ANALYSIS ON THE CONTROLLING-SEDIMENTATION CAPACITY OF CORE RESERVOIRS IN THE MAIN CHANNEL OF YELLOW RIVER, CHINA

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ABSTRACT

Defining the controlling-sedimentation capacity of reservoirs as sediment-trapping capacity and sediment-transporting capacity, and selecting residual ratio of reservoir capacity and sediment-releasing ratio as indices respectively, this paper built a numerical method for evaluating the controlling-sedimentation capacity of reservoirs, and calculate the sediment-trapping capacity for 4 core reservoirs (Longyangxia, Liujiaxia, Sanmenxia, Xiaolangdi) which have been in operation in the main channel of Yellow River and sediment-transporting capacity for Xiaolangdi reservoir. According to analysis on the capacity of sediment-controlling for those core reservoirs, the challenge and problem for the current water and sediment controlling mode were examined and discussed.

1. INTRODUCTION

Sedimentation is an inevitable problem for sandy river reservoirs. Reservoir sedimentation will cause the decline of the comprehensive benefits of the reservoir, the extension and immersion loss of the upstream backwater area, the difficulty of scouring and fetching water downstream, the pollution of water quality in the reservoir area, and especially the increase of the downstream flood risk (Han 2003), which has caused widespread concern in the society. According to a research report published by ICOLD in 2012 (ICOLD 2012), the total storage volume of globe reservoirs is 7,000 km^3, and in the past 35 years, the sedimentation storage volume has been 2000 km^3, with an average annual global storage volume lost ratio of 0.8%. In addition, with the gradual slowdown of the construction speed of the reservoir, the sedimentation rate showed an obvious trend of accelerating (ICOLD 2012). In the United States, more than 1,200 dams have been removed in the past century due to severe sedimentation. On the regional scale, the sedimentation rate of reservoirs in arid areas is the fastest, especially in the Middle East, Africa and Asia Pacific (Anton et al. 2016).

Compared with the serious problems caused by reservoir sedimentation, targeted researches on reservoir sedimentation started relatively late. Although there are case analyses on reservoir sedimentation and reservoir sedimentation management in the early stage, the seriousness of reservoir sedimentation problems has not received widespread attention from scholars and engineers before the 1950s (De Cesare & Lafitte 2007). The earliest sustainable management concept for reservoir sedimentation began to appear in the 1950s, and related researches began to increase significantly in the 1980s. At present, reservoir sedimentation treatment and sustainable management have become one of the key factors to be considered in the planning, design, construction, and operation of reservoirs. A large number of related research results have been able to provide engineers with comprehensive technical support in handling reservoir sedimentation (ICOLD 1989, Sloff 1991, Morris & Fan 1998, Batuca & Jordaan 2000, Jenzer-Althaus & De Cesare 2006, García et al. 2008, Morris 2014).

According to factors such as differences in reservoir construction goals, sedimentation volume, and sedimentation rate, Juracek (2015) proposed an evaluation method for the level of reservoir sediment management. High-level sustainable management of reservoir sedimentation must consider the overall spatial coordination and the application of comprehensive technical means. Specifically, it refers to the use of targeted measures to reduce, discharge, and store sand in upstream runoff producing area (C), reservoir area (R) and dam area (D), respectively (Sumi & Kantoush 2011, Kondolf et at. 2014).

Sediment reduction measures mainly include soil and water conservation measures in the runoff and sediment production area (C) upstream of the reservoir, shoreline fixation measures in the runoff and sediment production areas (C) and the reservoir area (R), and construction of sand traps dams in the upstream of the reservoir area (R), etc. The main purpose is to reduce the total amount of sediment entering the reservoir. Sediment removal measures mainly include sand transport in the reservoir area (R) bypass tunnel, flushing from the bottom hole by lowing water level, sediment releasing by density current, and coordinated with measures such as artificial turbulence to increase sediment turbulence. The main purpose is to increase the ability of sediment to be transported into and out of the reservoir. Sediment storage measures, mainly including dam (d) heightening, dead water level rising, bottom hole and diversion port elevation heightening, and artificial dredging measures, etc. The main purpose is to increase the storage capacity of reservoirs (Anton et al. 2016).

As far as the reservoir itself is concerned, sediment-trapping and sediment-transporting are the basic means for handling sediment. Therefore, the evaluation of controlling-sedimentation capacity of different reservoirs should also be carried out from these two dimensions. This is also the research goal of this paper.

2. METHODS AND DATA

2.1 Research methods

The sediment-trapping capacity of reservoirs is firstly reflected in the change of sedimentation volume. Reservoir sedimentation development will eventually cause itself to enter a relative equilibrium state. This evolution process usually shows a non-linear trend of fast first and then slow. Here we use Shamov's empirical formula (Tu & Yang 2006) to describe this non-linear process:

$$V = V_0 e^{-\alpha T} \tag{2-1}$$

Where, V is the residual reservoir storage capacity (km^3), V_0 is the maximum sedimentation storage capacity (km^3), T is the sedimentation year (a), and α is the sedimentation loss rate of reservoir storage.

The formula (2-1) are transformed into the dimensionless number λ (residual ratio of reservoir capacity):

$$\lambda = V / V_0 = e^{-\alpha T} \tag{2-2}$$

The dimensionless number λ indicates the relative sediment-trapping capacity of the reservoir, and its value ranges from 0 to 1.

The sediment releasing capacity of reservoirs is expressed by the sediment-releasing ratio η of the flood. The definition of sediment-releasing ratio is:

$$\eta = \frac{Q_{s,out}}{Q_{s,in}} \tag{2-3}$$

Where, $Q_{s,out}$ is the average sediment transport rate (kg/s) of the reservoir outflow during the flood, $Q_{s,in}$ is the average sediment transport rate (kg/s) of the reservoir inflow during the flood.

For the process of reservoir inflow, this relationship can be presumed approximately:

$$Q_{s,in} = K_1 Q_{in}^2 \tag{2-4}$$

Where, Q_{in} is the average discharge of inflow (m^3/s), K_1 is the coefficient to be determined.

For the output process of the reservoir, we believe that the sediment concentration of outflow is approximately equal to the average sediment concentration of the section in front of the dam.

$$Q_{s,out} = Q_{out} S_{out} = Q_{out} K_2 \frac{v^3}{gh\omega} \tag{2-5}$$

Where, Q_{out} is the average outflow discharge of the reservoir (m^3/s), S_{out} is the average outflow sediment concentration of the reservoir (kg/m^3), v is the average velocity at the section in front of the dam (m/s), g is the acceleration of gravity (m/s^2), h is the average water depth at the section in front of the dam (m), ω is the average sediment settling velocity at the section in front of the dam (m/s), K_2 is the coefficient to be determined.

$$v = \frac{Q_{out}}{Bh}, V = K_3 B h^2 \tag{2-6}$$

Where, B is the average river width of the section in front of the dam (m), V is the residual water storage capacity of reservoir (m^3), K_3 is the coefficient to be determined.

Substitute equations (2-4) ~ (2-6) into equations (2-3) to obtain:

$$\eta = K\left(\frac{Q_{out}^2}{Q_{in}V}\right)^2 \frac{1}{B}\frac{1}{\omega} \tag{2-7}$$

Where, $K=K_2/[gK_1K_3^2]$ is the coefficient to be determined.

It can be known from equation (2-7) that the sediment-releasing ratio should be a function of the following variables:

$$\eta = f(\left(\frac{Q_{out}^2}{Q_{in}V}\right), \frac{1}{B}, \frac{1}{\omega}) \tag{2-8}$$

Given from above, it can be inferred that with the continuous reduction of the residual storage capacity of the reservoir, the sediment removal capacity of the reservoir is continuously increasing, Essentially it is due to the decrease in water storage and water supply, which leads to a significant increase of the velocity under the same outflow condition in front of the dam, and it makes the sediment-releasing volume increase geometrically.

In addition, the average river width of the section in front of the dam is also an important influencing factor. This factor also directly affects the outflow velocity under the same outflow flow discharge. The average settling velocity of outflow sediment, or the median particle size of the outflow sediment, is also negatively related to the sediment-releasing ratio of reservoirs. The larger the median particle size of reservoirs is, the easier it is to deposit in the reservoir, resulting in a lower sediment-releasing ratio.

2.2 RESEARCH DATA

The research object of this paper is the four control reservoirs in the main stream of the Yellow River. The spatial distribution and characteristic data are shown in Figure 1 and Table 1.

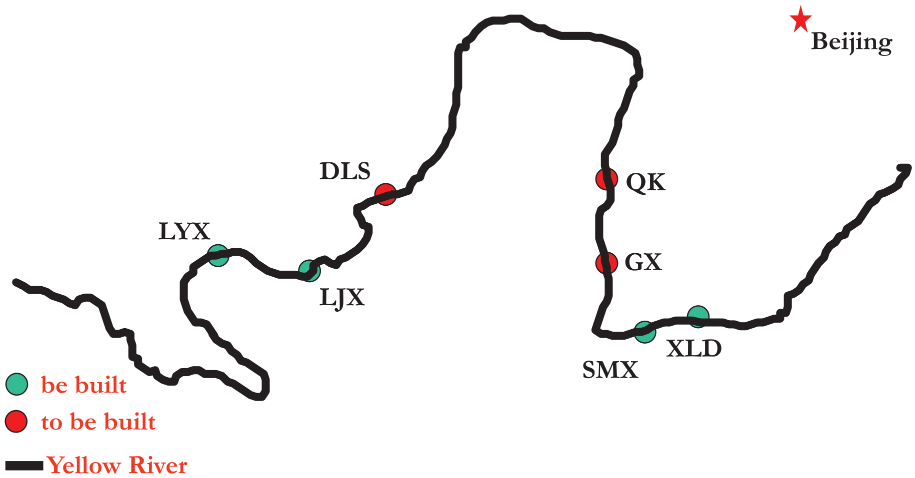

Figure 1 : The spatial distribution of four control reservoirs in the main channel of the Yellow River

(LYX-Longyangxia Reservoir; LJX-Liujiaxia Reservoir; DLS-Daliushu Reservoir; QK-Qikou Reservoir; GX-Guxian Reservoir; SMX-Sanmenxia Reservoir; XLD-Xiaolangdi Reservoir)

Table 1 : The characteristic data of four control reservoirs in the mainstem of the Yellow River

Reservoirs	Distance from river source	Normal water lever	Original storage	Sediment-trapping storage
	(km)	(m)	(10^9 m^3)	(10^9 m^3)
Longyangxia	1684	2600	247	53.5
Liujiaxia	2019	1735	57.4	15.5
Sanmenxia	4444	335	57.8	36
Xiaolangdi	4574	275	126.5	75.5

3. RESULTS AND DISCUSSION

3.1 Analysis of sediment-trapping capacity of reservoirs

The storage capacity curves of Longyangxia, Liujiaxia, Sanmenxia and Xiaolangdi reservoirs are shown in Figure 2 below.

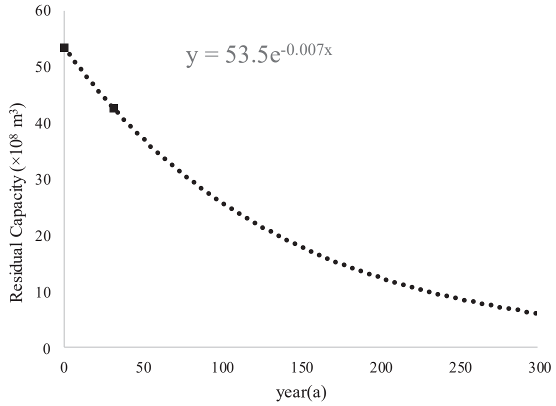

Figure 2a : The storage curves of Longyangxia reservoir

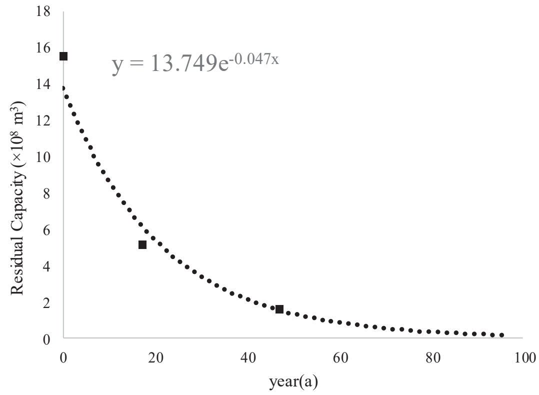

Figure 2b : The storage curves of Liujiaxia reservoir

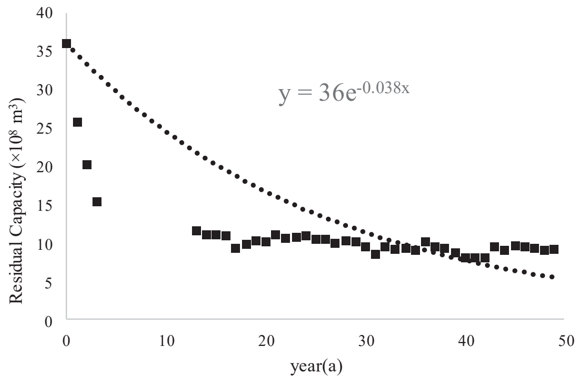

Figure 2c : The storage curves of Sanmenxia reservoir

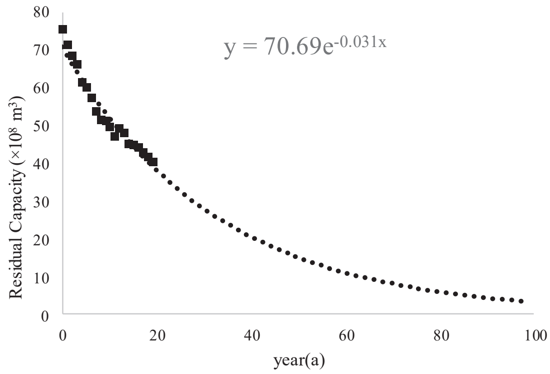

Figure 2d : The storage curves of Xiaolangdi reservoir

It is believed that if the residual ratio of reservoir capacity λ drops below 20%, the reservoir is close to the state of dynamic equilibrium. The number of years when the above four reservoirs reach the state of dynamic equilibrium can be calculated respectively: 230 years for Longyangxia, 34 years for Liujiaxia(has done), 42 years for Sanmenxia(has done), and 52 years for Xiaolangdi.

3.2 Analysis of sediment-transporting capacity of reservoirs

According to the analysis of the above-mentioned sediment-trapping capacity, it can be seen that the Longyangxia reservoir has large storage capacity and less incoming sediment, which can completely accommodate the sediment in the reservoir for a long time, and the problem of reservoir sedimentation is not prominent. According to the existing operation mode, Liujiaxia reservoir and Sanmenxia reservoir have entered the state of relative balance of erosion and deposition, and the capacity of sediment-trapping has been basically lost. Only Xiaolangdi reservoir is still in the stage of continuous reduction of sediment-trapping capacity, so the residual storage capacity of the reservoir continues to decrease, which leads to the continuous enhancement of sediment releasing capacity under the same water and sediment conditions. Therefore, this section will focus on the analysis of sediment-transporting capacity of Xiaolangdi reservoir.

According to formula (2-8), if sediment-releasing ratio η is used to measure the sediment transporting capacity of Xiaolangdi reservoir, then η is a function of reservoir inflow discharge Q_{in}, outflow discharge Q_{out}, residual reservoir storage capacity V, the channel width of section in front of dam B and average sediment settling velocity ω. In particular, considering that the inflow and sediment conditions of the upper reaches of Xiaolangdi reservoir are completely controlled by Sanmenxia reservoir, formula (2-4) is usually not satisfied, so it is necessary to introduce inflow sediment concentration S_{in} as a variable. In order to combine the sediment-transporting capacity of Xiaolangdi reservoir with the reservoir operation, the residual storage capacity V is replaced by the backwater length L of the reservoir, and the average settling velocity ω is replaced by the medium diameter of sediments D_{50}, then the formula (2-8) can be rewritten as follows:

$$\eta = f(Q_{in}, Q_{out}, S_{in}, B, L, D_{50}) \tag{3-1}$$

When formula (3-1) is dimensionless, it can be written as the following formula:

$$\eta = K'\left(\frac{Q_{in}}{\sqrt{gD_{50}^5}}\right)^{\gamma_1}\left(\frac{Q_{out}}{\sqrt{gD_{50}^5}}\right)^{\gamma_2}\left(\frac{S_{in}g}{\gamma}\right)^{\gamma_3}\left(\frac{B}{D_{50}}\right)^{\gamma_4}\left(\frac{L}{D_{50}}\right)^{\gamma_5} \tag{3-2}$$

From 2002 to 2019, there are 13 flood events of Xiaolangdi reservoir with significant sediment releasing process (in which the daily average sediment concentration is more than 10 kg/m^3), the basic parameters of flood events are shown in Table 2, and the final calibration results are shown in Figure 3:

Table 2 : Flood information table of Xiaolangdi reservoir with significant sediment releasing process

Time	Sediment-releasing ratio (/)	Average inflow discharge (m^3/s)	Average outflow discharge (m^3/s)	Average inflow sediment concentration (kg/m^3)	River width (m)	Length of backwater (10^3 m)	Medium diameter of sediment (10^{-3} m)
2002.7	0.1792	1216	2605	158.72	1098.93	93.96	0.007
2004.8	1.2201	1105	1917.5	100.39	1177.33	53.44	0.005
2005.7	1.2597	671	2243.3	118.17	1177.33	74.38	0.008
2006.7~8	2.9787	916	1576.7	26.43	1179.27	51.78	0.006
2007.7~8	0.7398	1387	2370.75	68.3	1253.47	41.1	0.007
2008.7	1.0012	1366.7	2603.3	114.84	1256.2	41.1	0.009
2010.7	1.3228	1655.5	2396.7	89.23	1341.53	27.19	0.011
2011.7	1.2045	1723.5	1877.25	52.61	1499.27	31.85	0.012
2012.7	1.3159	2454	2366	41.89	1488.64	34.8	0.024
2013.7	1.6636	2079.3	2826.7	32.93	1577.57	22.1	0.014
2014.7	0.4214	2174.25	2290	97	1612.5	34.8	0.009
2018.7	2.6903	2338.57	2976.19	35.89	1915.4	15.26	0.021
2019.7	4.2158	2376.92	3134.23	21.07	1946.1	13	0.02

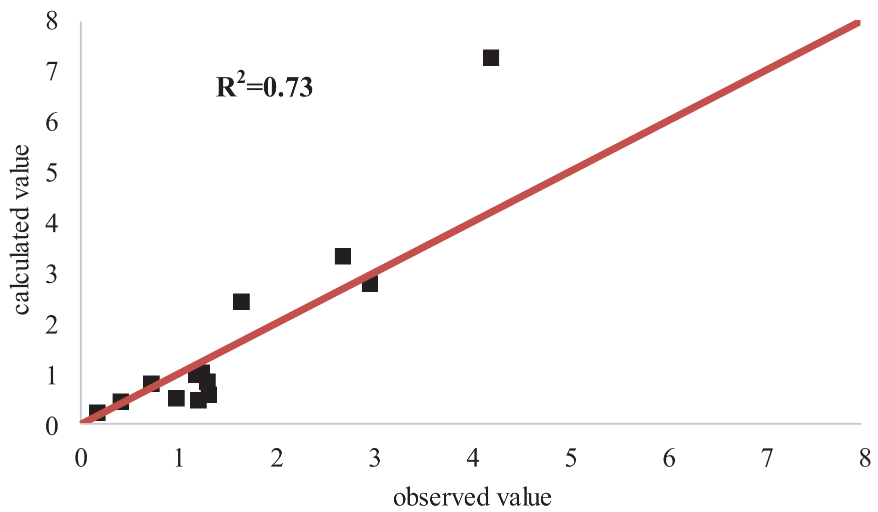

Figure 3. Simulation calculation results of sediment-releasing ratio of Xiaolangdi reservoir floods

The formula after parameter calibration is as follows:

$$\eta = 1.63\times10^{-4}\times(\frac{Q_{in}}{\sqrt{gD_{50}^5}})^{-1.435}(\frac{Q_{out}}{\sqrt{gD_{50}^5}})^{0.901}(\frac{S_{in}g}{\gamma})^{-0.942}(\frac{B}{D_{50}})^{1.686}(\frac{L}{D_{50}})^{-0.361} \tag{3-3}$$

From the further analysis of formula (3-3), it can be seen that the sediment-transporting capacity of Xiaolangdi reservoir has a negative relation with the inflow and a positive relation with the outflow, that is, the effect of sediment-releasing by lowing water level is stronger than that by damming water. It is negatively correlated with the sediment concentration in the reservoir, that is to say, the lower the sediment concentration is, the better the sediment releasing effect is. The negative correlation with the length of backwater indicates that lowering the water level can further improve the sediment-transporting capacity. However, the positive correlation between the sediment transporting capacity and the width of the river channel in the reservoir area may be related to the special geomorphic characteristics of the upper narrow and lower wide of Xiaolangdi reservoir area, which does not really reflect the accurate qualitative relationship between the river width and the sediment-releasing ratio. The analysis of the relationship between the sediment-releasing ratio and the influencing factors also depends on the application of further numerical simulation methods and the results of scenario analysis.

4. CONCLUSIONS

The main conclusions are as follows:

(1) It is defined that the controlling-sedimentation capacity of reservoirs includes two dimensions of sediment-trapping capacity and sediment transporting capacity, and the corresponding indexes and calculation methods are introduced respectively;

(2) Based on the analysis of the evolution process of sediment-trapping capacity of four core reservoirs in the main stream of the Yellow River, it is pointed out that Liujiaxia reservoir and Sanmenxia reservoir have reached a relatively balanced state of erosion and deposition, while under the existing water and sediment conditions and reservoir operation mode, it will take 230 years to reach a balance in Longyangxia reservoir and 52 years in Xiaolangdi reservoir.

(3) Many factors influencing the sediment-releasing ratio of Xiaolangdi reservoir are analyzed. A dimensionless multiple regression model of sediment-releasing ratio is established for 13 typical flood events, which can be used to predict the future sediment-releasing effect of Xiaolangdi reservoir.

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