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Study on Siltation Characteristics Analysis in Key Reservoirs of Heavily Silt-Carrying Rivers

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Abstract:

Most of the rivers have a large amount of mud and sand in China. After the construction of reservoirs, the water flow will slow down. The sediment carried by the upstream water will settle, silt up the storage capacity and shorten the service life of reservoirs. Haibowan Reservoir in the main stream of the Yellow River is selected as the study area. This paper was based on the measured data of 37 underwater topographic sections and the hydrologic stations during the four years. It then systematically analyzed the sediment deposition and spatial distribution characteristics in the reservoir area since the operation of the reservoir by using the sediment transport balance method and the section method. The results show that: the water and sediment conditions of the downstream river changed significantly after the reservoir was put into operation in 2014, and the annual average sediment transport decreased from 109 million tons to 21 million tons. From 2014 to 2020, the accumulative sediment deposition of the reservoir area is 313 million tons, and the average sediment discharge ratio decreased greatly, from 68.97% (before the reservoir construction) to 20.10%. The siltation mainly occurs in the “damsite section” and “midstream” of the perennial backwater area, and it is mainly the horizontal siltation with U-shaped section. Both scour and siltation occur in the upper and lower reaches of the reservoir, and the morphology is basically V-shaped. In general, the longitudinal morphology of silting is zonal silting. The sand siltation at the end of the reservoir and the tailrace elevation are not obvious. Therefore, it is preliminarily inferred that there is excessive sand transport capacity at the end of the reservoir, which becomes the local erosion basis, and the whole reservoir will not have a uniform equilibrium decline trend. It is necessary to identify the siltation volume of the reservoir area and analyze the spatial distribution rules and the main influencing factors, because it lays a foundation for the water and sediment regulation and the manual siltation removal.

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***Keywords**: Sediment, Siltation distribution, Siltation morphology, Haibowan Reservior.*

I. INTRODUCTION

The Yellow River is the mother river of the Chinese nation, which breeds and shapes the splendid Chinese civilization. It is an ecological barrier and an important economic zone and energy base in the northern China. Ecological protection and high-quality development in the Yellow River Basin, which concerns the great rejuvenation and sustainable development of the Chinese nation, has become a national strategy. The Yellow River has less water and more sediment, and the relationship between water and sediment is not coordinated. It is famous for "being more likely to silt, breach the dyke and move" [1]. The problem of water and sediment changes has always been the focus and difficulty of the research, especially the silting shrinkage of the main channel in the downstream Yellow River as well as the elevation of the riverbed, forming "overhanging river". Hydro-junction project is one of the main measures to regulate the process of water and sediment reasonably, alleviate the silting and shrinkage of river channel, and reverse the unbalance trend of water and sediment. Along with the construction and operation of the backbone reservoir, a lot of sediment in the reservoir and even the silting waste of the reservoir capacity are caused while regulating the water and sediment distribution pattern and alleviating the accumulative deposition of the downstream river channel. For example, in the main stream of the Yellow River mainstream, Sanmenxia reservoir, Yanguoxia reservoir, Qingtongxia reservoir are forced to reconstruct because of the sediment accumulation [2]. Therefore, it is of great significance to study and analyze the sediment problem in reservoirs.

In recent years, researchers have conducted a lot of research about the reservoir sedimentation. For example, Li et al. [3], Zhang et al. [4], Hu et al. [5] conducted the in-depth study of the coordinative dispatch mode of water and sediment in the reservoir groups of the Yellow River. They created three basic patterns of water and sediment scheduling and developed the artificially-shaped density flow technology [6]. This, to some extent, has improved the present situation of reservoir sedimentation and gives full play to the reservoir development objectives. Jia et al. [7] and Sun et al. [8] analyzed the sedimentation process in the reservoir area by using the numerical simulation method. Li et al [9], Zhang et al.[10] conducted in-depth studies on sediment discharge methods such as traceability scour and density flow technology based on measured data and laboratory tests. Based on the prototype observation data, Sun et al [11], and Li et al [12] analyzed the variation characteristics about the water and sediment of the reservoir inflow, the reservoir operation and the siltation in corresponding reservoir areas. The above studies mainly focus on large river reservoirs (three Gorges reservoir, Xiaolangdi reservoir), but few systematically analyze the siltation problem of plain reservoirs. However, siltation is an important and key problem to be solved in the construction and operation of reservoirs, especially when reservoirs are built on heavily silt-carrying rivers.

This paper took the Haibowan reservoir as an example. Based on the measured data, this paper analyzed the characteristics of sedimentation in the reservoir area since the operation of the reservoir by using the water-sediment balance method and the section method. The characteristics include the amount of sedimentation, sediment discharge ratio, spatial distribution and velocity of sedimentation. This study is

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intended to provide support for the scientific and reasonable operation of Haibowan reservoir [12].

II. METHODS AND DATA

2.1 General Situation of the Research Area

Haibowan Reservoir, located at the head of the Inner Mongolia section of the Yellow River, is a large (2-type) plain reservoir which is used for ice prevention and power generation. The total reservoir capacity is 487 million m^3, the normal pool level is 1076.00m, and the dead water level is 1069.00m. The overall topography of Haibowan reservoir area is "narrow and steep at the top, wide and slow at the bottom". The backwater terminal is about 33 ~ 36km away from the dam site, and a total of 37 test sections were arranged with an interval of 0.8~1.0km. According to the section distribution location, the reservoir channel is divided into four sections: the front section of the dam (DM1-DM10), the midstream section of the reservoir (DM11-DM20), the upstream section of the reservoir (DM21-DM30) and the bottom section of the reservoir (DM31-DM37). The general situation of the research area and the section layout of the reservoir are shown in Figure 1.

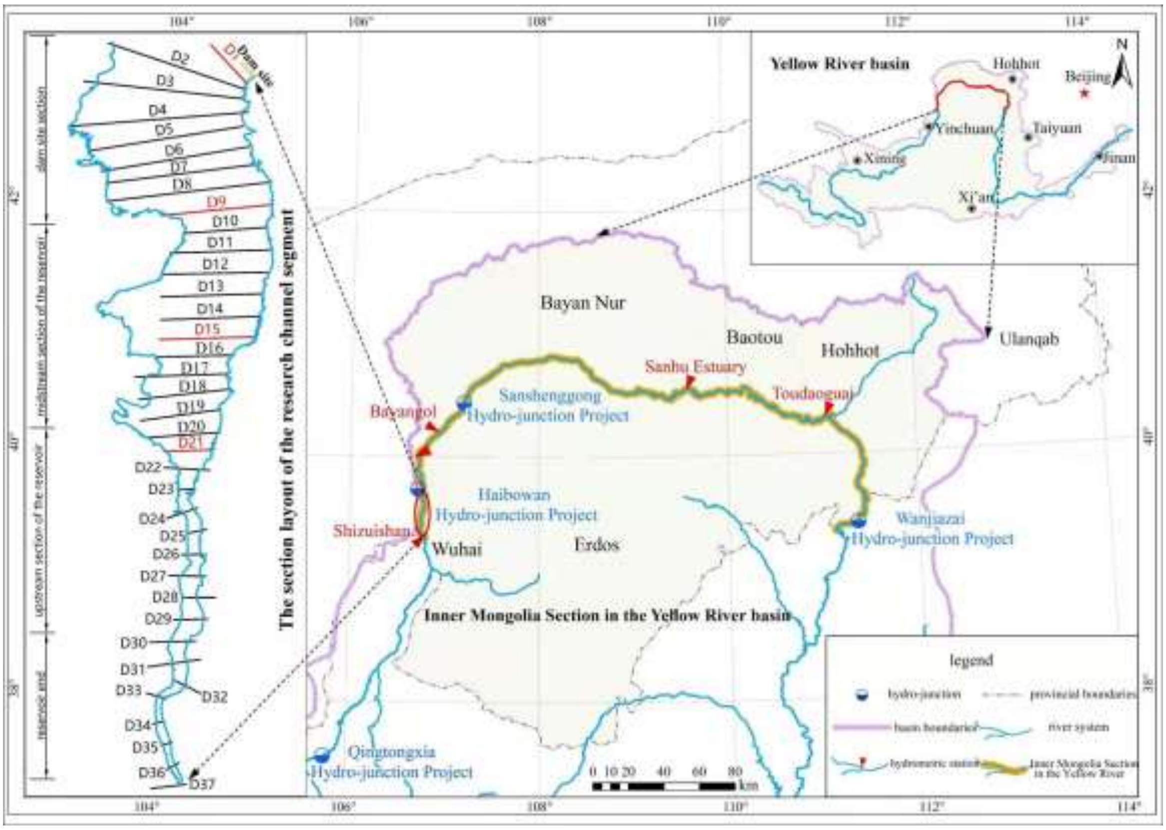

Fig 1: General situation of the research area and the section layout of the reservoir

2.2 Data Sources

The runoff volume and sediment runoff data of Shizuishan station (inflow), Dengkou (No.2) Station (outflow) and Bayangol station (downstream river channel) are obtained from the hydrology yearbook of the People's Republic of China (Vol. 4).

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The topographic data of the reservoir area are collected from the measured data of 37 laid-out sections in the prototype observation and analysis report of the sediment in Haibowan Reservoir area (see Figure 1 for their distribution locations).

2.3 Research Methods

The sediment balance method and the section topography method are two main methods to analyze the sediment scour and silting changes. In this paper, the spatial and temporal distribution characteristics of the siltation in Haibowan reservoir area were analyzed in depth with the complementation of the two methods [13]. The sediment balance method is mainly based on the measured sectional sediment runoff, and the sediment balance principle is used to calculate the scour and silting volume, which can intuitively reflect the water and sediment movement law within a relatively short time. The section method is to analyze the temporal and spatial distribution characteristics of the siltation at different stages by using the measured data of large sections.

2.3.1 Siltation calculation of the reservoir area

Based on the measured sediment data of the hydrology station, and the amount of the extracted and imported sediment in the study area is also considered. The sediment transport balance method (Formula 1) was used to calculate the sedimentation volume in the reservoir area. The calculation formula is as follows:

$$\triangle W_S = W_{IN} + W_{IM} - W_{OUT} - W_{EXT} \tag{1}$$

In the formula:

$\triangle W_S$—siltation volume of the reservoir area
W_{IN}—inflow sediment runoff
W_{IM}—Imported sediment runoff from tributaries between reservoir areas
W_{OUT}—outflow sediment runoff
W_{EXT}—Extracted sediment runoff from tributaries between reservoir areas

2.3.2 Siltation on-way analysis of the reservoir area

Based on the annual topographic data of 37 sections in the reservoir area, the distribution and morphology characteristics of the silting in the reservoir area were analyzed in this paper. The section data include two parts: the shore part and the underwater part. The starting distance and elevation of the shore part were measured by the dynamic CORS-RTK technique. Part of the shallow water area and the deep-water area were measured by the depth sounding rod and the multi-beam depth sounding instrument, respectively. Meanwhile, the digital elevation models of the reservoir area in 2016 and 2020 were established. With the inundation line of the reservoir area as the boundary, the kriging method was used to interpolate the common Kriging method. The average weighted value of the measured data of the section was used to estimate the values of the unknown points on the siltation plane of the reservoir area, and the distribution changes of the siltation plane were analyzed.

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III. RESULTS AND ANALYSIS

3.1 Water and Sediment Characteristics Analysis

The reservoir construction breaks the natural state of water and sediment in the river [14] and changes the constitutive relationship of the sand-carrying flow [15]. This paper takes the construction and operation time of Liujixia, Longyangxia and Haibowan reservoirs in the upper reaches of the Yellow River (Year 1968, 1986 and 2014) as nodes. The water and sediment data of Shizuishan in the upper reaches of Haibowan Reservoir and Bayangol hydrological station in the lower reaches of Haibowan Reservoir were divided into four periods: natural runoff period (before 1968), single reservoir operation period (1968-1986), operation period of the above two reservoirs (1987-2013) and the operation period of multiple reservoirs (2014-2020). After that, this paper studied the influence of the combined operation of cascade reservoirs on the variation characteristics of inflow water and sediment as well as the water and sediment characteristics of the downstream river.

According to the historical process lines of the annual runoff and sediment runoff at Shizuishan and Bayangol stations from 1951 to 2020 (Fig. 2 and 3), the variation trends of annual runoff and sediment runoff were basically the same under the influence of water storage and sediment blocking in upstream reservoirs. According to the construction and operation time of each reservoir, the characteristics of water and sediment indicators in the above four periods were recorded, as shown in Table I (non-flood season: November to June of the next year, flood season: July to October, and the years of operation are non-flood season and flood season).

It can be seen from Figure 2, Figure 3 and Table I that: after 1968, with the completion and operation of the reservoir, the annual runoff and sediment runoff of Shizuishan hydrological station basically showed a decreasing trend, and the effect of storing and retaining water and sediment was more significant in the flood season. The variation characteristics of water and sediment at Bayangaole station and Shizuishan station were basically the same. However, compared with Shizuishan station, the sediment runoff at Bayangaole station decreased significantly during the same period from 2014 to 2020. The main reason is that: after the operation of Haibowan reservoir, the inflow water got regulated. A large amount of siltation was deposited in the reservoir, which reduced the sediment runoff to the downstream river.

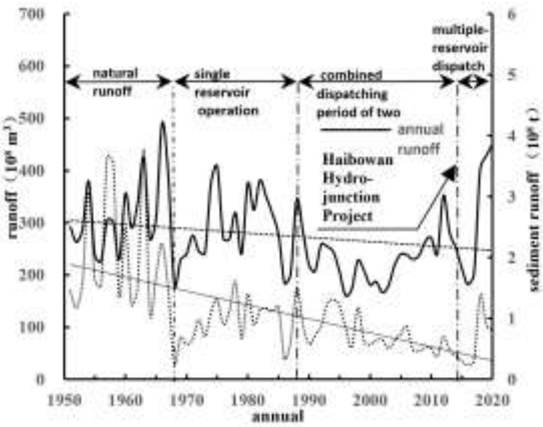

Fig 2: Water and sediment condition changes at Shizuishan station from 1951-2020

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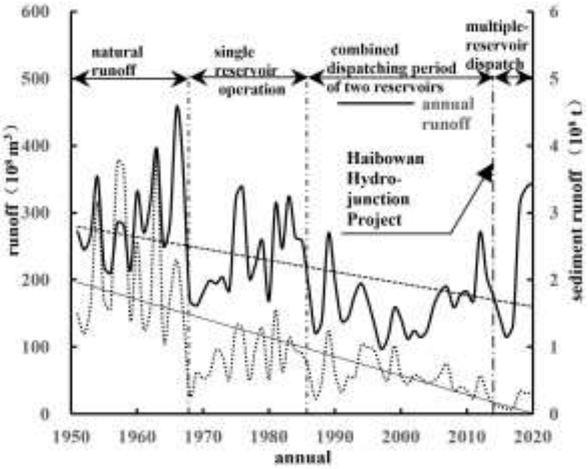

Fig 3: Water and sediment condition changes at Bayangol station from 1951-2020

TABLE I. Characteristic values of water and sediment volume at Shizuishan station and Bayangol station

hydrometric station	periods (years)	average runoff volume /100 million m^3			average sediment runoff /100 million t			flood season percentage/%	
		flood season	non-flood season	full year	flood season	non-flood season	full year	average runoff volume	average sediment runoff
Shizuishan	1951-1968	201	119	320	1.62	0.42	2.04	62.86	79.59
	1969-1986	159	136	295	0.69	0.28	0.97	53.77	71.54
	1969-1986	120	110	230	0.61	0.31	0.92	52.17	66.30
	1969-1986	178	190	368	0.41	0.21	0.62	48.37	66.13
Bayangol	1951-1968	180	108	288	1.62	0.31	1.93	62.50	83.94
	1969-1986	125	110	235	0.63	0.22	0.85	53.19	74.12
	1969-1986	68	117	185	0.22	0.28	0.50	42.16	56.00
	1969-1986	97	106	203	0.13	0.08	0.21	47.78	52.38

3.2 Siltation Characteristics

3.2.1 Siltation volume and sediment discharge ratio

According to the field survey, there are 53 agricultural and industrial water intakes in Haibowan

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Reservoir area, with an average annual water diversion volume of 188 million m3. The water diversion is accompanied by sediment diversion, and the average annual sediment diversion volume is 0.001 billion t (the average sediment concentration of Shizuishan station is 3.42kg/m3). Meanwhile, as the reservoir runs, the riverbed silts up and the reservoir capacity decreases year by year. In 2020, the reservoir capacity only accounted for 40% of the original reservoir capacity (487 million m3), which greatly reduces the function, safety and comprehensive benefits of the reservoir. Based on this, in April 2020, the reservoir management unit adopted the cutter suction dredger and the shipborne hydraulic facilities to carry out manual silting. The silting amount was 18 million m3 (about 24 million t), and the silting volume of the reservoir area was calculated according to the sand diversion meter. After considering the above factors, the operation time of Haibowan Reservoir was taken as the node, and this paper calculated the silting volume and the silting discharge ratio during two periods 2007- 2013 (before the reservoir construction) and 2014-2020 (after the reservoir construction), as shown in Fig. 4.

Before Haibowan Reservoir was constructed, the total siltation volume of the channel segment was 117 million tons, the average annual siltation volume was 17 million tons, and the average sediment discharge ratio was 68.97%. After Haibowan Reservoir was completed (2014-2020), the total siltation volume was 313 million tons, and the average annual silting volume is 45 million tons, about 2.6 times of that before the construction of the reservoir, and the average sediment discharge ratio was 20.10%, only 1/3 of that before the construction of the reservoir. The results show that: since the filling of Haibowan Reservoir in 2014, the upstream sediment was mostly intercepted in the reservoir, and the sediment runoff of the downstream river got significantly reduced. Meanwhile, the sediment discharge ratio in 2020 (42.16%) was higher than that in other years since the operation of the reservoir, mainly because the reservoir management units carried out water and sediment dispatching and the manual siltation removal this year.

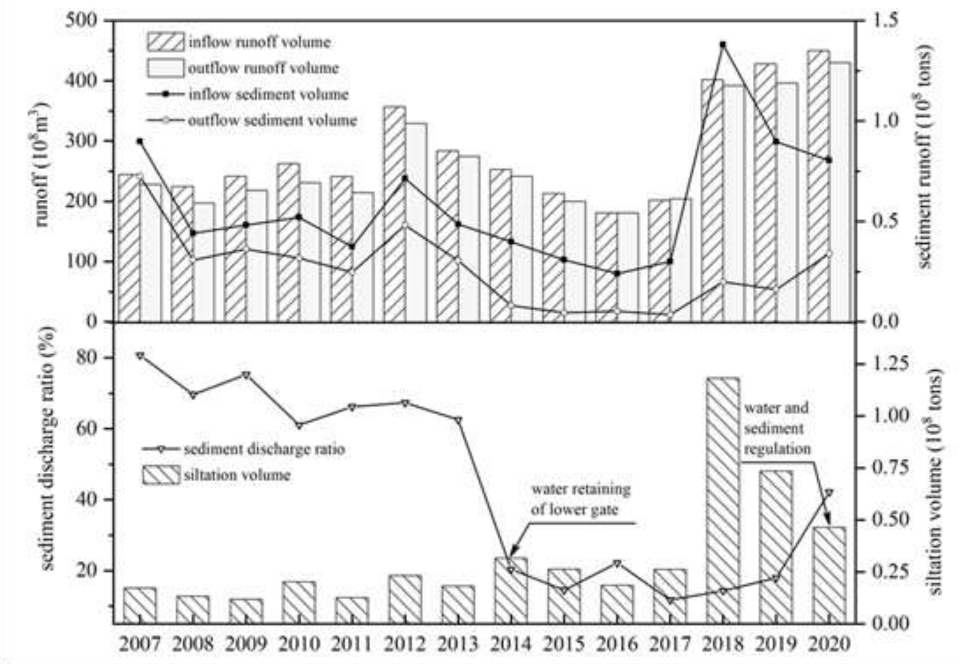

Fig 4: Inflow and outflow water and sediment conditions, siltation volume and sediment discharge ratio of Haibowan Reservoir over the years

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3.2.2 Spatial distribution of siltation in the reservoir area

Generally speaking, the siltation in Haibowan reservoir area is mainly distributed in the "dam site section" and "midstream section of the reservoir" in the perennial backwater area. It is characterized by the basic siltation in the whole section and local scour. However, there are scouring and silting in the upper and lower reaches of the reservoir, and no accumulative silting is found, and the silting is mainly in the main channel. The on-way distribution of siltation in the reservoir in different periods is shown in Fig. 5, and the topographic changes of the typical sections are shown in Fig. 6.

It can be seen from Figure 5 that: the siltation was concentrated in the dam site and the midstream section of the reservoir from 2014 to 2020, mainly because of the influence of the reservoir topography. The front and middle reaches of the dam have wide sections and the gradient dropped relatively slowly. Influenced by the elevation of the water level in the front of the dam, the sediment is likely to silt, while the scour and silting at the end of the reservoir are basically balanced, with little variation in the section morphology, and it is relatively stable. In 2020, the manual silting was carried out from DM18 to DM20 in the reservoir, and the silting volume was significantly reduced compared with that before silting (from 2014 to 2019), indicating that manual silting is of great significance for improving the silting.

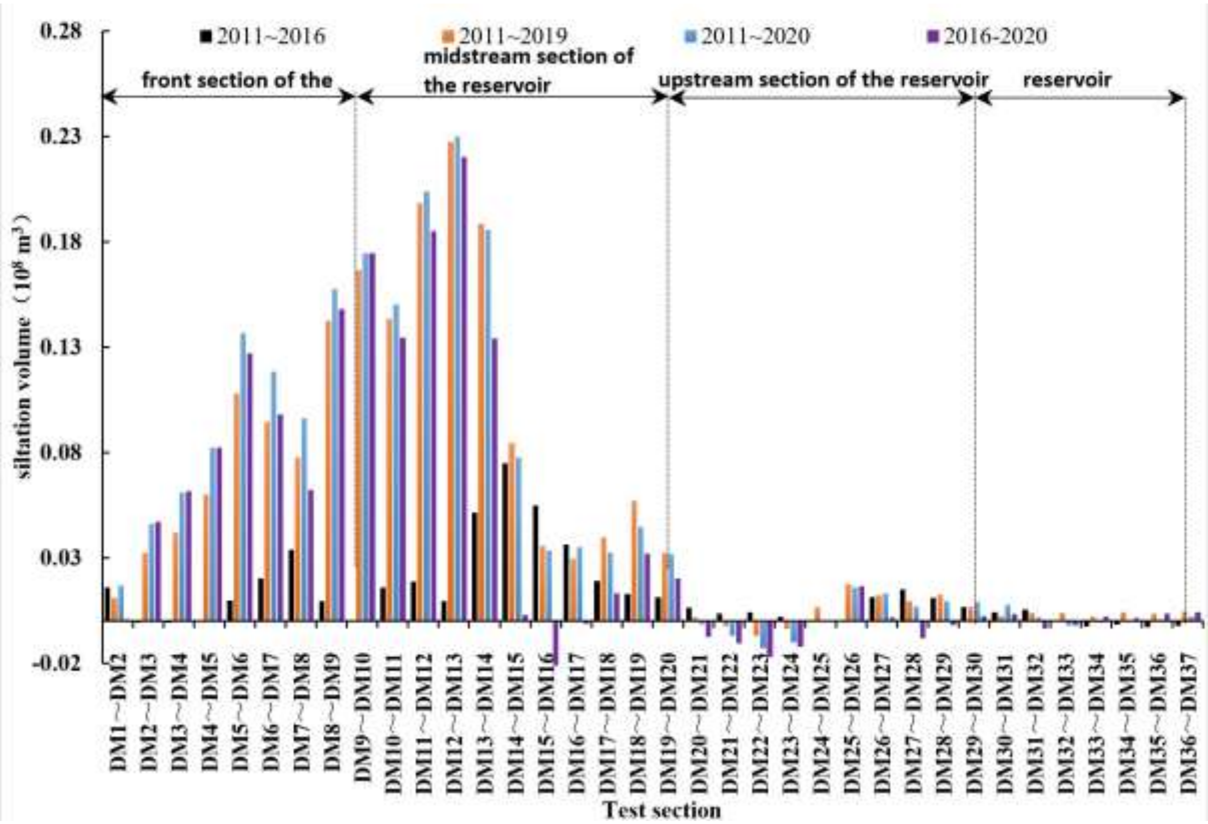

Fig 5: Spatial distribution of siltation in Haibowan Reservoir area

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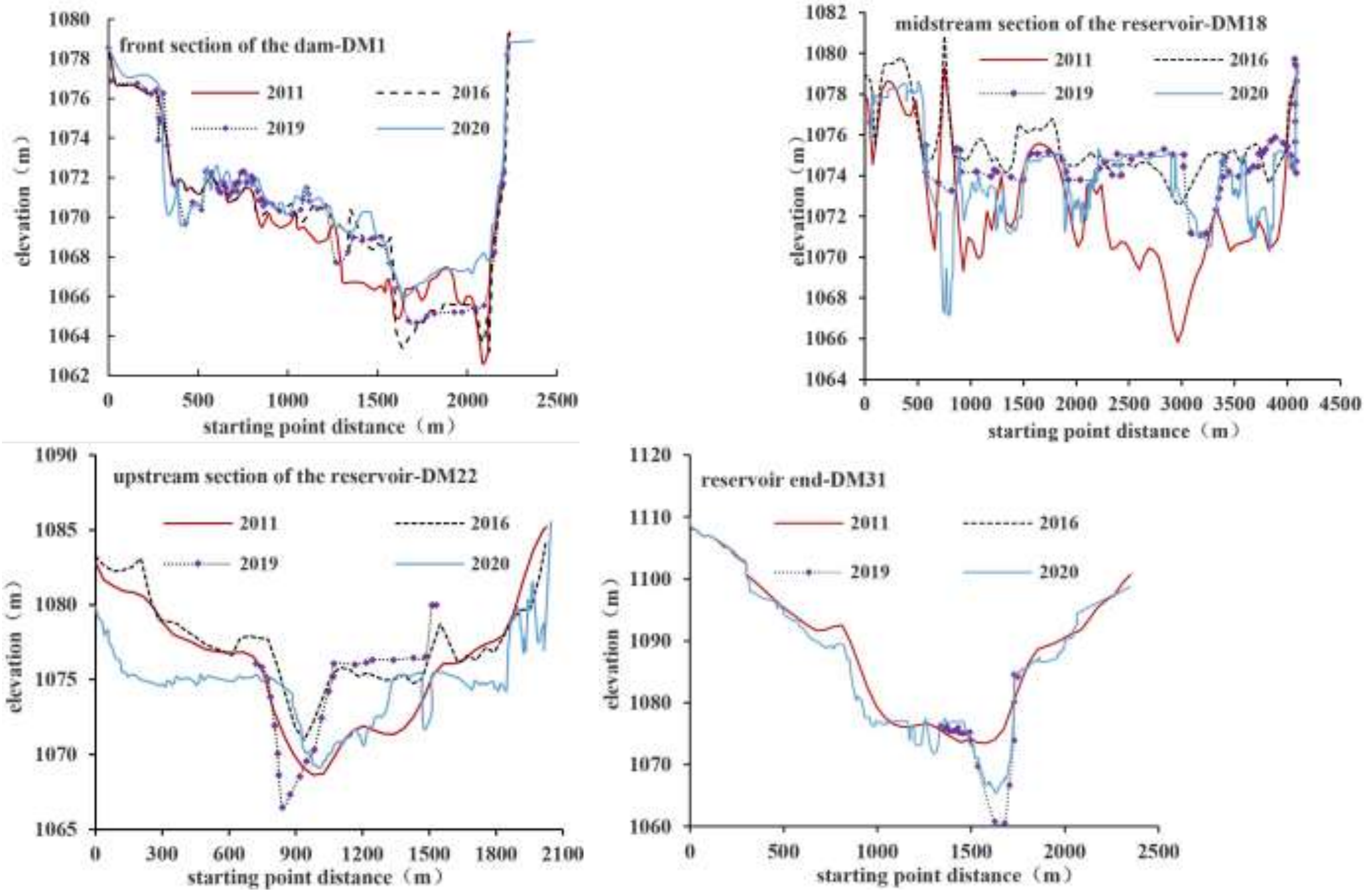

Fig 6: Typographic changes of the typical sections in Haibowan Reservoir (2014-2020)

3.2.3 Siltation speed

The siltation speed is the siltation volume per unit time, and the unit of the time scale is year [12]. According to the analysis and statistics, the siltation volume of Haibowan Reservoir presented an overall increasing trend, but the siltation speed is different in different reservoir sections due to the impact of the reservoir topography. The siltation speed of each reservoir section is shown in Fig. 7.

As can be seen from Figure. 7, the siltation speed in each reservoir section of Haibowan Reservoir tended to decrease from 2014 to 2020. After the reservoir impoundment in 2014, the elevation of water level caused a rapid decrease in sediment carrying capacity. A lot of siltation dropped in the whole reservoir section and the siltation speed rose quickly. After 2019, the variation of water level was relatively small, and the sediment carrying capacity of the water flow did not change much. The siltation rate showed a slowing trend. Meanwhile, the siltation speed of the dam site section is the highest compared with the other three reservoir sections. The main reasons are as follows: the dam site section is wide, the water level in the front of the dam increases the most, the flow speed and the sediment carrying capacity decreases greatly. The siltation dropped greatly with a relatively high speed.

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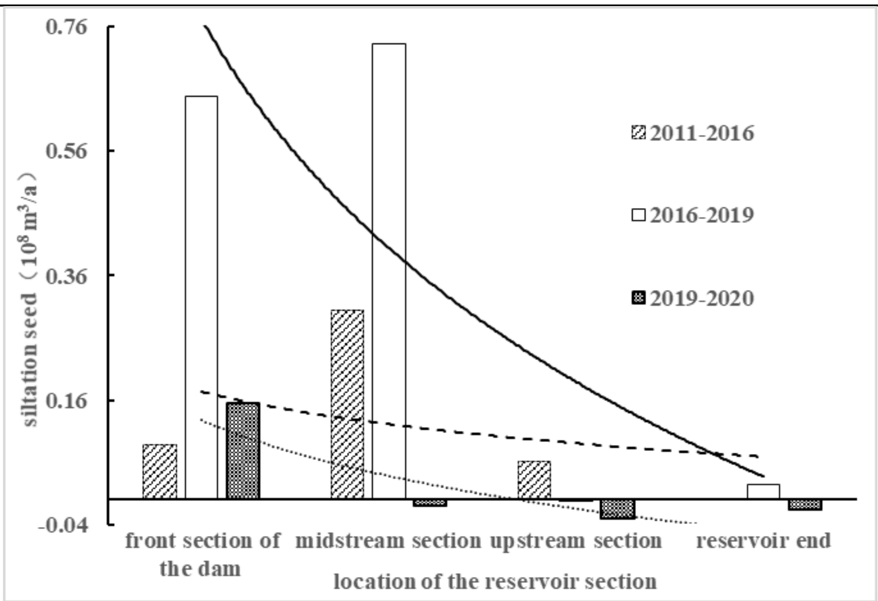

Fig 7: Siltation speed changes of Haibowan reservoir area (2014-2020)

3.2.4 Siltation morphology of the reservoir area

(1) Horizontal morphology analysis of the reservoir area

Based on the measured data of 37 sections in the reservoir area, with the starting point distance (distance from the left bank) as the horizontal ordinate and the river bottom elevation as the ordinates, the measured topographic elevation changes from 2014 to 2020 were plotted and their morphological distribution characteristics were analyzed. Four typical sections were selected for the analysis (see Fig. 8)

The dam site section (section DM9) and the midstream section of the reservoir (section DM15): the siltation morphology is mainly U-shaped, and the whole section is basically silted with local scouring. From 2014 to 2016, the dam site was mainly composed of silting channels with an average silting thickness of 1.47m. From 2016 to 2020, the dam site was mainly the horizontal siltation with a thickness of 3.20m. From 2014 to 2020, the middle reaches of the reservoir were dominated by horizontal siltation, with an average siltation thickness of 4.07m, and the main channel gradually disappeared. The main reason is that the dam site section and the middle reaches of the reservoir have open topography and wide sections. Moreover, the natural ratio dropped and the water flow got scattered at a low speed. Also, the average vertical flow speed was evenly distributed along the river, and the siltation happened in the sections of the river bed.

The upstream section of the reservoir (section DM21): The morphology of the sectional siltation is mainly V-shaped, and the sediment is mainly deposited in the main channel. From 2014 to 2019, the upstream section of the reservoir was mainly composed of silting channels. When the main channel silted to a certain extent, the water flow broke through the beach lip, and the main channel oscillated and began to silt in the adjacent low-lying areas. After 2019, the location of the main channel was basically stable, the section scouring and silting occurred in the hair trough, and the morphology of the swale was stable. The

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main reasons are as follows: The upstream section of the reservoir has a narrow section and the main channel has a lot of sediment. In addition, the gradient was coarse and was unevenly distributed along the section. The silt-carrying capacity was oversaturated, so the sediment content of the section was greater than its silt-carrying capacity and the main channel got silted.

At the end of the reservoir (section DM31): the siltation morphology of the section is basically the same as that of the upstream section of the reservoir, and it is mainly V-shaped. The siltation is mainly deposited in the main channel. As years 2018 and 2019 are the high flow year continuously and three heavy floods broke out in 2008, the scouring capacity was enhanced under the influence of the incoming water and sediment from the upstream. As a result, the main channel of this section was scoured from 2016 to 2019, with the maximum cutting depth of 4.5m.

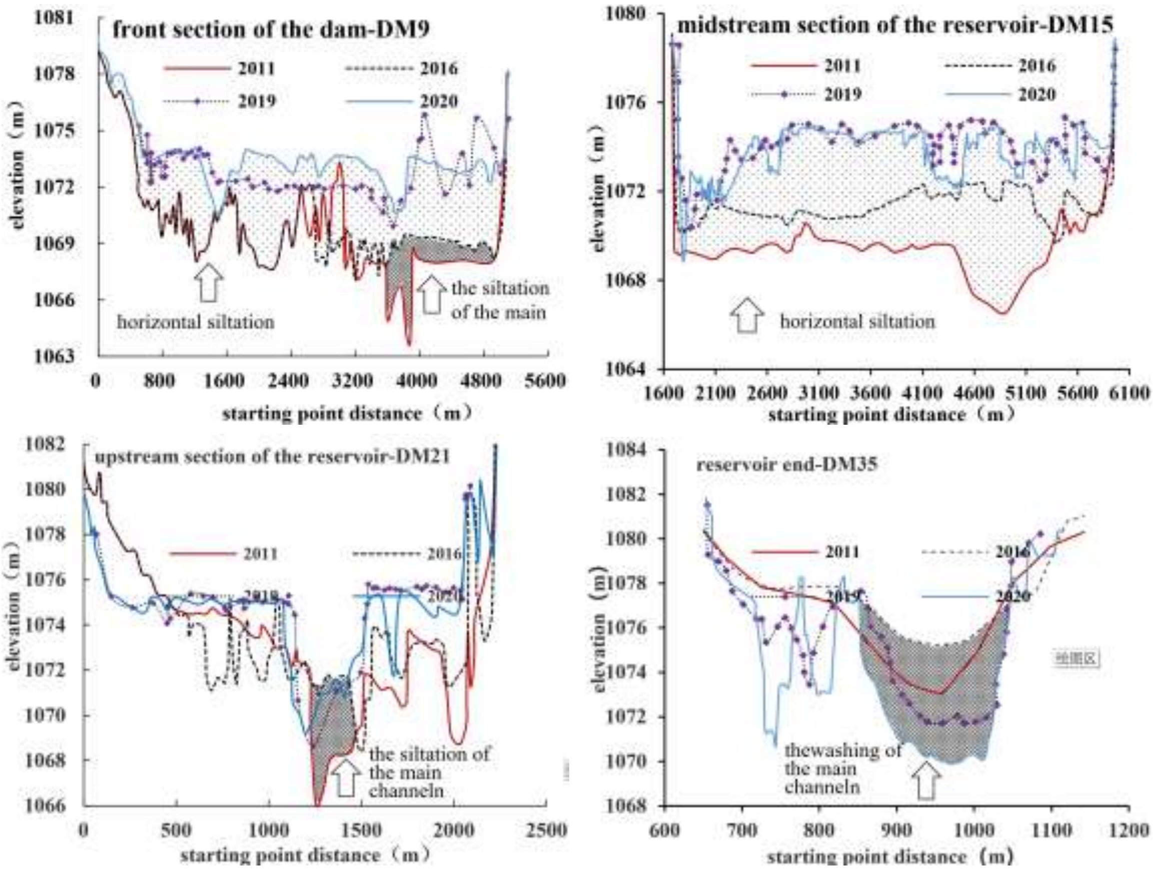

Fig 8: Typical cross-sectional plotting of the reservoir

(2) Longitudinal morphology analysis of the reservoir area

In general, the characteristics of the sediment movement in the reservoir area are determined by the conditions of incoming water and sediment, the changes of water level in the front of the dam, the e reservoir dispatch mode and the terrain conditions [16]. It is reliable to analyze the evolution law of the scouring and silting in the reservoir area by using the increase and reduction of the thalweg elevation. The longitudinal siltation morphology of Haibowan Reservoir is shown in Fig. 9.

It can be seen from Figure. 9 that: the longitudinal profile was in the form of banded siltation during the early period of the reservoir operation, and the elevation level of the thalweg point rose by 1.87m in the

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whole reservoir area. It was mainly because the empty reservoir retained the sediment in the early period of the reservoir operation, and the elevation of the water level in the front of the dam made the siltation evenly distributed along the process. In 2019-2020, the vertical profile showed a zigzag siltation pattern, and it was mainly affected by the upstream runoff and sediment, reservoir operation and dispatching mode, and topographic conditions.

Dam site section: From 2014 to 2016, the elevation of the thalweg point showed a horizontal rise, with an average increase of 1.09m. From 2016 to 2020, the elevation increased significantly, with a level increase of 3.57m. The main reasons are as follows: the reservoir adopted the operation mode of “storing water and blocking sediment”, the terrain in this section was open with a slow water flow, and the siltation was likely to occur. From 2019 to 2020, as the upstream inflow and sediment increased, the water level in the front of the dam increased and the siltation thickness increased.

In the midstream section of the reservoir: the elevation of the thalweg point was basically the same as that of the dam site from 2014 to 2019, and the elevation was 4.75m. The cross section had a large discharge area, but it was low in silt-carrying capacity and the siltation was likely to happen. Due to the manual dredging in this section in 2020, the elevation of the thalweg point got drastically adjusted with a large variation range, and the maximum cutting depth is about 6.71m.

In the upstream section of the reservoir: Similarly, the elevation of the thalweg point horizontally increased by 2.58m from 2014 to 2016. From 2016 to 2020, the elevation of the thalweg point showed an undercutting trend, with a depth of about 1.59m, and only a small amount of local uplift occurred, which was mainly caused by the increase of the upstream runoff and sediment in this period.

At the end of the reservoir: From 2014 to 2016, the elevation changes of the thalweg point were consistent with those of the upper reaches of the reservoir, and the level increased by 0.98m. In 2019, the elevation of the thalweg point showed an undercutting trend, but the end of the reservoir tail lock (28.17Km-31.00 Km) was in the siltation equilibrium state. In 2020, water and sediment regulation was carried out in this reservoir, resulting in the significant downcutting at the end of the reservoir tail lock. It was lower than the original state in 2014.

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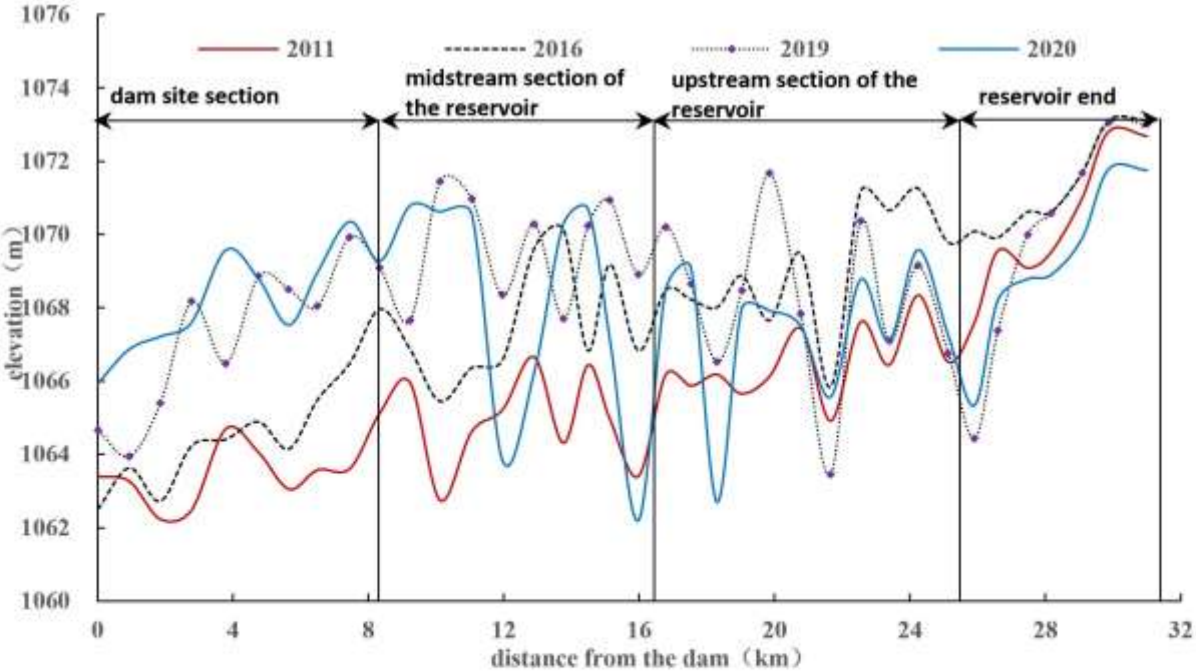

Fig 9: Thalweg profile change diagram of Haibowan Reservoir

IV. DISCUSSION

Sediment transport balance method, section method, gridding topography method, mathematical model and empirical formula are generally used to study the scouring and silting changes in the reach. Sediment balance method is based on the time scale and it can better analyze the variation law of the siltation volume in the time interval. Li [12] and An et al [13] used this method to calculate and analyze the scouring and siltation volume of the Three Gorges Reservoir area and Mingmeng Reach of the Yellow River in different periods. Based on the measured hydrological data, this paper fully considered the influence of agricultural irrigation, industrial water diversion and human activities (sand excavation of the river channel and manual dredging) on the siltation in the reservoir area, and analyzed the siltation volume and sediment discharge ratio before and after operation of Haibowan Reservoir from 2007 to 2013 and from 2014 to 2020 by using the sediment transport balance method. The results show that: after the operation of Haibowan reservoir, the average sediment discharge ratio and the downstream runoff decreased significantly. It effectively alleviated the siltation of the river bed and improved the flood discharge capacity. Because the left shore at the dam site section of HaiBoWan reservoir is near Ulanbuh desert, and it is the typical region where the desert and rivers evolve interactively. The reservoir siltation is influenced not only by the upstream water and sediment but also by the aeolian sand. However, it can be seen from the plane distribution of the reservoir siltation from 2014-2020 (Fig. 10) that: the siltation was serious in the right shore of the dam site and the silting thickness ranged from 3.43m to 5.33 m. However, the siltation depth of the left shore ranged from 1.54m to 2.48m. The siltation was slight, accounting for a small proportion of the total siltation volume in the whole reservoir area. It can be indirectly inferred that the siltation volume in the reservoir area is slightly affected by the aeolian sand. Meanwhile, the empirical value is mostly used for calculation

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in the research of the inflow sand blown by the wind currently. In order to analyze the influence of the sand blown by the wind on Haibowan Reservoir more accurately, the research can be conducted in the following aspects: the dust emissions, the material composition of sand, structure of sand driving wind, and sand dune movement law of Ulanbuh desert, which provides the basis for the research of the inflow sand-driving sand.

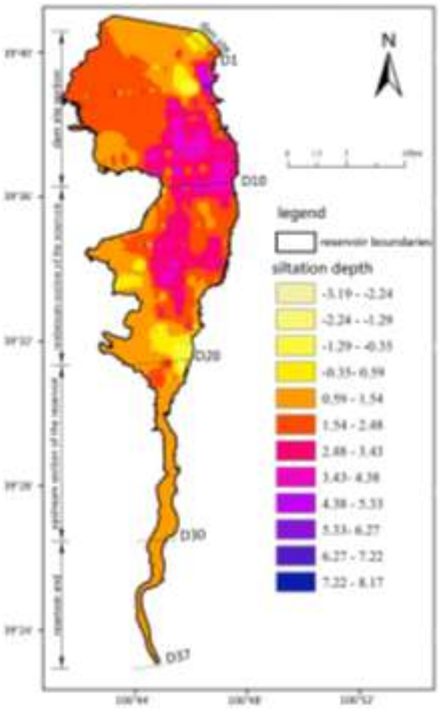

Fig 10: River bed scouring and silting changes of Haibowan Reservoir (2014-2020)

(2) The longitudinal silting morphology of the reservoir area includes delta silting, conical silting and ribbon silting. Wu et al. [17] studied the variation law of siltation morphology in different operation periods of the reservoir based on years of measured data of Sanmenxia Reservoir. Wang et al. [18] proposed that the siltation morphology of Xiaolangdi Reservoir was not fixed, but they can be mutually transformed by analyzing the siltation morphology of Xiaolangdi Reservoir in different periods. Based on the measured data of 37 sections, this paper systematically analyzed the siltation distribution characteristics in Haibowan reservoir area. The siltation is mainly distributed in the dam site section and the midstream section of the reservoir, and there is no cumulative siltation in the upstream section and the end section of the reservoir. In general, the longitudinal morphology of siltation is ribbon siltation, which was consistent with the research conclusion from Wei et al. [19]. Because when the section method was used to analyze the change characteristics of scouring and silting, it was easily influenced by the selection and spacing of cross sections. Zhang et al. [20] established the remote sensing inversion models of water depth and different bands by using the satellite remote sensing data, and then they obtained the topographic characteristics of the reservoir in different periods, laying a certain foundation for the future research.

(3) In 2020, combined with the characteristics of the reservoir, the reservoir management unit fully considered the floods and their changes in the high flow year, the normal flow year and the low flow year

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in the process of incoming water and sediment. The operation mode of "retaining clear water and regulating siltation" was adopted, and the regulation plan was formulated as follows: the siltation is discharged in the flood season and the siltation is regulated in the normal flow year. The results showed that: compared with the average sediment discharge ratio from 2014 to 2019, the sediment discharge ratio increased by 8.63%, which effectively alleviated the silting loss of the reservoir capacity and provided a solid foundation for transferring water and sediment regulation from experiment to production practice in the future. At present, the main water and sediment regulation methods adopted in China are "retaining clear water and discharging siltation" and "retaining clear water and regulating siltation", etc. Management units can further verify and improve the theory and design technology of "retaining clear water and regulating siltation" according to the actual operation situation of the reservoir area, and this optimized the regulation method and reduced the siltation in the reservoir area.

(4) In 2020, the reservoir management units combined the water and sediment regulation with the manual dredging. In the midstream and terminal sections of the reservoir, 024 million t of siltation was dredged by using the cutter-suction dredger, which further reduced the siltation loss of the reservoir capacity and adjusted the siltation morphology of the reservoir. However, a lot of stockpiled sediment not only caused a huge waste of limited land resources but also brought about the serious ecological environment and safety problems after dredging. At present, a lot of researches have been conducted on this issue, and multiple methods for the efficient sediment utilization has been put forward, including engineering material application, land improvement and land creation, river channel flood control and treatment, etc.[21], which provided certain scientific basis and technical reference for the reservoir management units to carry out the reasonable disposal and resource utilization of siltation.

V. CONCLUSIONS

Based on the measured data, this paper analyzed the siltation volume, the sediment discharge ratio and the spatial distribution characteristics of siltation morphology in the reservoir area by means of sediment transport balance method and section method. It is of certain guiding significance for water and sediment regulation of Haibowan reservoir.

(1) Since the operation of Haibowan Reservoir in 2014, the siltation volume in the reservoir area has shown an increasing trend under the influence of the water level in the front of the dam and the inflow sediment volume. The cumulative siltation volume has reached 313 million tons, which is half of the total storage capacity, and it is far greater than the dead storage capacity (56 million tons). This poses a threat to the functions of the reservoir area such as ice prevention and power generation. Working out the siltation volume of the reservoir area provides scientific support for the reservoir management unit to adjust the operation mode.

(2) The general characteristics of the silting distribution in the reservoir are as follows: the silting is ribbon silting vertically, and it is mainly distributed in "dam site section" and "midstream section of the reservoir", and there is no cumulative silting in "midstream and terminal section of the reservoir". The cumulative length of silting reaches accounts for 1/3 of the total length of the reservoir, and the silting

volume accounts for more than 85% of the total silting volume of the reservoir. The identification of the siltation characteristics and spatial distribution in reservoir area is the premise and basis for scientifically putting forward the feasible water and sediment control and the manual dredging measures.

(3) In 2020, the reservoir management unit realized the integrated and comprehensive treatment of river channels and beach area by using measures like manual dredging and the water and sediment regulation. The sand discharge ratio increased by 25.29% compared with that in 2014-2019. It effectively alleviated the silting loss of storage capacity. According to the calculation of the reservoir silting volume and its distribution characteristics, the manual dredging should be carried out regularly in the dam site section and the midstream section of the reservoir. When the inflow sediment concentration is high and the silt-carrying volume of the water flow is concentrated in the reservoir, the operating water level is strictly controlled and the dispatching mode of “retaining clear water and regulating siltation” is optimized.

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