of the QLL after 30 years. Some deposition becomes visible in the center of the QLL after 90 years, and a relatively stable balance between deposition and erosion is observed in the whole QLL after 150 years.

1. Introduction

The Fuhe River (FHR) is one of the five rivers emtting into the Poyang Lake (PYL) catchment and it is located in the southeast of the Jiangxi Province, China. It rises in the east of the Linghua Peak and junction of Guangchang, Shicheng and Ningdu counties, Jiangxi Province, and then finally flows into the PYL at Sanyang town. With a main channel length of 349 km and a drainage area of 15811 km² upstream of the Lijiadu hydrological station (LHS) downstream the FHR, the average annual runoff volume and sediment transport volume reach about 12.8 billion m³ and 13.7 million t, respectively. Moreover, the channel downstream the LHS is 71 km in length with an approximate 0.015 percent slope.

In this study, a river diversion project is planned to implement in the realm of the Tacheng village, Nanchang county and Jiaqiao town, Jinxian county, which is designed to block part of Tacheng reach, FHR and excavate an artificial channel between Qiuju, Jinxian county and Dengjia, Nanchang county.
In this case, the main stream of the FHR would empty into the PYL catchment through the Qinglan Lake (QLL) and be gentle in slope.

However, in essence, the project is an attempt to alter flow pattern downstream the FHR, which would have an inevitable influence on the relatively stable balance of hydrodynamic and sediment transport (ST) in both upstream the excavated channel and QLL. It is necessary to investigate the characteristics of hydrodynamic and ST and assess the influence. Thus, a movable-bed physical model is established in this study, with aim of clarifying bed evolution change between before and after the implement within both the new excavated channel and QLL.

2. Model design and validation

2.1 Similarity criteria and scales design

In order to meet the study requirement and limit of model size, a movable-bed physical model is designed with a plane scale 1:200 \( (a_p = 200) \), namely model size / prototype size, which is the same below), a vertical scale 1:80 \( (a_v = 200) \) and a model distortion ratio 2.5 \( (\eta = 2.5) \), namely plane scale / vertical scale). The other main scales are designed as following with the principles in [1, 2].

According to the Froude similarity criteria, the flow velocity scale \( a_v \) is set to be equal to the vertical scale \( a_h \) to the power of 0.5 as

\[
a_v = a_h \frac{1}{2} = 8.94 \tag{1}
\]

Under the law of flow continuity and resistance similarity criteria, the flow discharge scale \( a_Q \) and roughness scale \( a_n \) can be calculated by the expression respectively as

\[
a_Q = a_v a_n a_h = 143108 \tag{2}
\]

\[
a_n = a_h^{1/3} a_n^{1/2} \tag{3}
\]

Li [3] presented a unified formula for both convection-dominated transport and turbulent diffusion-dominated transport expressed as

\[
a_w = a_v (a_h a_n^{-1})^m \tag{4}
\]

where, \( m = 1 \) when convection transport dominated, as well as \( m = 0.5 \) when turbulent diffusion transport dominated. In this study, for prototype grain size of the suspended load (SL) in the FHR is relatively fine and bed material load in SL could be the major participant in bed evolution, convection transport can be assumed dominated and \( m = 1 \) is applied in equation (4). Thus, it can be calculated by the expression as \( a_w = a_v (a_h a_n^{-1}) = 3.58 \).

Furthermore, the grain size scale can be reverse derived from the Stokes settling velocity formula [4] for prototype grain size finer than 0.1 mm, while it can be also reverse derived from the settling velocity formula presented by Zhang [2] for prototype grain size coarser than 0.1 mm.

Under this similarity criteria, the incipient velocity scale \( a_w \) is set to equal to the flow velocity scale \( a_v \). It can be written in this equation as

\[
a_w = a_v = 8.94 \tag{5}
\]

With a bulk density \( \gamma_s = 1056 \text{ kg/m}^3 \), a type of light plastic material is introduced to manufacture model sand in this study. Under the condition that the SL similarity is satisfied, settling velocity of prototype sediment and model sand are calculated with formula presented by Zhang [2] and Chen [5], respectively. The obtained calculated incipient velocity scale is close to 8.94, which showing a fulfillment of the incipient motion similarity in this study.

According to the bulk density for prototype sediment (equal to 2650 kg/m\(^3\)) and model sand, the suspended sediment concentration (SSC) scale can be calculated theoretically as
With a dry bulk density for prototype sediment (equal to 1400 kg/m$^3$) and model sand (equal to 650 kg/m$^3$), the bed evolution time scale is calculated as

$$a_s = a_r (a_{r-1}^{-1})^{-1} = 0.085$$  \hspace{1cm} (6)

Besides, the ST volume scale can be estimated with the flow discharge scale $a_d$ as well as above validated SSC scale and bed evolution time scale in the following expression as

$$a_{w_s} = a_d a_s a_r = 6.86 \times 10^6$$  \hspace{1cm} (8)

In practice, the above estimated value of SSC scale, bed evolution time scale and ST volume scale could be for reference and mostly derived from validation.

2.2 Validation

Covered the area from 2 km upstream the excavated channel to 7 km downstream the QLL outlet, and the modeling channel reaches approximately 20 km. The bathymetry data measured from the reach downstream the FHR in May 2013 and DEM data from the QLL in 2011 are both applied to shape the bed in this model. Figure 1 shows the plane layout of the physical model and observation locations.

![Figure 1. Plane layout of the physical model and observation locations.](image)

In hydrodynamic validation, the water level and velocity are both validated against the observed data during the low water period in May 13 and high water period in June 21 2014, respectively. To obtain a better simulation accuracy, the surface is locally improved. Figure 2 shows a comparison of longitudinal water level profile between the simulated and observed data in May 13 2014 and a comparison of cross-section velocity distribution at DM5 in June 21 2014. It can be seen that simulated data agree well with the observed data.

According to the bed material gradation measured in both the reach upstream the excavated channel and reach downstream the QLL outlet, as well as the suspended sediment gradation obtained from the LHS, the model sand gradation can be determined. Though the ST validation can't be conducted for the lack of available bathymetry data in the excavated channel and QLL, with the fulfillment of all similarity criteria and a proper model sand gradation, this model can still provide a reliable ability to simulate the bed evolution process.
3. Model experiments

3.1 Experiment condition

As a 6-years cycle of consecutive condition, the observed runoff discharge and suspended sediment concentration data from the LHS during 2006 and 2008~2012 are applied repeatedly every 6 years to investigate the change of hydrodynamic characteristics between before and after the implement, as well as predict bed evolution process in both the excavated channel and QLL after the implement.

3.2 Results analysis

3.2.1 Hydrodynamic results

Figure 3 shows the hydrodynamic results on both longitudinal water level profile along the channel and a cross-section velocity distribution at CL6 in 20-year return period river-dominated flood. It can be seen in figure 3(a) that the water level decreases significantly in the reach upstream of the excavated channel after the implement and consequently velocity increases in the inlet reach of the channel (see CL6 in figure 3(b)). For the FHR emptying into the QLL, water level rises slightly after the implement.

Generally, the cross-section averaged velocity increases in the QLL and upstream of the excavated channel during both river-dominated flood and lake-dominated flood.

3.2.2 ST results

Figure 4 presents the ST results on bed evolution process in the reach downstream of excavated channel along with the QLL area after 30, 42, 48, 66, 90, 138 and 150 years of the implement, respectively. In this bathymetry map, white represents a relatively small deposition, red represents a massive deposition, while a 16 m contour line is also applied to indicate the development floodplain in the QLL.

At 30 years after the implement (T=30), a massive deposition in belt-shape would occur in the right of the excavated channel and hence the mainstream flow to the left of the channel. A deposition body
higher than 16 m with an approximate size 400m×300m could be seen in the intersection area of channel and QLL (area A). However, deposition is still relatively light in the reach upstream of the QLL.

At 66 years after the implement (T=66), the deposition body of the area A would develop to the left, while a deposition body in the middle and downstream of the QLL (area B) show a further development after connected with the left bank. The mainstream is baffled by another deposition body with a size 700m×300m in the middle of the QLL. Thus, the channel width in the reach upstream of the QLL is shrunk to only about 50 m.

At 90 years after the implement (T=90), a relatively large deposition body with a size of 2000m×500m develop to connect with area B. A new runway is shaped under the effects of erosion within the joint area between area B and left floodplain.

At 150 years after the implement (T=150), the mainstream retained within a narrower runway would cause more erosion breakpoint in the joint areas. However, the bed evolution could reach a relatively stable balance between deposition and erosion in the study domain.

Figure 4. Bed evolution in the reach downstream of excavated channel and the QLL area

Figure 5 shows evolution process of 15 m contour line in the excavated channel after 30, 42, 54, 114 and 150 years of the implement, respectively. A massive deposition body in the right would develop through the channel at 30 years after the implement, which further develop to the middle and even to the left at 150 years after the implement.
4. Conclusions

This study establishes a movable-bed physical model for investigation on characteristics of hydrodynamic and ST in a planned excavating channel downstream the FHR and QLL. The model is then validated by the observed water level and velocity data, which indicates that the model design, similarity scales and model sand can all satisfy the study requirement. The hydrodynamic experimental results show velocity increases in the QLL and upstream of the excavated channel during flood season. The ST experimental results show significant bed evolution process after the implement. Finally, the bed evolution would reach a relatively stable balance in the whole QLL after 150 years implement.

Acknowledgments

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References

[1] Xie J H 1990 River simulation (Beijing: Water Conservancy and Electric Power Press) (in Chinese)
[2] Zhang R J 1998 River sediment dynamics (Beijing: China Water Power Press) (in Chinese)
[3] Li B R 1991 Physical Model Design for River Sedimentation in China Journal of Hydrodynamics Ser. A 6 113-22. (in Chinese)
[4] Julien P Y 1995 Erosion and Sedimentation (New York: Cambridge University Press)
[5] Chen Z C, Wang G Q, Zhan X L 1996 Experimental study of settling velocity and incipient velocity of fine plastic particles Journal of Hydraulic Engineering 2 24-29. (in Chinese)