



Research on Water Scour Conditions of Wanjiazhai Reservoir, China

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Abstract. Flood control, power generation and agricultural irrigation are the primary functions of reservoirs. The main reason for the serious deposition in the Yellow River reservoir is the high concentration of sediment in the water flow. Due to the establishment of the Yellow River cascade reservoir and the joint scheduling among reservoirs, the flow rate of the downstream reservoir decreases in flood season, which reduces the hydrodynamic flushing efficiency in the reservoir area. Wanjiazhai Reservoir is selected as the research sample in the present study, which is a first-level cascade reservoir in the connecting area of the upper and middle reaches of the Yellow River. In this study, a numerical model was built to analyze factors that influenced the operation and flushing of the upstream reservoir. And a formula was recommended to apply to the Wanjiazhai Reservoir on the basis of the sediment deposition pattern discrimination formula. Besides, various flushing methods and methods reducing the sediment deposition were carried out and analyzed. Results indicated that when the inflow rate increased, the maximum particle diameter of the incipient sediment was larger. When the inflow rate reached 1200 m³/s, the diameter of the initial the incipient sediment varied from 0.015 mm to 0.094 mm. And the diameter range of the initial the incipient sediment was 0.014 mm–0.094 mm, when the inflow rate was 1800 m³/s. When the inflow rate reached 2500 m³/s, the diameter of the initial the incipient sediment varied from 0.010 mm to 0.094 mm. Notably, all sediment were discharged from the reservoir. Moreover, the sediment of the reservoir was flushed at a flow rate of 1200 m³/s–1800 m³/s under the premise of meeting the upstream water storage.

Keywords: Wanjiazhai Reservoir · Hydrodynamic simulation · Reservoir scour · Sediment starting size

1 Introduction

Wanjiazhai Reservoir is located in the canyon between the Tuoketuo section and the Longkou River section, which is lied in the upper section of the Yellow River main stream (Maria et al. 2015). The frequent torrential rain during summer and autumn, large flood peak flow, abundant sand source and high concentration of sediment in

water flow occurred in this area make it a typical sandy section (Medeiros et al. 2019). The Yellow River passes through the Inner Mongolia Plateau, where wind erosion and water erosion exist alternately and interact with each other (Lu and Siew 2006). With the improvement of the cascade reservoir system in the Yellow River mainstream, the annual average inflow rate of the Wanjiashai Reservoir reduced significantly compared with how it was before implementing the joint regulation schedule of water and sediment. From 1998 to 2004, the annual average inflow rate was 1,278,000 m³, which was far lower than the designed value. As a result, after the 13-years operation of the hydro-junction, the sediment deposition in reservoir area reached 4,278,000 m³, which reaches the 47.7% of the total reservoir capacity. The sediment affects the flood control, irrigation and navigation seriously (Fu 2016).

Massive studies have investigated how to adjust the water and sediment outflow process, to reduce the sediment deposition, increase the efficiency of sediment flushing and the storage capacity. For example, Zhang and Zhang (1982) put forward methods of calculating the sediment deposition volume, location of sediment deposition and the variation of the reservoir storage capacity with time by analyzing multiple operations of reservoirs in flood season. Similarly, Zhang et al. (2018) compared more than 100 floods with high concentration of sediment in the Sanmenxia reservoir from 1961 to 2013, and analyzed their characteristics. Results revealed how floods with high concentration of sediment affected the reservoir using different sediment discharge methods. Besides, a calculation formula of sediment discharge rate in floods with high concentration of sediment were discharged using backwater. And another calculation formula of outflow sediment transport rate under open sediment discharge were adopted. Wei et al. (2005) analyzed all the inflow water and sediment data of XLD reservoir from 1999 to 2002, and calculated the quasi-two-dimensional sediment mathematical model of the Yellow River. It turned out that the model was in good agreement with the measured data in real reservoir area, including the scouring and deposition process of the riverbed, alterations in the river morphology, flow patterns in flood season and the change of water level. Tu (1980) concluded the discharge calculation formula of sediment under the discharge method of density current by investigating connections among the sediment discharge of large domestic reservoirs. Moreover, in Zhang's study (2004), fuzzy-neural network was used to calculate the scouring of sediment deposition in flood season. However, the research focusing on alterations in the along flow pattern under different water inflow volume and the particle diameter range of the incipient sediment under the influence of flow patterns in the reservoir area were still rare (Fig. 1).

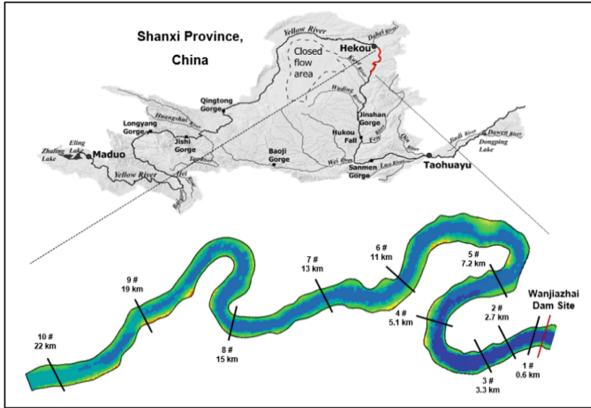


Fig. 1. Location of the Wanjiashai Reservoir in China

2 Hydraulic Numerical Model

2.1 Numerical Model

Basing the incompressible Reynolds equation, the two-dimensional unsteady flow model which describes the unsteady flow of the open canal was built.. The water head is given by the following equations:

$$h = \eta + d \tag{1}$$

$$\frac{\partial h}{\partial t} + \frac{\partial(h\bar{u})}{\partial x} + \frac{\partial(h\bar{v})}{\partial y} = hS \tag{2}$$

$$\begin{aligned} \frac{\partial(h\bar{v})}{\partial t} + \frac{\partial(h\bar{u}\bar{v})}{\partial x} + \frac{\partial(h\bar{v}^2)}{\partial y} = & f\bar{u}h - gh\frac{\partial\eta}{\partial y} - \frac{h}{\rho_0}\frac{\partial p_a}{\partial y} - \frac{gh^2}{2\rho_0}\frac{\partial\rho}{\partial y} + \frac{\tau_{sy}}{\rho_0} - \frac{\tau_{by}}{\rho_0} \\ & - \frac{1}{\rho_0}\left(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y}\right) + \frac{\partial}{\partial x}(hT_{xy}) + \frac{\partial}{\partial y}(hT_{yy}) + hv_sS \end{aligned} \tag{3}$$

where \bar{u} and \bar{v} are the average flow velocity, m/s. t represents time, s. d represents the depth of still water, m. η represents the elevation of riverbed, m. h is the hydraulic head, m. u and v are components of velocity in x axis and y axis, m/s. g represents the gravitational acceleration, m/s^2 . ρ is the density of water, kg/m^3 . s_{xx} , s_{xy} , s_{yx} and s_{yy} are the components of radiation stresses. P_a is the atmospheric pressure, Pa. ρ_0 is the relative density of water, kg/m^3 . u_s and v_s are the water flow velocity, m/s.

2.2 Model Establishment and Verification

The simulated area of the model is the front bend of the Yellow River midstream. The upstream boundary of the model is the first front bend, and the downstream boundary is

based on the actual measured water level of Wanjiashai reservoir. The roughness coefficient is 0.024. The model contains 9000 average-sized grids. The length of the biggest grid is less than 100 m, and its area is less than 2000 m².

The model was verified based on the actually measured hydrological data of the Hamaoer hydrometric station and the Wanmatou hydrometric station located in the flow entrance and the dam site from July 3 in 2011 to July 16 in 2022. The verification result is shown in Fig. 2. The calculated water level of the Wanjiashai reservoir from the model is slightly different from the actually measured water level, and the curve trend of them are consistent. Among results, the maximum differential value between the actually measured water level in Hamaoer hydrometric station and the simulated water level is 0.10 m, with a maximum relative error rate of 1.23%. The maximum differential value in Wanmatou hydrometric is 0.04 m with a maximum relative error rate of 0.49%. Therefore, the topography and the roughness (0.025) established by the model are reasonable. It is feasible to use this model to simulate the evolution process of water and sediment from the front turning of the Yellow River midstream to the river section of the Wanjiashai reservoir dam site.

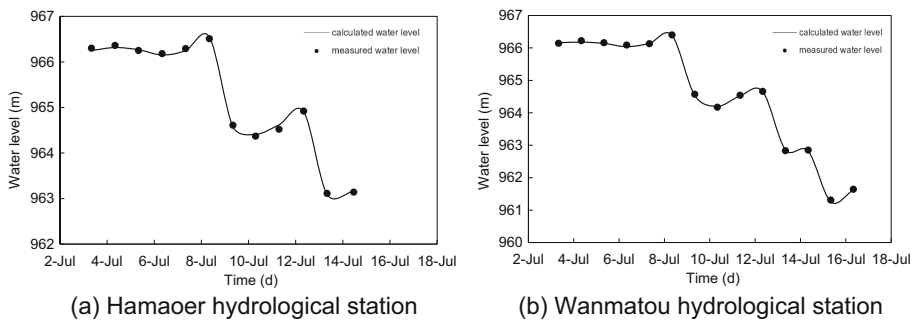


Fig. 2. Comparisons between calculated results and measured data

Considering factors such as the actual inflow rate, the annual precipitation, and the united dispatching, the outflow water level of the reservoir is set as 948 m, which can maintains the reservoir flushing. Owing to the united dispatching of the upstream reservoir, the inflow rate of the reservoir can be allocated by the upstream reservoir. The inflow rate of the upstream reservoir was set as five calculation groups, which were 500 m³/s, 800 m³/s, 1200 m³/s, 1800 m³/s and 2500 m³/s, respectively.

3 Variations of Hydraulic Parameters

3.1 Average Flow Velocity

The control variable method was applied to analyze the flow velocity under different inflow rates in this study. The average flow velocity and the water depth along the riverway in different flow rates are shown in Table 1. With the increasing inflow rate,

the flow velocity in water area 7.2 km away from the dam axis is significantly affected by the inflow rate variations, and the flow velocity in water area 1 km away from the dam axis is slightly affected by the inflow rate variation. When the inflow rate increases from 1200 m³/s to 1800 m³/s, the increasing range of the average flow velocity is 0.17 m/s. When the inflow increases from 1800 m³/s to 2500 m³/s, the increasing range of the average flow velocity is 0.16 m/s. When the inflow increases from 800 m³/s to 1200 m³/s, the flow velocity variation is the most affected, and the increasing range of the average flow velocity is 0.21 m/s. Figure 3 demonstrates the alternative figure of the along flow velocity at different reservoir inflow rates. Under the same flow rate, the reservoir area 3.3 km away from the dam axis has the minimum flow velocity. And there is the maximum increasing range of the flow velocity within 4 km–7.2 km of the reservoir area. As the inflow rate goes up, the increasing range of the flow velocity gets larger. In water area 7.2 km away from the dam axis, the water flow velocity is significantly affected by the inflow rate, and its maximum increasing range of the average flow velocity reaches 211%. This hydrometrical section is located in the most front position of the delta deposition with a large channel gradient, whose average flow velocity is majorly affected by the inflow rate.

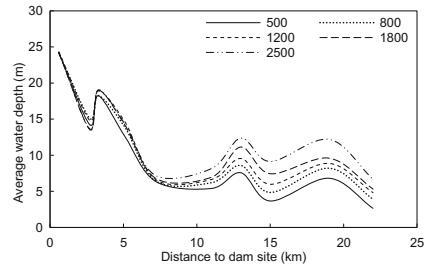
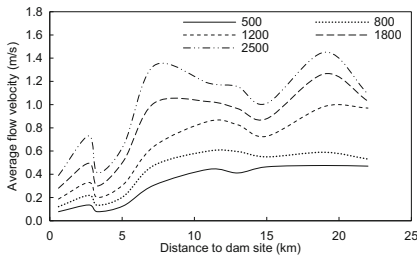


Fig. 3. Flow velocity in different inflow rates

Fig. 4. Water depth in different inflow rates

Table 1. Average flow velocity and water depth along the riverway in different inflow rates

Inflow rate (m ³ /s)	500		800		1200		1800		2500	
	Average flow velocity (m/s)	Average water depth (m)	Average flow velocity (m/s)	Average water depth (m)	Average flow velocity (m/s)	Average water depth (m)	Average flow velocity (m/s)	Average water depth (m)	Average flow velocity (m/s)	Average water depth (m)
0.6	0.08	24.16	0.12	24.16	0.19	24.34	0.28	24.22	0.39	24.23
2.7	0.14	14.25	0.22	15.13	0.33	14.84	0.50	13.56	0.73	13.66
3.3	0.08	18.24	0.13	18.26	0.20	18.92	0.30	18.98	0.41	19.06
5.1	0.13	12.60	0.21	13.86	0.31	14.63	0.52	14.16	0.65	14.31
7.2	0.43	6.37	0.48	6.43	0.64	6.62	1.01	6.80	1.34	7.18
11	0.44	5.40	0.60	6.20	0.86	6.65	1.03	6.96	1.18	8.16
13	0.41	7.57	0.60	8.58	0.83	9.55	0.96	11.14	1.15	12.37
15	0.46	3.67	0.55	4.85	0.73	5.98	0.88	7.44	1.01	9.13
19	0.48	6.82	0.59	8.20	0.98	8.87	1.27	9.60	1.45	12.20
22	0.47	2.65	0.53	3.90	0.97	4.82	1.03	5.32	1.09	6.67

3.2 Average Water Depth

Based on the effect of different inflow rates to the water depth in reservoir area, it is found that when the reservoir inflow rate increases, the water depth in the reservoir area 19 km away from the dam axis is mostly influenced, and the water depth in the reservoir area within 1 km from the dam axis is minimally affected by the inflow rate variation. When the inflow rate increases from 1200 m³/s to 1800 m³/s, the increasing range of the average flow velocity in the reservoir area is the largest and reaches 0.90 m/s. When the inflow rate increases from 1800 m³/s to 2500 m³/s, the increasing range of the average flow velocity is 0.88 m/s. When the inflow rate increases from 500 m³/s to 800 m³/s, the increasing range of the average flow velocity is approximately 0.78 m. When the inflow rate increases from 800 m³/s to 1200 m³/s, the increasing range of the average water depth is 0.67 m.

Figure 4 shows alteration of the water depth at different inflow rates. In the same inflow rate, the variation trend of along water depth in the reservoir is basically consistent. And the water depth grows smaller with the increasing distance from the dam axis. Within 7.2 km of the dam axis, the water depth is basically not affected by the flow rate. However, in 7.2 km away from the dam axis, the influence of flow rate on the water depth is bigger, and the water gets deeper when the flow rate increases. Influenced by the topography, there are two sudden increases of the water depth in 13 km and 19 km away from the dam axis.

4 Diameter Analyses of the Reservoir Flushing Sediment

4.1 Calculation Formula of Incipient Sediment

It is considered that the reservoir sediment is mainly derived from the Yellow River midstream, and the sediment particle is smaller. Affected by the soil quality in the Yellow River midstream, the inflow sediment is finer and has certain agglutinating power among each other. Therefore, the Zhang's sediment incipient velocity formula is applied to calculate the diameter of the incipient sediment, which is set as criterion of the incipient sediment under certain flow rate. It is also used to initially estimate the diameter range of the incipient sediment in flood season. The sediment incipient velocity formula is displayed as follows:

$$U_c = \left(\frac{h}{d}\right)^{0.14} \left[17.6 \frac{\rho_s - \rho}{\rho} d + 6.05 \times 10^7 \frac{10 + h}{d^{0.72}} \right]^{0.5} \quad (4)$$

where U_c is the velocity of the incipient sediment, m/s. h is the water depth, m. d is the particle diameter of sediment, m. ρ is the density of water, kg/m³. α is the effective volumetric weight coefficient.

4.2 Sediment Discharge Analysis

After studying the sediment deposition of the reservoir at different inflow rates, the connection between the diameter range of the incipient sediment and the flow velocity

was clarified. According to the actually measured data, the diameter range of sediment in the reservoir is 0.007 mm–0.094 mm. The first 7.2 km of reservoir belongs to the front dam funnel area, where the hydrodynamic parameters are larger than other areas since the existence of the dam outfall and the sediment flushing outlet. Thus, sediment in this area can be discharged during the outflow process. The calculation result of the incipient sediment in the river section 7.2 km–22 km away from the dam axis is shown in Table 2.

Table 2. Minimum particle diameter of incipient sediment in different inflow rates (Unit: mm)

Distance to dam site (m)	Inflow rate (m ³ /s)				
	500	800	1200	1800	2500
7.2	No motion	0.100	0.046	0.017	0.010
11	No motion	0.051	0.022	0.017	0.014
13	No motion	0.067	0.034	0.028	0.021
15	0.070	0.053	0.032	0.025	0.022
19	0.108	0.065	0.019	0.015	0.013
22	0.029	0.050	0.015	0.014	0.015

When the inflow rate reaches 500 m³/s, the volume of the incipient sediment is little, and the flushing effect of water flow is limited. When the inflow rate reaches 800 m³/s, sediment with a diameter of 0.050 mm–0.094 mm is able to be started in the reservoir area. When the inflow rate is 1200 m³/s, sediment with a diameter of 0.015 mm–0.094 mm enables to start. When the inflow rate is 1800 m³/s, sediment with a diameter of 0.014 mm–0.094 mm enables to start. When the inflow rate is 2500 m³/s, sediment with a diameter of 0.010 mm–0.094 mm can be started, which can be all discharged from the reservoir.

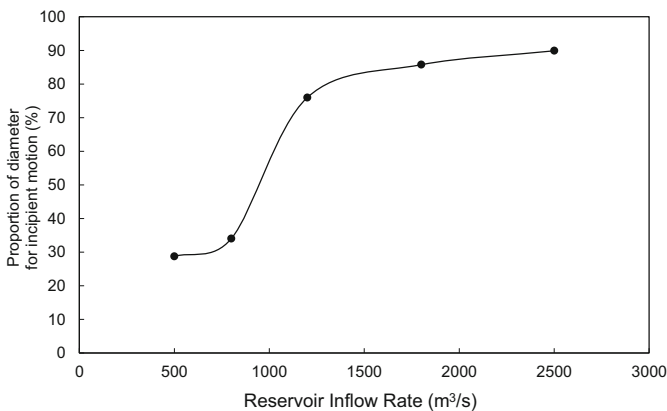


Fig. 5. Proportion of incipient sediment diameter

What's more, percentage of the incipient sediment diameter at different inflow rates is shown in Fig. 5. When the inflow rate increases from 500 m³/s to 800 m³/s, the percentage of the particle diameter range of the incipient sediment to the total particle diameter range of sediment increases from 28.73% to 34.02%. The increasing range is little, which is about 5.29%. When the inflow rate increases from 500 m³/s to 800 m³/s, the water flow is 0.5 time larger with an increasing range of 41.95%. The most effective sediment flushing effect appears under the largest increasing range of inflow rate. When the inflow rate increases from 1200 m³/s to 1800 m³/s, the increasing percentage is 9.77%. When the inflow rate increases from 1800 m³/s to 2500 m³/s, the increasing percentage is 4.13%, which is less. The diameter range of the flushable incipient sediment and the discharge flow rate both reaches the biggest when the flow rate is 2500 m³/s. Compared with the flow rate of 1200 m³/s, the discharge flow rate is 1.08 times larger. While the sediment flushing ability is limited with an increasing range of 18.30%. Besides, oversized outflow rate also affects the flushing of the downstream river course. In addition, the inflow rate of the reservoir has been few in recent years, and sediment flushing at a large flow rate has certain adverse impacts on the normal storage of the upstream reservoir. Therefore, it is inappropriate to choose 2500 m³/s as the flow rate of sediment flushing in the reservoir. However, at a flow rate of 1200–1800 m³/s, the proportion of the incipient sediment particle is more than 75% and has a strong effect on sediment flushing. Besides, the discharge flow rate is moderate, which makes it reasonable for using this range as the recommended flow rate of flushing the sediment and deposition.

5 Conclusions

Based on the actually measured hydrology and topography data, a mathematical model was built in the present study to conclude characteristics of flow velocity and water depth along the Wanjiashai Reservoir and clarify the particle diameter range of the incipient sediment by using the sediment starting velocity formula. Various flushing effects of sediment at different flow rates in flood season and characteristics of sediment particle diameter in the reservoir area were analyzed and studied. Results indicated that the riverbed gradient in the front position of the delta deposition was large, which is 7.2 km away from the dam axis. The flow velocity there was large and sensitive to the flow rate variation. However, the water depth within 7.2 km of the reservoir area was not sensitive to the flow rate, and the sensitivity within 7.2 km–22.0 km of the reservoir area increased with the flow rate. Additionally, when the flow rate increased, the maximum diameter of the initial sediment of movement was larger. And, when the inflow rate reached 1200 m³/s, the sediment with a particle diameter of 0.015 mm–0.094 mm can be started and discharged from the reservoir area. When the inflow rate reached 1800 m³/s, the particle diameter range of the incipient sediment was 0.014 mm–0.094 mm. When the inflow rate reached 2500 m³/s, the range was 0.010 mm–0.094 mm. When the inflow rate increased from 800 m³/s to 1200 m³/s, the proportion of the particle diameter of the incipient sediment increased the most, and the flushing effect was significantly enhanced. When the flow rate increased from

1800 m³/s to 2500 m³/s, the sediment flushing effect was limited. In summary, considering the flushing effect and downstream scouring, the appropriate flow rate is 1200 m³/s–1800 m³/s.

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