Siltation and Desilting Practices in A Runoff Reservoir on Heavy Sediment-Laden River

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Abstract. Sediment deposition in the reservoir of run-of-the-river power station is severe, in this paper we take upper Marsyangdi reservoir as an example to analyze sedimentation and desilting process according field data measured from September 2016 when the reservoir had just been impounded in order to find strategy for managing reservoir sedimentation. The ratio of Upper Marsyangdi reservoir capacity and volume of sediment into the reservoir is about 0.2. The reservoir arrived silt-stable in a year after impoundment with a depth of 12m deposition at the dam site. Most of sediment deposit in the periods that at the initial and the end of flood reason and it is found the flow rate is the key factor influencing trap efficiency because that due to damming velocity of medium flow decreased significantly compared to natural condition which caused numerous deposition. Based on result of analysis of deposition the desilting condition is determined. Empty flushing is proposed to release deposition after flood season when flow rate is greater than 100m³/s and the new capacity will last to next flood season. In order to reduce sediment concentration into diversion channel a desilting should be done in flood season when flow rate is larger than 200m³/s and flow rate for impound should not be more than 1/10 of that into reservoir which can avoid deposition during impoundment near dam site.

1 Research background

It is usually necessary to build reservoirs in order to generate electricity in hydropower stations. However, during the process of reserving river water, reservoirs also intercept large amounts of sediment. According to the statistical data of 2001, the annual average amount of silt in the world's larger reservoirs accounted for 0.5% to 1% of the reservoirs' remaining storage capacities^[1]. These sediment accumulations not only occupy large amounts of the storage capacities, but also cause abrasions to the turbine blades of the hydropower stations^[2, 3]. Therefore, the reservoirs which have been constructed on sandy rivers generally have larger capacities, in order to include sufficient space for containing silt and siltation, and to reduce deposition by reservoir regulation for the purpose of maintaining the long-term operations of both the reservoirs and the power stations^[4]. However, due to limited development conditions, some runoff power plants have been gradually constructed on sandy rivers in recent years. For these power plant reservoirs, silt and sediment can be easily deposited, which have negative effects on the normal operations of the power stations. The existing research findings have mainly focused on the siltation processes and treatment measures of large reservoirs^[5-10]. At the current time, studies regarding the siltation processes and causes of silt accumulations in the runoff power station reservoirs are lacking. The Upper Marsyangdi Power Plant in Nepal is a typical runoff power plant located on a sandy river. Since its completion,

sediment and silt deposits have rapidly accumulated in the reservoir area. In this research study, the actual measured water and sediment data from the Marsyangdi Power Plant were used for analyzing the processes and causes of the siltation in the reservoir. The key factors affecting the siltation processes were determined, and desilting suggestions for this particular reservoir were proposed according to the analysis results.

The Upper Marsyangdi Reservoir is located in the upper reaches of the Marsyangdi River of Nepal. The normal water level is 902.25. The back-water height at the front of the dam is approximately 14 m. The total storage capacity under normal water level conditions is approximately 500,000 m³. The reservoir barrage is located on the Marsyangdi River. The Nardi River flows as a tributary to the Marsyangdi River at an upstream position 150 m from the dam. In September of 2016, the Marsyangdi Power Station had begun to officially store water and started to generating power. Also, a systematic observation of the sediment transport in the reservoir was carried out from March 27, 2017 to November 20, 2017, in order to obtain comparatively complete data of the landforms; water; silt and sediment; reservoir inflow process; sediment concentration process; sediment grading; and water levels in front of the dam. The measured section position is shown in Fig. 1.

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Figure 1. Cross-sectional position.

2 Inflowing water and silt and the reservoir siltation process

Fig. 2 shows the actual measured water and silt processes of the main stream of the Marsyangdi River and its tributary, the Nardi River. The water and sediment coming into the Upper Marsyangdi Reservoir was mainly concentrated in the months of June to September. The amount of water and silt resulting from the flood season accounted for over 90% of the annual volume. The annual runoff of the main stream was approximately 3 billion m^3 , and the tributary runoff was approximately 300 million m^3 . Also, the tributary flow was determined to be approximately 1/10 that of the main stream. The main silt source of the reservoir originated from the main stream flow, while the silt content of the tributary river was nearly zero. The total amount of suspended sediment in the river during the measured period was approximately 2.969 million tons, and the average monthly incoming silt was approximately 2500 tons during the non-flooding periods. Furthermore, the actually measured data of the four-month period of this study showed practically no silt amounts during the non-flood period, with an annual incoming silt amount determined to be approximately 2.98 million tons.

Figure 2. Water and sediment flow processes in the reservoir.

From the viewpoints of the longitudinal sections and typical cross-sections of the siltation, it was found that after one year of operation (November 16th, 2017), the siltation elevation in front of the dam was approximately 900 m, and the siltation thickness had reached 11 to 12 m. The delta dam head had reached the front of the dam, and the reservoir area had basically reached a balanced siltation level. From the perspective of siltation processes, the reservoir siltation was determined to be concentrated between June 5th to July 7th, and August 29th to November 16th. In other words, the siltation was concentrated at the beginning and end of the flood season. The longitudinal sections and typical cross-sections before and after the siltation are shown in Figs. 3 and 4, respectively. The

siltation elevation reductions in front of the dam were measured in-situ on the longitudinal sections on November 20, 2017. The reductions were caused by an open out-flowing flushing process which had been implemented to remove the silt accumulations during the period from November 16th to 18th of 2017. The affected area at the time of the silt removal had reached 600 m upstream of the dam.

Figure 3. Comparison of longitude profile at different time.

(a) 662m upstream from the dam

(b) 500m upstream from the dam

(c) 183m upstream from the dam

Figure 4. Geomorphology process of typical cross-sections.

According to the results of a comparison which was made between the actual measured cross-sections on June 5, 2017 and November 20, 2017, the total amount of the main stream siltation in the 864 m upstream section of the reservoir area was approximately 162,800 m³, as detailed in Table 1. Considering that the measurement data of the section had not reached the end of the reservoir, it was determined from the observed impacts of the sediment removal and the actual measured section data on November 16, 2017, that the actual siltation volume in the reservoir area was over 300,000 m³, and the sediment blocking efficiency was greater than 15%.

Table 1. Statistical data of the siltation characteristics in the reservoir area

Cross section	Distance from the dam (m)	Deposition area (m ²)	Accumulative deposition volume (m ³)
CS1	13	59.7	0.08
CS2	88	33.3	0.43
CS3	183	127.8	1.19
CS4	340	197.1	3.74
CS5	500	281.9	7.57
CS6	662	283.1	12.15
CS7	864	125.9	16.28

3 Analysis on the factors affecting the reservoir siltation

From the perspective of the siltation process in the cross-sections, the reservoir siltation was determined to be mainly concentrated during two periods: June 5th to July 7th, and August 28th to November 16th. It was determined from the longitudinal sections that the average rise in the siltation level from June 5th to July 7th was approximately 1.7 m. The average rise of the longitudinal sections from August 28th to November 16th was determined to be 7.5 m. The longitudinal profile changes during the later period had mainly occurred in front of the dam, with a maximum siltation elevation of nearly 12 m.

3.1. Influences of the water levels on the siltation

Fig. 5 details the water level change processes in front of the dam of the Upper Marsyangdi Reservoir. The water levels of this reservoir were determined to be relatively

stable. The highest water level during this study's measurement period was 902.55 m, which occurred on April 21, 2017. The lowest water level was 901.33 m, which occurred on May 2, 2017. The water level difference between the maximum and minimum was 1.22 m. From a long-term perspective, the water levels in front of the dam were relatively stable, with minimal changes observed. The inflowing water during the flood season was above the required amount for power generation (56 m³/s), and the excess water was discharged through a gate in order to maintain the stability of the water levels in front of the dam at approximately 902.25 m. Therefore, it was concluded that reservoir siltation basically had nothing to do with water level regulation in front of the dam.

Figure 5. Water level of upper Marsyangdi reservoir.

3.2 Influences of the water and sediment processes on the siltation

Many of the previous related research findings have shown that the siltation processes of rivers tend to be well correlated with the sediment concentrations, sediment transport rates, or incoming sediment coefficients^[1, 8]. Figures 6 to 8 illustrate the changes in the sediment concentrations, sediment transport rates, and incoming sediment coefficients of the Upper Marsyangdi Reservoir during different time periods. It can be seen from the figures that the change rules of these three variables were basically the same, in which rising levels had begun on June 5, 2017; reached peak levels on July 7, 2017, and then high values were maintained until August 28th. The sediment concentrations and incoming sediment amounts both reached yearly maximums during the period ranging from July 8th to August 28th. In regard to the incoming sediment coefficient, it was observed to be the same as that during the period ranging from June 5th to July 7th. During the period from July 8th to August 28th, the siltation volume in the reservoir area was observed to be significantly smaller than during the other two periods. It could be seen that the relationship between the siltation and these three variables was obvious. Therefore, it was concluded that none of the three were direct factors which had caused the siltation changes.

Figure 6. Sediment concentration process

Figure 7. Suspended sediment discharge process.

Figure 8. Inflow sediment coefficient process.

This study divided the inflow volumes and corresponding sediment concentration processes of the Upper Marsyangdi Reservoir according to the time periods, and it became evident that there was a high correlation between the flow rates and the siltation amount, as shown in Fig. 9. During the period ranging from July 8th and August 28th, the inflow rate was observed to be significantly larger than that during the other time periods, with inflow rates all above 200m³/s. However, during the other two periods, there were basically no inflow rates greater than 200m³/s. Then, by comparing these three time periods, it was found that the reservoir siltation had mainly occurred with the small and medium flow rates. The reason for this phenomenon was that there were artificial controls of the water level changes in the water flow state of the natural river channel. This particularly had major impacts on the open area of the medium and small flows. However,

since the sediment concentrations of the small and medium flows were still relatively large, a 1 kg/m³ sediment concentration rate could even be reached in the incoming flow. Therefore, when these high-concentrated flows reached the reservoir, the inflow rates were obviously reduced, and incoming water contained enough sediment to rapidly form siltation in the reservoir area.

Figure 9. Flow and sediment process at the inlet of the reservoir.

4 Suggestions for the operation of the reservoir

When compared with the incoming water and sediment, the storage capacity of the Upper Marsyangdi Reservoir is very small. In order to ensure normal power generation, the water levels in the reservoir are maintained, and siltation is difficult to avoid. Therefore, it is necessary to regularly open and remove the sediment accumulations in order to ensure the long-term safe operation of the power plant.

The reservoir underwent an open discharge test during the period ranging from November 16th to November 18th of 2017. The average daily inflow rate was between 54 and 65 m³/s. Due to the small inflow rate, the duration of the sand removal action lasted for a long period of time. The impacts of the sand removal action were limited to within the area 600 m upstream of the dam. The amount of flushed sediment totaled approximately 130,000 m³, which was less than half of the total siltation in the reservoir.

In accordance with the results of the abovementioned analysis of the factors affecting the reservoir siltation, the siltation of Upper Marsyangdi Reservoir was determined to be mainly concentrated at the beginning and end of the flood season. The reservoir during the main flood season was found to be slightly silted. At the range of 200 m in front of the dam, there was a basic balance of flushing and siltation observed. In this study, in accordance with the siltation characteristics of the examined reservoir, combined with the operation mode of the reservoir, it was recommended open discharge and sediment removal processes be conducted every year after the flood season. The flow rate of the sediment removal should be above 100 m³/s. Previously, the sediment removal volume caused by a one time removal action was above 130,000 m³. During the period ranging from November of 2016 to April of 2017, the total amount of inflow sediment in the reservoir

was determined to be approximately 20,000 tons. By calculating according to the 1.3 t/m^3 dry bulk density of the reservoir, including all the incoming sediment deposited into the reservoir, the siltation amount was determined to be only $15,000 \text{ m}^3$. Therefore, the storage capacity formed by the flushing action at the end of the flood season could be maintained during the non-flooding seasons, which would effectively increase the adjustable storage capacity of the reservoir. Furthermore, the water supply guarantee rate for power generation could be increased during the non-flood periods. On the other hand, when the next flood season occurred, the large water depth which had been maintained in front of the dam could reduce the amount of sediment entering the diversion canal. Then, in accordance to the situation of the water and sediment prior to the flood season of the current year, the reservoir landform observations could be strengthened. If the sediment had reached the front of the dam during the flood season, it would be necessary to conduct an open discharge for sediment removal when the flow reached over $200 \text{ m}^3/\text{s}$, in order to maintain a certain range in front of the dam, reduce the amount of sediment entering the diversion canal, and delay turbine abrasions. It was determined from the analysis of the actual observations of 2017, that after the sediment removal actions were completed, the reservoir had filled at a speed of no more than $1/10$ of the flow rate of the main stream, which was basically equivalent to the flow of the tributary. In this manner, the re-deposition of the dam could be avoided during the water storing process. According to the water storage principle, the time required to fill the reservoir was within seven hours. Therefore, based on this information, it was estimated that the entire open discharge and sediment removal action, as well as the re-filling water process, could be completed within 24 hours. Therefore, there would be no obvious affects on the power generation process.

5 Conclusions

It was observed in this study that, when compared with the incoming water and sediment, the storage capacity of the Upper Marsyangdi Reservoir was very small. It was determined from the actual measured data of the reservoir after one year of operation, which the siltation in the reservoir area had mainly occurred during two periods: the beginning and the end of the flood season. It was observed that when the flow rate during the main flood season was over $200 \text{ m}^3/\text{s}$, there is basically no siltation within the scope of 300 m in front of the dam, and there was a small amount of siltation above this range. There was no direct relationship observed between the siltation and the amount of sediment and incoming sediment coefficient. The main reason for the siltation of the reservoir was due to the fact that the reservoir back-water had a major impact on the open area of the medium and small flows, and the sediment concentrations of these flows were relatively high. Therefore, when the medium and small flows entered into the reservoir, the inflow rates were obviously reduced. Since the incoming water contained high concentrations of sediment, siltation had rapidly formed in the reservoir area.

In accordance with the analysis results of reservoir siltation situation, it was recommended that the examined reservoir should perform sand-removal flushing actions at least once a year. These measures should be carried out after the flood season, with a flow rate of over $100 \text{ m}^3/\text{s}$. The increased storage capacity following the sediment removal can then be used until the flooding season of the next year. Furthermore, if it is determined that the siltation in the reservoir area is high prior to the beginning of the flood season, it is recommended to carry out sediment removal actions when the flow rate has reached over $200 \text{ m}^3/\text{s}$ in order to reduce the sediment concentration in the diversion canal during the flood season. Then, following the sediment removal actions during the flood season, the flow rate of the stored water in the reservoir should be maintained at $1/10$ of the main stream flow rate, which would basically the same as that of the tributary flow. In this way, siltation during the water storage process could again be avoided.

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References

1. Jinming Xie, Baosheng Wu, Xiaoying Liu. Review of reservoir sedimentation management. *Journal of Sediment Research*, (2013)
2. Thapa B S, Dahlhaug O G, Thapa B. Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine. *Renewable & Sustainable Energy Reviews*, **49**, (2015)
3. Sangal S, Singhal M K, Saini R P. Hydro-abrasive erosion in hydro turbines: a review[J]. *International Journal of Green Energy*, **2016**, (2018)
4. Morris G L, Fan J. *Reservoir sedimentation handbook : design and management of dams, reservoirs, and watersheds for sustainable use*. McGraw-Hill, (1998)
5. Zhaoyin Wang, Chunhong Hu. Strategies for managing reservoir sedimentation. *International journal of sediment research*, **24**,4(2009)
6. Issa I E, Alansari N, Knutsson S, et al. Monitoring and Evaluating the Sedimentation Process in Mosul Dam Reservoir Using Trap Efficiency Approaches[J]. *Engineering*, **7**, 4(2015)
7. Sumi T, Okano M, Takata Y. Reservoir Sedimentation Management With Bypass Tunnels in Japan, *International Symposium on River Sedimentation*. (2004)
8. Han Q W, Yang X Q. A review of the research work of reservoir sedimentation in China. *Journal of China Institute of Water Resources and Hydropower Research*, (2003)

9. Sumi, T., & Kantoush, S. A. Integrated Management of Reservoir Sediment Routing by Flushing, Replenishing, and Bypassing Sediments in Japanese River Basins Dam. Proceedings of the 8th International Symposium on Ecohydraulics, Seoul, Korea, (2010)
10. Kantoush, S. A. and A. J. Schleiss. Channel Formation in Large Shallow Reservoirs with Different Geometries during Flushing. Journal of Environmental Technology. **30**, 8(2009)