Analysis and Research on the Influencing Factors of Sediment Discharge of Wanjiazhai Reservoir in 2018

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Abstract. Sediment discharge method has great impact on the service life and comprehensive benefits of the reservoirs in sediment-laden river. In this paper, the actual operation process of Wanjiazhai Reservoir in 2018 was taken as the research object to analyze changes in runoff and sediment process and erosion and deposition in the reservoir area, and to explore possible influencing factors for reservoir sediment discharge. According to the results, the erosion in the reservoir area of Wanjiazhai Reservoir in 2018 was 112.6 million t, the erosion period was concentrated in August and September, and the erosion positions were concentrated at the elevation of 935-966 m; the deposition morphology in the reservoir area changed obviously after twice sediment flushing in 2018, and the channel has been subject to deepening and widening accompanied by reservoir bank collapse; there is a negative correlation between the outflow sediment concentration/sediment discharge ratio of the reservoir and the reservoir water level.

1. Introduction
Construction of a reservoir in sediment-laden river will change the runoff and sediment conditions of the natural river, break the relative balance of the channel morphology, cause re-adjustment of river runoff and sediment process and morphology, lead to reservoir deposition[1], affect reservoir benefits, and shorten reservoir service life [2,3]. As an important link for solving reservoir deposition and keeping long-term effective storage capacity of the reservoir, reservoir sediment discharge is of important practical significance to determining reservoir operation mode and giving play to reservoir functions [4]. At the initial operation stage of Wanjiazhai Reservoir, the inflow water and sediment amount was obviously smaller than the design, the reservoir operation water level was high at the sediment discharge stage, and the deposition problem of the reservoir area was becoming more and more serious. The longitudinal section of sediment deposition (average elevation of river bottom) of Wanjiazhai Reservoir basically reached the design deposition balance state by October 2010. Different sediment discharge (sediment flushing) methods have been taken for the reservoir in recent years to delay reservoir sediment deposition, and certain effect has been obtained.

Since the sediment discharge mode of Wanjiazhai Reservoir has direct impact on the reservoir service life and comprehensive benefits, sediment discharge law had been exploring constantly at the initial sediment discharge practice stage. Different scholars have researched the deposition morphology and the erosion and deposition influencing factors of Wanjiazhai Reservoir. Based on analysis of the changes in sediment deposition as well as longitudinal and horizontal section morphologies of the reservoir in 2000 - 2020, Cheng et al. [5] believe that the longitudinal of the reservoir area is of delta deposition morphology below 966 m, and the reservoir tail section has obvious erosion in recent years. According to analysis of reservoir operation and the post-flood
reservoir erosion and deposition by 2005, Lu et al. [6] believe that there is deposition in 0 - 56.6 km reach in front of the dam and slight erosion in 56.6 - 72.3 km reservoir tail reach. For the research on reservoir erosion and deposition influencing factors, Ren et al. [7] analyzed the impact on sediment deposition from reservoir operation mode at the initial reservoir operation stage; Lin et al. [8] analyzed the impact on the deposition morphology of the reservoir area from the operation mode of Wanjiazhai Reservoir during spring flood test, and they believed that proper lift of operation water level before spring flood did not lead to increase of the deposition in the reservoir tail section; Ren et al. [9] analyzed the spatial and temporal distribution characteristics of the sediment deposition in the reservoir area of Wanjiazhai Reservoir, proposed that the sediment distribution characteristics in the reservoir area were closely related to inflow runoff and sediment, reservoir operation water level, etc., and the reservoir deposition ratio was less than 0 when the operation water level of Wanjiazhai Reservoir was lower than 952 m.

Therefore, analyzing the changes in reservoir sediment erosion and deposition and spatial form under different runoff and sediment conditions and operation modes, and exploring sediment discharge influencing factors and their change law are of important significance to keeping long-term effective storage capacity of Wanjiazhai Reservoir. In this paper, the actual operation process of Wanjiazhai Reservoir in 2018 is taken as the research object to analyze changes in runoff and sediment process and erosion and deposition in the reservoir area, and explore possible influencing factors for reservoir sediment discharge, which provides important reference for further optimization and scientific scheduling of the operation mode of Wanjiazhai Reservoir.

2. Wanjiazhai Reservoir overview

Wanjiazhai water multi-purpose dam project is located in the upper part of the middle section of the Yellow River, with Pianguan County, Shanxi Province, on the left bank of the dam site, and Jungar Banner, Inner Mongolia, on the right bank [10]. The Wanjiazhai Reservoir started operating in October 1998; by the end of 2000, all six generator units had been constructed and put into production, during which the operation water level was low and the reservoir water level fluctuated substantially [11]. The normal water level is 977 m, the maximum operation water level is 980 m, and the original reservoir capacity is 896 million m³.

The Wanjiazhai Reservoir is a canyon shaped reservoir. It is very narrow and has multiple curves and a large gradient, with U shape for most of the sections. The average width of the surface of the reservoir is around 350 m. The end point of the reservoir backwater is Guashang, where the longitudinal gradient becomes sharp. The reach between Toudaoguai and Guashang is a transitional section where the plain type river changes to the mountain type river. The reservoir area is below Guashang, which is 72 km long and a narrow, mountainous river with a large gradient that has an average natural gradient of 1.17%.

3. Inflow and Outflow Runoff and Sediment Process

The Yellow River encountered a few dry series with less inflow water and sediment since operation of Wanjiazhai Reservoir. However, much water came from upstream of the Yellow River in 2018, bringing about a large amount of inflow water and sediment. According to the hydrological statistics of Toudaoguai Hydrological Station, in 2000-2018 (reservoir operation year: The November of the last year to the October of the next year, the same below), the annual average discharge of Toudaoguai Hydrological Station is 16.761 billion m³ (Table 1), the annual average sediment content is 43 million t, and the annual average sediment concentration is 2.45 kg/m³. In 2011 - 2017, the annual average inflow water amount of Wanjiazhai Reservoir is 17.357 billion m³ and the inflow sediment amount is 38.4 million t. In 2018, the annual average inflow water amount of Wanjiazhai Reservoir is 31.261 billion m³ and the inflow sediment amount is 96.6 million t. Compared with 2011 - 2017, the inflow water amount and the inflow sediment amount increase by 80.1% and 151.4% respectively.

In 2018, the outflow water amount of Wanjiazhai Reservoir is 30.768 billion m³ and the outflow sediment amount is 209.2 million t. In 2011 - 2017, the annual average outflow water amount of
Wanjiazhai Reservoir is 16.983 billion m³ and the outflow sediment amount is 26.1 million t. Compared with 2011 - 2017, the outflow water amount and the outflow sediment amount increase by 81.1% and 701.5% respectively.

**Table 1** Statistics of Average runoff and sediment of Toudaoguai in Different Periods

| Year       | Operational year Flood season | Operational year Non-flood season | Flood season | Non-flood season |
|------------|-------------------------------|-----------------------------------|--------------|------------------|
| 2000-2005  | 127.61                        | 44.19                             | 83.42        | 0.27             | 0.14             | 0.13             |
| 2006-2010  | 178.26                        | 68.48                             | 109.79       | 0.58             | 0.28             | 0.30             |
| 2011-2017  | 173.57                        | 78.29                             | 95.28        | 0.38             | 0.24             | 0.15             |
| 2018       | 312.61                        | 209.48                            | 103.13       | 0.97             | 0.75             | 0.21             |
| 2000-2018  | 167.61                        | 71.84                             | 95.77        | 0.43             | 0.25             | 0.18             |

4. Analysis of Reservoir Sediment Discharge Effect

4.1. Time Variation of Reservoir Erosion and Deposition

The year-by-year erosion and deposition amount, month-by-month deposition amount and deposition amount in different periods of the reservoir in 2018 were figured out with sediment transport rate method based on the measured data of all hydrological stations of Wanjiazhai Reservoir in November 2017 - October 2018, as shown in Table 2. The Inflow and Outflow sediment amount of Wanjiazhai Reservoir in 2018 was 96.6 million t and 209.2 million t respectively, and the reservoir area erosion amount was 112.6 million t. According to year-by-year reservoir deposition amount, deposition occurred in non-flood season, erosion occurred in flood season, and erosion was concentrated in August and September in the year.

Different reservoir operation modes could lead to different reservoir sediment deposition ratios (the amount of sediment deposition per unit of sediment into the reservoir, %) in different months of the year. Most non-flood season sediment deposition ratios were 100%, which indicated that sediment barely left the reservoir. August in the flood season had the lowest deposition ratio (666.8%), which showed that there was great sediment discharge amount, and the reservoir was subject to effective erosion.

**Table 2** Erosion and Deposition Amount and Deposition Ratio of Wanjiazhai Reservoir in Different Periods of 2018

| Time     | Inflow Sediment Amount -Million t- | Outflow Sediment Amount -Million t- | Erosion and Deposition Amount -Million t- | sediment deposition ratio - %-
|----------|-------------------------------------|-------------------------------------|------------------------------------------|-----------------------------|
| November | 0.026                               | 0.000                               | 0.026                                    | 100.0                      |
| December | 0.004                               | 0.000                               | 0.004                                    | 100.0                      |
| January  | 0.002                               | 0.000                               | 0.002                                    | 100.0                      |
| February | 0.003                               | 0.000                               | 0.003                                    | 100.0                      |
| March    | 0.049                               | 0.019                               | 0.030                                    | 61.3                       |
| April    | 0.029                               | 0.000                               | 0.029                                    | 100.0                      |
| May      | 0.049                               | 0.000                               | 0.049                                    | 100.0                      |
| June     | 0.051                               | 0.000                               | 0.051                                    | 100.0                      |
| July     | 0.173                               | 0.115                               | 0.059                                    | 33.9                       |
| August   | 0.193                               | 1.477                               | -1.285                                   | -666.8                     |
| September| 0.186                               | 0.459                               | -0.273                                   | -146.9                     |
| October  | 0.200                               | 0.022                               | 0.178                                    | 89.2                       |
| Flood season | 0.752                           | 2.073                               | -1.321                                   | -175.7                     |
| Non-flood season | 0.214                         | 0.019                               | 0.195                                    | 91.1                       |
| Operational year | 0.966                       | 2.092                               | -1.126                                   | -116.6                     |
4.2. Spatial Variation of Reservoir Erosion and Deposition
The erosion and deposition amount of different reservoir sections of Wanjiazhai Reservoir in different periods of 2018 was calculated based on the measured section topographic data of Wanjiazhai Reservoir in 2018. The spatial distribution of sediment deposition in different reservoir sections and different periods is shown as Figure 1. Wanjiazhai Reservoir Area was subject to erosion with the erosion amount of 137.6 m³ on the whole in 2018. The deposition amount in the non-flood season (October 2017 - May 2018, the same below) was 18.7 million m³, and deposition was concentrated in reservoir section WD23 - WD54 (22.45 - 55.16 km from the dam), where the deposition amount was 10.9 million m³, accounting for 58.4% of the deposition amount of the period. All reservoir sections in the reservoir area were subject to erosion with the cumulative erosion amount of 156.3 million m³ in the flood season (May 2018 - October 2018, the same below). The main erosion body was in the reservoir section below section WD54, where the erosion amount was 151.7 million m³, accounting for 97.2% of the deposition amount of the period. From the perspective of trunk and tributary distribution, the cumulative erosion amount of the trunk was 155.2 million m³, and that of the tributaries was 1.1 million m³.

According to the erosion amount distribution in different elevation sections of Wanjiazhai Reservoir Area (Figure 2), major reservoir area erosion was concentrated in elevation 935 - 966 m. From the perspective of periods, main deposition body occurred in elevation 950 - 978 m during October 2017 - May 2018; and the main erosion in May 2018 - October 2018 was concentrated in elevation 935 - 966 m.

4.3. Changes in Reservoir Section Morphology
Wanjiazhai Reservoir Area had intense erosion due to twice sediment flushing in 2018, and the deposition morphology in the reservoir area changed obviously. According to the longitudinal deposition section of Wanjiazhai Reservoir (Figure 3), the elevation of the thalweg point of the reservoir section 60 km upstream from the dam in October 2018 had recovered to the level before reservoir construction compared with the initial landform in 1997, and the elevation of the thalweg point of partial sections was even lower than that before reservoir construction. Besides, the elevation of the thalweg point of the reservoir section 35 - 60 km from the dam was slightly higher than that before reservoir construction, and individual sections were obviously higher than that before reservoir construction.

It can be learnt from the large section change of the reservoir area (Figure 4) that there is obvious section morphologic change. The channel has been deepened and widened, accompanied by reservoir bank collapse. The horizontal section was subject to significant erosion in the flood season. The sections in different reservoir sections have different morphologic changes. For the section in front of the dam, there was obvious bottomland collapse and slump, and the channel discharge area increased greatly while having intense channel deepening and widening. For the section slightly far from the dam, the channel was deepened and widened, and bottomland collapse and slump intensity was
weakened. For the reservoir section in the middle of the reservoir area, the channel was deepened, and it was accompanied by widening. It shows that the storage capacity of Wanjiazhai Reservoir has been recovered through scheduling in the flood season of 2018.

5. Analysis of Reservoir Sediment Discharge Influencing Factors

5.1. Relationship between Reservoir Control Water Level and Sediment Discharge Effect

Reservoir sediment discharge is affected by multiple factors, such as inflow flow condition, reservoir operation water level, topographic condition and sediment discharge duration. Reservoir sediment discharge effect is closely related to reservoir water level under certain inflow runoff and sediment conditions and reservoir area landform. Based on the relationship between the daily average outflow sediment concentration and the reservoir water level in the sediment discharge period in 2002 - 2018 of Wanjiazhai Reservoir (Figure5), there is a negative correlation between the outflow sediment concentration/the sediment discharge ratio and the reservoir water level of Wanjiazhai Reservoir. Namely, outflow sediment concentration increases along with decrease of reservoir water level. When the water level in front of the dam of Wanjiazhai Reservoir is higher than 966 m, the reservoir barely ejects sediment. When the water level is lower than 966 m, the outflow sediment concentration increases along with decrease of water level. Among them, when the operation water level exceeds 957 m, the daily average outflow sediment concentration is not greater than 10 kg/m³ in general; when the operation water level exceeds 950 m, the daily average outflow sediment concentration is not greater than 20 kg/m³ in general; when the operation water level is lower than 950 m, the outflow sediment concentration increases rapidly. Except the initial stage of dewatering erosion, when the
daily average outflow sediment concentration is greater than 25 kg/m³, the operation water level is usually lower than 935 m.

However, it should be noted that the points in the circles of the figure represent the outflow sediment concentration at the initial dewatering sediment discharge stages of 2015, 2017 and 2018 respectively. There is great outflow sediment concentration that is obviously greater than other periods of the same water level at the initial dewatering sediment discharge stage. This is because that the high deposition surface in front of the dam is easy to have retrogressive erosion, particularly bottomland collapse in front of the dam along with decrease of the reservoir water level during initial dewatering of reservoir water level, so that the outflow sediment concentration will be increased obviously.

Figure 5 Relationship between the Water Level during Sediment Discharge (Sediment Flushing) Operation of Wanjiazhai Reservoir and Outflow Sediment Concentration in 2002 – 2018

The reason why the outflow sediment concentration of Wanjiazhai Reservoir is obviously affected by operation water level is that the outflow sediment is mainly the deposition sediment in the reservoir area, the lower the reservoir water level, the shorter the backwater distance and the damming sediment transport distance are, and the longer the erosion distance of the open flow section is, so the outflow sediment concentration will be increased, and the sediment discharge ratio of the reservoir will be improved.

5.2. Time Relationship between Outflow Sediment Concentration and Low Water Level Sediment Discharge

According to analysis of the time relationship between the outflow sediment concentration and the reservoir water level lower than 950 m in the sediment discharge period of Wanjiazhai Reservoir in 2014, 2015 and 2017 (Figure 6), the outflow sediment concentration is still high, and there is still certain erosion space in the reservoir area before reservoir storage. Moreover, if the low water level operation duration is extended, the reservoir area will be subject to constant erosion, and better erosion effect can be obtained.

Based on the time change process of the outflow sediment concentration along with erosion during the 2nd dewatering erosion period in 2018 (Figure 7), the 1st erosion in 2018 takes a long time. Among them, the first 4d had great outflow sediment concentration increments that were greater than 80 kg/m³, and the largest one was 117 kg/m³. But it started decreasing since the 5d, and the sediment concentration increments were basically maintained within 40 - 60 kg/m³ until 11d due to low water levels (which were lower than 930 m). However, the water level increased to above 935 m since 12d, and the sediment concentration increment decreased to below 25 kg/m³. When the operation water level decreased to 230.77 m again in 17d, the sediment concentration increment increased to 43.6 kg/m³. Afterwards, the sediment concentration increment dropped to below 10kg/m³ quickly along with reservoir filling. During the 2nd dewatering erosion in 2018, the outflow sediment concentration increment was relatively small with the largest increment of 47.6 kg/m³ due to impact from the 1st erosion and the high operation water levels (the lowest one was 931.84 m).
Based on comparison with the outflow sediment concentration increment during the 2nd dewatering erosion in 2018, the 1st dewatering erosion in 2018 has better effect is due to three reasons: The first reason is favorable boundary conditions. Wanjiazhai Reservoir has mainly been subject to deposition since operation without long-time and low water level sediment flushing, and there was adequate sediment supply during reservoir erosion. The second reason is strong flow power. The average inflow discharge during open discharge sediment discharge was 1721 m³/s. The third reason is the long dewatering erosion duration. To be specific, the low water level sediment discharge duration was 20d, of which the reservoir operation water level in 8d was lower than 930 m.

6. Conclusions
(1) The Inflow and Outflow sediment amount of Wanjiazhai Reservoir in 2018 was 96.6 million t and 209.2 million t respectively, and the reservoir area erosion amount was 112.6 million t. Erosion was concentrated in August and September in the whole year, and concentrated in the elevation of 935 - 966 m.

(2) Wanjiazhai Reservoir Area had intense erosion due to twice sediment flushing in 2018, and there was 156.3 million m³ erosion amount below the elevation of 980 m in the flood season. The deposition morphology of the reservoir area changed obviously. The channel has been deepened and widened, accompanied by reservoir bank collapse.

(3) There is a negative correlation between the outflow sediment concentration and the reservoir water level of Wanjiazhai Reservoir under certain inflow runoff and sediment conditions and reservoir area landform. When the water level in front of the dam of Wanjiazhai Reservoir is higher than 966 m, the reservoir barely ejects sediment. When the operation water level is lower than 950 m, the outflow sediment concentration increases quickly.

(4) Extension of low water level sediment discharge duration is beneficial to tapping the reservoir erosion potentials and improving the reservoir erosion effect.

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