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Estimation of sedimentation in the Manwan and Jinghong reservoirs on the Lancang river

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ABSTRACT

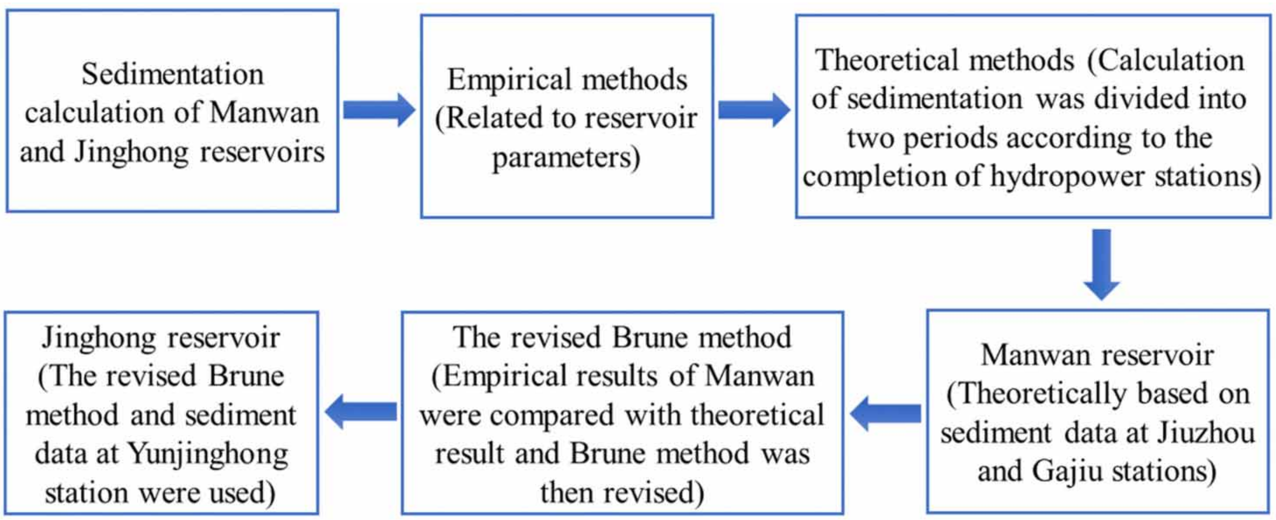
The Lancang reservoirs play an essential role in China's national economy and life, and the study of reservoir siltation is of great significance to ensure its sustainable service for the nation and people. In this paper, reservoir sedimentation is quantified in stages by empirical models and theoretical methods using reservoir information and sediment data to reveal the latest status of siltation in the Lancang reservoirs. Results show that the storage capacity loss of the Manwan and Jinghong reservoirs reached 51.4% and 1.54% by 2019, which illustrates that the situation of siltation is serious. The theoretical trapping efficiency of Manwan reservoir was about 69% and the estimation result of the Brune method performed best with a value of 67.5% among the empirical methods. The Brune method was then modified with a correction coefficient and the revised Brune method can be used for the estimation of trapping efficiency in other reservoirs. Overall, this paper presents relatively accurate information for managers to understand the current state of siltation in the Lancang reservoirs, and can provide scientific guidance and data support for them to take measures to reduce sedimentation and ensure the sustainability of reservoirs.

Key words: Jinghong reservoir, Lancang river, Manwan reservoir, reservoir sedimentation

HIGHLIGHTS

- Phased calculation of sedimentation in the Manwan and Jinghong reservoirs is presented.
- A detailed update on the sedimentation of Lancang reservoir is shown to support its sustainable service.
- The Brune method performed best for estimating trapping efficiency and could be applied to other Lancang reservoirs for reference.

GRAPHICAL ABSTRACT



1. INTRODUCTION

When it comes to hydraulic engineering, one of the most important problems is the trapping of sediment (Walling 2006). It is assumed that the global sediment flux that is trapped in reservoirs is over 30% (Vorosmarty *et al.* 2003), and 1% of the world's existing reservoir volume is lost each year due to sedimentation (WCD 2000). As a result, sediment flux measured from hydrological stations exhibits significant decreases. This circumstance also happens in the Lancang–Mekong River. With hydropower stations constructed one after another, the changes of water discharge and sediment flux in the Lancang River as well as their impact on the lower Mekong have become the focus of research (Räsänen *et al.* 2012; Liu *et al.* 2013; Zhai *et al.* 2016; Han *et al.* 2019; Binh *et al.* 2020). Studies have shown a decrease in the sediment flux of the Lancang river and it is generally agreed that in the Lower Mekong 50% of the total suspended sediment originates from China (Milliman & Meade 1983; Roberts 2001; ADB 2004). Sediment brings important nutrients to the downstream and has a significant impact on the production and life of downstream areas. At the same time, changes in the amount of sediment also play a key role in power generation, navigation, as well as river bank erosion, and may even affect the change of national boundaries, ecological security of river basins and sustainable development. Therefore, research on reservoir sedimentation to grasp detailed information on sediment changes is of great importance. In addition, sedimentation is also a problem that has to be paid great attention to in the operation and management of reservoirs.

As mentioned above, the changes of water and sediment have attracted much attention from scholars and some results have been achieved. However, there is little recent systematic research on the reservoir sedimentation in Lancang River. Kummu & Varis (2007) estimated the theoretical trapping efficiency of proposed dams as well as the amounts of sediments that trapped in reservoirs. Subsequently, Kummu *et al.* (2010) developed a protocol to estimate the trapping efficiency of reservoirs in the Mekong basin by means of the Brune method and made a prediction of the trapping efficiency if eight dams are all constructed. Fu & He (2007) estimated the trapping efficiency of the Manwan dam based on the sediment load data from the hydrological stations upstream and downstream of the Manwan reservoir and compared the result with that estimated by modified Brune and Siyam models. Furthermore, Fu *et al.* (2008) calculated the sedimentation in the Manwan reservoir and also revealed its impacts downstream. It can be seen that there is a paucity of recent research on reservoir sedimentation and most studies are about the Manwan reservoir. Detailed and up-to-date theoretical calculations of reservoir sedimentation are lacking. However, as an international river, the Lancang River occupies an important position in the production, life and economic development of the riparian countries (Hecht *et al.* 2019). Quantitative study on the sedimentation of the Lancang cascade is essential to assess the current status and further ensure its sustainability. Only by mastering the situation of reservoir siltation and exploring effective methods to reduce the sedimentation can the river and hydropower stations be better servers of the national economy as well as of people's livelihoods and thus make them sustainable. As a result, it is of great scientific value and practical significance to analyze the current state of reservoir siltation in the Lancang river.

In this paper, we first present several empirical methods to estimate trapping efficiency and give a result of estimation. Then, annual sedimentation is calculated theoretically using suspended sediment data from the upstream and downstream of reservoirs during the period 1964–2019. Finally, a simple comparison and analysis is performed between the measured and calculated values.

2. DATA

The Lancang-Mekong River is a large international river and flows through six countries, that is, China, Myanmar, Laos, Thailand, Cambodia and Vietnam. The upper Mekong, known as Lancang in China, contains a rich resource of hydropower (Liu *et al.* 1998; He *et al.* 2005) and eight dams have so far been completed with the Manwan dam first constructed in 1992 and the Nuozhadu dam the last finished in 2011 (Figure 1). Reservoir information for the Lancang cascade is shown in Table 1.

The Manwan reservoir, located in the middle reach of the Lancang River, was the first dam constructed in the mainstream of the Lancang as seen in Table 1. With Jiuzhou station upstream and Gajiu station downstream, the data of sediment inflow and outflow can be easily obtained. Jiuzhou station is located about 270 km upstream from the Manwan dam and remains in a natural state of fluvial sediment transport. Gajiu station is located downstream of the dam site by a distance of about 2 km. After the construction of Manwan reservoir in 1992, sediment discharge at Gajiu station was immediately changed. The difference of sediment discharge between Jiuzhou and Gajiu stations before and after the reservoir constructed can be used to assess the amount of reservoir sedimentation. Yunjinghong hydrological station, located about 3.5 km downstream of Jinghong reservoir, has plenty of measured data about water and sediment. However, there is no suitable data from the

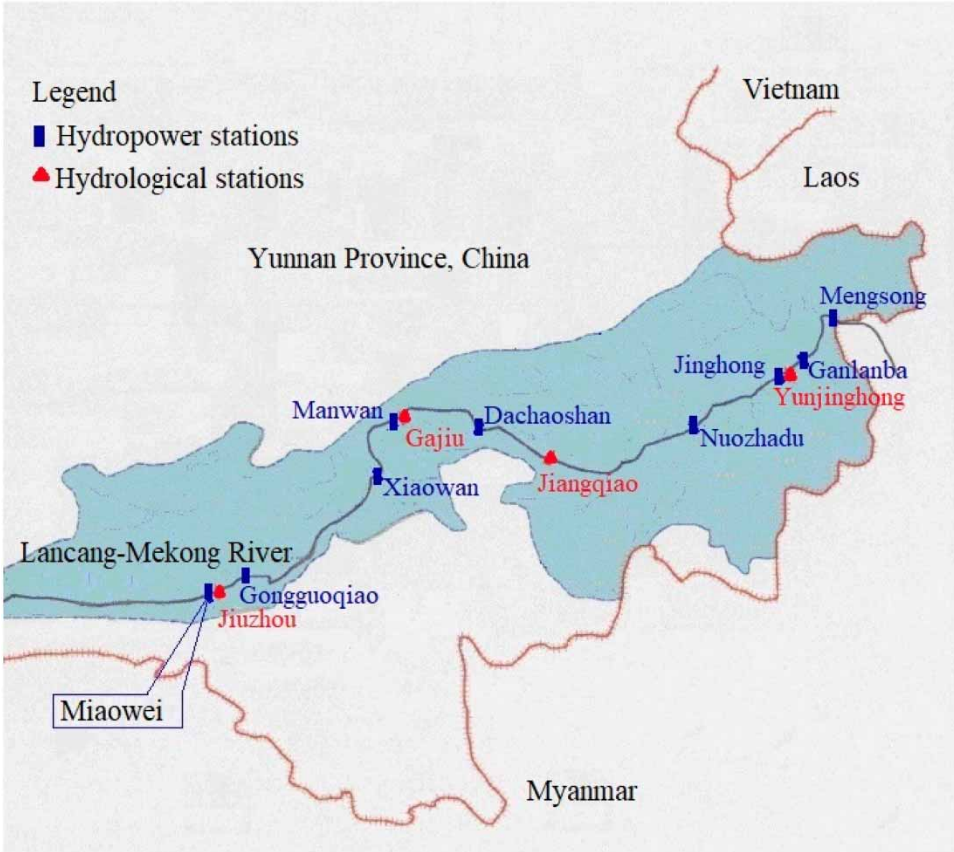


Figure 1 | Location map of Lancang cascade.

Table 1 | Reservoir information for the Lancang cascade

Reservoir	Operation time	Watershed area/km^2	Mean annual runoff/km^3	Total storage/km^3
Gongguoqiao	2011	97,300	31.1	0.51
Dachaoshan	2001	121,000	42.3	0.93
Manwan	1993	114,500	38.8	0.92
Nuozhadu	2011	144,700	55.2	22.4
Jinghong	2008	149,100	58.0	1.14
Xiaowan	2008	113,300	38.5	14.56

Sources: Kummu *et al.* 2010; Fan *et al.* 2015.

upstream hydrological station available for the reservoir. Thus, only the sediment data from Yunjinghong station were used in the calculation of sedimentation in Jinghong reservoir. Annual suspended sediment data at Jiuzhou, Gajiu and Yunjinghong stations were obtained from the Yunnan Hydrology and Water Resources Bureau for corresponding hydrological stations and the multi-year average values were then calculated and listed in Table 2. Normally, the single-point method is used to observe suspended sediment in the Lower Mekong (Hou *et al.* 2020). The acquired data has a large error and is often questioned by scholars. However, the sediment data in this paper is measured by hydrological stations using the depth integration method according to the Code for measurement of suspended load in open channels (2015). Thus, the data has high quality.

The Manwan and Jinghong reservoirs studied in this paper are located in the middle and lower reaches of the Lancang river. In order to better understand their potential to sedimentation, it is essential to explain the situation of land use in the upper and middle reaches. The upper reaches of Lancang river belong to the Qinghai-Tibet Plateau, which is the least

Table 2 | Data used in the calculation of reservoir sedimentation

Station	Data series	Average suspended sediment/10^6 t	Location
Jiuzhou	1964–2008	25.63	Upstream of Manwan
Gajiu	1964–2019	28.95	Downstream of Manwan
Yunjinghong	2002–2019	13.06	Downstream of Yunjinghong

populated area in the entire basin. Overall, the growth and decline of forests in the upper reaches is not obvious (Zhang & Xu 2003). The middle and upper reaches, from the territory of Yunnan Province to Nuozhadu hydropower station, bear the densest population as well as the highest degree of economic development due to the flat terrain and suitable climate. As a result, the human interference is stronger and impacts on land use are the most pronounced. The rate of forest coverage has decreased drastically since the late last century and the regional ecological environment has been greatly affected, which has led to a serious condition of soil erosion (Jiang *et al.* 2006). The population density in the lower reaches is lower and there is also less human interference. At the same time, the natural environment is better and the vegetation can recover at a faster rate. Therefore, the situation of land use in the lower reaches is relatively stable.

3. METHODS

There are various ways to quantitatively assess reservoir sedimentation, empirically and theoretically. Most empirical methods are made with regard to reservoir capacity and the inflow sediment, while theoretical methods are made mainly about the sediment in and out of the reservoir, that is, sediment data from upstream and downstream hydrological stations. As Manwan reservoir is large with fixed gauging stations upstream and downstream, it is possible to measure the sediment inflow and outflow (Xu *et al.* 2006; Dai *et al.* 2008; Kummu *et al.* 2010). With the sediment inflow and outflow known, sediments trapped in the reservoir can be calculated theoretically. However, there are reservoirs for which inflow and outflow were not both measured. Under this condition, the storage capacity and the measured sediment inflow can be used to estimate the sedimentation. The sediment yield can also be estimated by comparing the reservoir drainage area with measured sediment outflow (Dendy 1974).

3.1. Empirical methods

3.1.1. Brown method

At first, the methods for estimation of trapping efficiency (*TE*) were mostly based on empirical relationships. One of the first researchers was C. B. Brown who reported in 1943 that the ratio of original storage capacity to the inflow of water is a predominant factor that governs the storage loss of reservoirs (Heinemann 1984; Brown 1943). In the following year, Brown developed a curve between *TE* and the ratio of original capacity to the watershed area by means of data from 15 reservoirs, that is

$$TE = 100\left(1 - 1\Big/\left(1 + 0.0021\beta\frac{C}{W}\right)\right) \tag{1}$$

where C is the storage capacity of reservoirs in m^3, W is the drainage area in km^2. The value of β is between 0.046 and 1 with an average value of 0.1. Here 0.1 is adopted in the equation.

3.1.2. Brune method

The Brune method was first developed from reservoirs in the United States, and then widely used for other reservoirs around the world (Siyam *et al.* 2001; Kummu & Varis 2007). With the method providing the most suitable estimation of long-term average TE for large reservoirs (Vorosmarty *et al.* 1997, 2003; Morris & Fan 1998; Kummu & Varis 2007), it is frequently used in the empirical calculation of reservoir sedimentation. Moreover, Brune also provided a capacity-inflow ratio (C/I) which was much better than the ratio of capacity-watershed (C/W) used before. Since then, most empirical methods concern the ratio C/I.

$$TE = 1 - \frac{0.05}{\sqrt{\Delta\tau_R}} \tag{2}$$

where $\Delta\tau_R = \sum_{1}^{n_j} C_i/I$, C_i is the storage capacity for the i-th reservoir (km^3) and I is the mean annual inflow (km^3/year) at the dam site.

3.1.3. Morris and Heinemann

After Brune, a number of equations were proposed to calculate TE by means of capacity/inflow ratio (C/I). Morris (1963) demonstrated an adequate fit by the following equation

$$TE = \frac{C/I}{0.012 + 1.02C/I} \tag{3}$$

Based on the relation between TE and C/I presented by Brune and Morris, Heinemann (1981) made a modification. Although his study was specifically aimed at small ponds, given the fact that the capacity of selected ponds ranges from 3×10^3 to 4×10^6 m^3, this approach can also be extended for use in larger reservoirs. The Heinemann (1981) method was expressed as follows:

$$TE = -22 + \frac{119.6C/I}{0.012 + 1.02C/I} \tag{4}$$

3.1.4. USDA-NRCS

USDA-NRCS (1983) transformed the envelope curves developed by Brune into curves for three kinds of sediments. Correspondingly, there are three curves: the upper curve, median curve and lower curve. The three curves were further translated into an MS Excel thanks to the work of the Summit County Soil and Water Conservation District (Harbor *et al.* 1997). Different sediment textures correspond to different curves and the corresponding equations are shown in Table 3.

Fu *et al.* (2015) took bedload samples from Gajiu and Yunjinghong during 2006–2011 and performed particle size analysis indicating that the maximum average particle size was 0.92 mm and 0.17 mm for the two sites, respectively. The authors also took samples from the reservoir areas of Manwan and Jinghong in 2008 and found that the median sizes of bedload at the two places were 11.0–40.6 μm and 6.7–18.9 μm (Sun *et al.* 2021), respectively. In summary, the dredged sediments in Manwan and Jinghong reservoirs can be regarded as a mixture of coarse and fine sediments, thus the median curve is adopted. Moreover, the C/I value of Manwan and Jinghong reservoirs are 0.0237 and 0.0212, respectively, which are both between 0.02 and 1. Therefore, Equation (5) is chosen for the empirical calculation of Manwan and Jinghong reservoirs:

$$TE = 97 - (1.275|\ln(C/I)|^{2.47}) \tag{5}$$

3.2. Theoretical methods

Reservoir sedimentation is generally estimated by the amount of sediment inflow and outflow. The theoretical calculation of sediment siltation is mainly based on the data of sediment transport from upstream and downstream hydrological stations.

Table 3 | Equations for the calculation of TE (%) by USDA-NRCS (1983), according to the C/I ratio for different textures

	$C/I > 1$	$1 > C/I > 0.02$	$C/I < 0.02$
Upper curve (sand-gravel)	100	$100 - (0.485\|\ln(C/I)\|^{2.99})$	$124 - (6.59\|\ln(C/I)\|^{1.52})$
Median curve (mixture)	97	$97 - (1.275\|\ln(C/I)\|^{2.47})$	$128 - (11.51\|\ln(C/I)\|^{1.304})$
Lower curve (clay-silt)	94	$94 - (3.38\|\ln(C/I)\|^{1.92})$	$94 - (3.38\|\ln(C/I)\|^{1.92})$

Source: Harbor *et al.* (1997).

For reservoirs with only upstream or downstream sediment data, the trapping efficiency is combined with upstream or downstream data to calculate reservoir sedimentation.

3.2.1. Manwan reservoir

In this paper, the Jiuzhou hydrological station upstream of Manwan reservoir and Gajiu hydrological station downstream of Manwan were selected as the sediment control stations for the inflow and outflow sediments to estimate the sedimentation in Manwan reservoir. Generally speaking, when the external environment is not very different, sediment transport in the upstream and downstream of a river is quite relevant. Therefore, we have taken 1993, the year when Manwan reservoir was built and operated, as the node. Sediment transport of Jiuzhou and Gajiu during 1964–1993 is regarded as that under the natural state, while sediment transport during 1993–2008 is that impacted by reservoir construction and operation. Reservoir sedimentation and storage capacity loss of Manwan could then be calculated separately in the two periods by linear regression analysis. Therefore, data stability and causality of the time series at Jiuzhou and Gajiu stations needs to be tested before linear analysis is performed, which is necessary to avoid pseudo-regression simulation.

The stability and causality of suspended load series are mainly achieved by the Augment Dickey-Fuller (ADF) test (Fuller 1976; Dickey & Fuller 1979) and Granger causality test. Test results are listed in Tables 4 and 5. The ADF test results show that the probability values of suspended sediment at Jiuzhou and Gajiu are both less than 0.05, which indicates that the data series of the two stations are both stable. The stability can also be judged by the fact that ADF test value is less than the critical value at a significance level of 1%. Moreover, the ADF test also provides a prerequisite for the Granger causality test of suspended sediment series from the two stations as the causality test first requires the data series to be stable. The Granger test in Table 5 gets a conclusion that the null hypothesis H_0 (Suspended load at Jiuzhou does not cause that at Gajiu) is rejected, which means there is indeed a causal relationship between the suspended sediment of Jiuzhou and Gajiu and this can provide theoretical support for the simulation of suspended load at Gajiu under natural state, using that at Jiuzhou.

3.2.1.1. Calculation of sedimentation during the first period. Data series of suspended sediment load at Gajiu and Jiuzhou stations were from 1964 to 2008. The correlations of suspended sediment load for the two stations are quite significant before and after reservoir construction, that is pre-dam 1964–1992 and post-dam 1993–2008. The correlation results with a significance value of 0.01 are shown in Figure 2. As is seen, suspended load at the two stations correspond to two combined processes during the two periods and each shows a good correlation. This also demonstrates that the two stations can be regarded as sediment control stations for siltation estimation of Manwan reservoir.

During the two periods, the relationships of suspended load between the two stations were simulated by linear regression, in which suspended load at Jiuzhou is the independent variable and that at Gajiu is the dependent one. Regression models of the two periods were obtained as the following equations.

$$S_{gj} = 1.46S_{jz} + 11.29 \tag{6}$$

$$S'_{gj} = 0.70S'_{jz} - 3.75 \tag{7}$$

Table 4 | ADF test results for the time series of annual suspended load at Jiuzhou and Gajiu stations

Variable	Critical value	Significance level	Test value	Probability	Stable or not
Suspended load at Jiuzhou	−3.59	1%	−7.01	0.00	Stable
Suspended load at Gajiu	−3.59	1%	−3.66	0.01	Stable

Table 5 | Results of Granger causality test for suspended load series at Jiuzhou and Gajiu stations

Null hypothesis H_0	Probability	F statistics value	Conclusion
Suspended load at Jiuzhou does not cause that at Gajiu	0.82	0.20	H_0 is refused

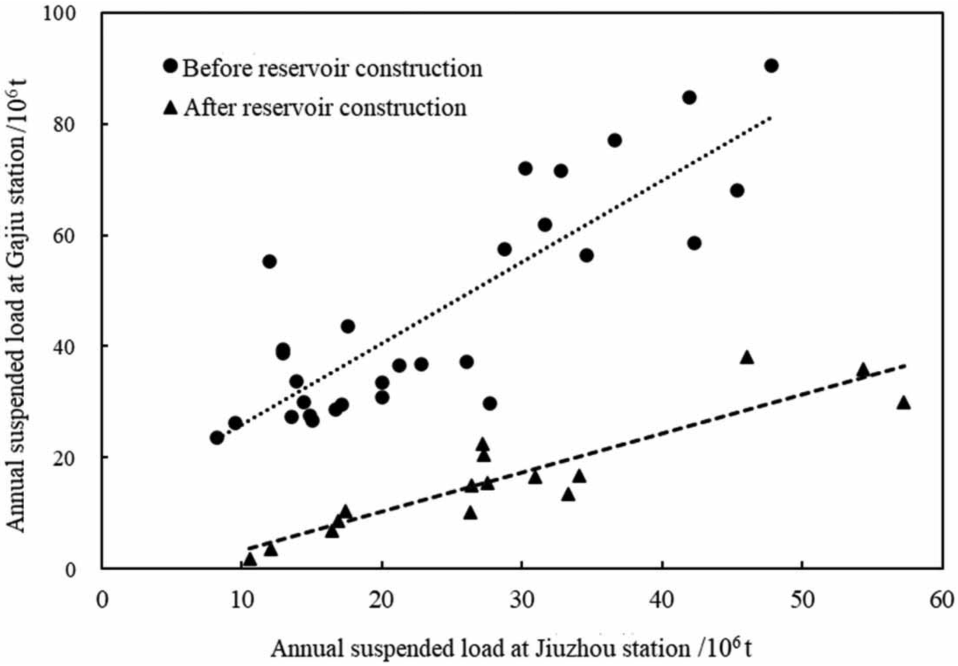


Figure 2 | Correlation of suspended load between Jiuzhou and Gajiu hydrological stations.

where S_{gj}, S_{jz} are suspended loads of Gajiu and Jiuzhou stations before the Manwan dam was constructed and S'_{gj}, S'_{jz} are the corresponding values after the completion of the Manwan reservoir.

R^2, the coefficient of determination, for the two equations, was 0.71 and 0.83, respectively, which shows that Equations (6) and (7) fit well for the two suspended load series. The changes in the two coefficients and the goodness of fit illustrate that the annual suspended load downstream was reduced and tended to be stable. Then, the differences between the estimated and measured values at Gajiu station were presumed to be the amount of sedimentation caused by the Manwan dam. The annual amount of sediment trapped in reservoir and the total amount are both shown in Table 1. As is seen, the maximum sedimentation occurred in 2000 with a value of 64.87 million t and the minimum was 24.92 million t in 1994. The amounts of sediment interception around 2000 were relatively high and this should be related to the construction of the Dali-Baoshan and Dali-Yangbi highways. The implementation of these key projects is often accompanied by an increase in soil erosion, which leads to an increase in sediment flux and reservoir sedimentation for the corresponding section of Lancang river. The average annual sediment load at Gajiu was estimated as 37.04 million t during 1993–2008 under the condition that Manwan operates and the total amount was 592.56 million t. If we estimate that 3% of the suspended sediment is bedload (He 2004), then the average annual sedimentation of Manwan was 38.15 million t and the amount of sediment intercepted in Manwan reservoir during the 16 years of operation was about 610.43 million t. It should be noted that the amount of siltation in the reservoir area caused by riverbank landslides and collapse was not included. Taking the average bulk density of sediment as 1.4 t/m^3, the loss of reservoir capacity caused by sediment interception in Manwan hydropower station was about 436 million m^3 to 2008, which accounts for 47.4% of the total reservoir capacity of 920 million m^3.

It can be seen from Table 6 that the simulated multi-year average suspended load at Gajiu station was 53.6 million t during 1993–2008, which can be regarded as the natural annual value of suspended load at the Manwan dam site. The trapping efficiency of a reservoir is the ratio of the amount of sediment deposited in the reservoir to that entering the reservoir during the same period, that is

$$TE = \frac{S_{in} - S_{out}}{S_{in}} = \frac{S_{trapped}}{S_{in}} \tag{8}$$

where S_{in} is the amount of incoming sediment, S_{out} is the amount of outgoing sediment, and $S_{trapped}$ is the amount of sediment trapped in the reservoir. According to Equation (8), the trapping efficiency of Manwan reservoir is calculated as 69.0%.

Table 6 | Annual amount of sedimentation at Manwan reservoir during the first period

Year	Simulated annual suspended load at Gajiu/10^6 t	Annual sedimentation of Manwan reservoir/10^6 t
1993	78.48	40.33
1994	26.73	24.92
1995	51.05	30.56
1996	49.74	39.59
1997	35.32	28.35
1998	90.64	54.69
1999	56.50	39.98
2000	94.86	64.87
2001	49.81	34.83
2002	50.94	28.52
2003	59.93	46.53
2004	51.52	36.13
2005	61.01	44.30
2006	28.88	25.35
2007	35.96	27.35
2008	36.75	26.28
Average	53.63	37.04
Total	858.15	592.56

3.2.1.2. Calculation and correction of trapping efficiency in Manwan reservoir. According to the aforementioned empirical methods, the trapping efficiency of Manwan reservoir can be estimated by means of reservoir parameters and hydrological data. As is shown in Table 7, the trapping efficiency of Manwan reservoir is between 56.4% and 67.5%, which is less than the value 69% calculated by theoretical methods. Among them, the Brune method performed best and obtained the closest value to the theoretical calculation result. Fu & He (2007) modified the coefficient in the Brune method based on the accumulated measured data to make it suitable for reservoirs in Lancang river. According to the theoretical result of this paper, the revised Brune method is shown as follows.

$$TE = 1 - \frac{0.0477}{\sqrt{\Delta\tau_R}} \tag{9}$$

Theoretically, the revised method can be used to estimate the trapping efficiency of reservoirs with similar size on the Lancang river, such as Jinghong reservoir. For reservoirs lacking the measured topography and sediment data, it is a relatively simple method to estimate the trapping efficiency. With the reservoir capacity and average annual runoff at the dam site known, the trapping efficiency can be obtained.

Table 7 | Estimated trapping efficiency of Manwan reservoir and error compared with theoretical result

Method	Manwan reservoir /%	Error /%
Brown (1943)	62.8	−9.0
Brune (1953)	67.5	−2.2
Morris (1963)	65.5	−5.1
Heinemann (1981)	56.4	−18.3
USDA-NRCS (1983)	63.8	−7.5

3.2.1.3. Calculation of sedimentation during the second period. The amount of sedimentation in Manwan reservoir during the first period of 1993–2008 was calculated as aforementioned. In 2009, another large reservoir, Xiaowan hydropower station, was completed and began to store water, which greatly alleviated the problem of reservoir sedimentation in Manwan. After the construction of Xiaowan station, the multi-year average suspended load at Gajiu station dropped to 2.053 million t during 2009–2019. Therefore, years from 2009 to 2019 were recognized as the second period for the calculation of sedimentation in Manwan reservoir. At this time, Jiuzhou station could no longer be used as the inlet hydrological station of Manwan reservoir. Therefore, reservoir sedimentation and capacity loss can be deduced by combining the data series of annual sediment load with the trapping efficiency of Manwan reservoir. The sedimentation of Xiaowan reservoir can also be reflected from the side. The calculation of sedimentation during this period is accomplished by the following equation.

$$S_{trapped} = TE \cdot S_{out}/(1 - TE) \tag{10}$$

Regarding the multi-year average suspended load at Gajiu station as that of Manwan reservoir, combined with Equation (10), the multi-year average sedimentation of Manwan reservoir during this period can be obtained as 4.57 million t. According to the estimation that bedload accounts for 3% of suspended load, the annual amount of sedimentation in Manwan reservoir is 4.71 million t. Taking the average bulk density of sediment to be 1.4 t/m^3, the annual storage loss of Manwan reservoir is about 3.36 million m^3 due to sediment siltation, accounting for 0.37% of the total storage capacity. From 2009 to 2019, the total sedimentation of Manwan reservoir was 51.70 million t, resulting in a capacity loss of 36.93 million m^3, which accounts for 4.0% of the total storage capacity.

According to the calculation of both theoretical and empirical methods, the total sedimentation of Manwan reservoir from the closing of gates in 1993 to 2019 is about 662.1 million t. Taking the average bulk density of sediment to be 1.4 t/m^3, the total storage loss of Manwan reservoir is about 472.9 million m^3 due to siltation, accounting for 51.4% of the total storage capacity. Of this, the annual sedimentation during 1993–2008 was 38.1 million t, and the loss of storage capacity was about 4.27% of the total capacity. After the completion of Xiaowan hydropower station, sedimentation in Manwan reservoir was greatly eased. The annual siltation in Manwan reservoir was 4.70 million t during 2009–2019, and the loss of storage capacity was reduced to about 0.37% per year.

3.2.1.4. Comparison between calculation and design values of storage capacity loss. Based on the above results, the cumulative storage loss of Manwan reservoir for a certain number of years can be calculated and Table 8 shows the comparison between the calculated cumulative storage loss and design values of Manwan reservoir. Due to the confidentiality requirements for the sedimentation results of measured topography, we will not make relevant comparisons here. As is shown in Table 8, the cumulative storage loss of Manwan reservoir for 5 years, 10 years and 15 years is 17.5%, 34.6% and 47.4%, respectively. The theoretical result for 15 years is consistent with the design value, indicating that the method used in this paper has high accuracy. The storage capacity loss of Manwan during 1993–2013 was 49.2%, which is far less than the design value 61.0%. That was because the operation of Xiaowan station greatly changed the amount of sediment in Manwan reservoir after 2008, thus the change in reservoir capacity was significantly smaller than before. Under the condition that Manwan and Xiaowan reservoirs normally operated and no major bank collapse occurs, it is expected that the Manwan reservoir will maintain an annual storage loss of about 0.37%.

3.2.2. Jinghong reservoir

The Yunjinghong hydrological station, about 3.5 km downstream of Jinghong reservoir, has multi-year measured sediment data, which can be used as the outlet hydrological station of Jinghong reservoir. However, there is no suitable hydrological

Table 8 | Comparison between calculation and design values for storage capacity loss of Manwan reservoir

	Years				
Storage capacity loss/%	**5 (1998)**	**10 (2003)**	**15 (2008)**	**20 (2013)**	**26 (2019)**
Design value	/	/	47.4	61.0	/
Calculation value	17.5	34.6	47.4	49.2	51.4

station available upstream of the reservoir. Therefore, the trapping efficiency of Jinghong reservoir can be calculated by the modified Brune method. The annual suspended sediment at Yunjinghong is regarded as the annual amount of outflow sediment from Jinghong reservoir, combined with its trapping efficiency, the amount of sedimentation and storage capacity loss can be computed year by year.

Dachaoshan hydropower station is located upstream of Yunjinghong station and was completed at the end of 2001. After that, Jinghong hydropower station was constructed in 2008, and at the end of 2012, the Nuozhadu hydropower station between Dachaoshan and Jinghong station was finished. Obviously, the process of sedimentation in Jinghong reservoir is affected by the operation of Nuozhadu reservoir. Therefore, the sedimentation process of Jinghong reservoir during 2009–2019 was divided into two stages by taking the year 2012 as the boundary when Nuozhadu station was operated, that is, the time from 2009 to 2012 is recognized as the first period and the period from 2013 to 2019 is the second. Then the two stages of sedimentation in Jinghong reservoir can be calculated separately.

Based on the storage capacity and annual average runoff at the dam site, the trapping efficiency of Jinghong reservoir is calculated to be 66.0% using the revised Brune method. As the annual amount of outflow sediment from Jinghong reservoir is known, the annual amounts of inflow sediment and intercepted sediment of Jinghong reservoir during 2009–2019 can be obtained by Equation (10) and are listed in Table 9.

From 2009 to 2012, the annual average amount of sedimentation in Jinghong reservoir was 2.74 million t and the total amount was about 10.96 million t. According to the estimation of bedload accounting for 3% of suspended load, the annual amount of sedimentation in Jinghong reservoir was about 2.82 million t and the total amount from 2009 to 2012 was 11.29 million t. Taking the average bulk density of sediment to be 1.4 t/ m^3, the total storage capacity loss of Jinghong reservoir during this period was about 8.1 million m^3 due to siltation, which accounts for 0.7% of the total storage capacity in 1.14 billion m^3.

After the completion of Nuozhadu station, the annual suspended sediment of Jinghong reservoir was reduced to 1.87 million t during 2013–2019 and a total amount of 13.09 million t sediment was blocked. According to the estimation that bedload accounts for 3% of suspended load, the annual amount of sedimentation in Jinghong reservoir is 1.93 million t and the total amount from 2013 to 2019 is 13.49 million t. Taking the average bulk density of sediment to be 1.4 t/m^3, the total storage capacity loss of Jinghong reservoir during this period is about 9.6 million m^3, accounting for 0.84% of the total storage capacity.

Based on the calculation results of the two periods, it can be seen that the total amount of sedimentation in Jinghong reservoir from 2009 to 2019 is about 24.78 million t and the total storage capacity loss caused by sedimentation is about 17.7 million m^3, accounting for 1.54% of the total storage capacity in 1.14 billion m^3. Of this, the annual storage capacity loss from 2009 to 2012 was approximately 0.175% and it was reduced to about 0.12% per year during 2013–2019 after the completion of Nuozhadu hydropower station.

Table 9 | The annual amount of intercepted sediment in Jinghong reservoir during 2009–2019

Year	Annual intercepted sediment/10^6 t	Annual inflow sediment/10^6 m^3
2009	4.44	6.73
2010	2.59	3.93
2011	2.83	4.28
2012	1.10	1.66
2013	1.41	2.14
2014	0.74	1.12
2015	2.24	3.39
2016	1.46	2.21
2017	3.38	5.12
2018	2.88	4.37
2019	0.99	1.50

4. RESULTS AND DISCUSSION

From the impoundment of Manwan reservoir in 1993 to 2019, a total of about 662.1 million t sediment was intercepted. The total loss of storage capacity due to sedimentation was about 472.9 million m^3, accounting for 51.4% of the total capacity. Of this, the amount of annual siltation during 1993–2008 was about 38.1 million t, accounting for 4.27% of the total storage capacity. After the completion of the upstream Xiaowan hydropower station in 2008, the sedimentation in Manwan reservoir was greatly alleviated. From 2009 to 2019, the annual amount of sedimentation in Manwan reservoir was reduced to 44.7 million t, and the annual storage capacity loss was also reduced to 0.37%. Based on the measured suspended sediment data at Jiuzhou and Gajiu stations, the sediment interception rate of Manwan reservoir was found to be 69% using the theoretical method. The trapping efficiency estimated by empirical methods was between 56.4 and 67.5%, and it can be concluded that the result of the Brune method is the closest to the calculation result. Therefore, the Brune method was revised through correction coefficient and can be used in the calculation of sedimentation in Jinghong reservoir.

From the operation of Jinghong reservoir to 2019, a total of about 24.78 million t sediment was blocked, and the total volume loss because of siltation was about 17.7 million m^3, accounting for 1.54% of the total volume. Of this, the annual sedimentation volume during 2009–2012 was about 2.0 million t, causing a loss of 0.175% to the storage capacity. After the upstream Nuozhadu hydropower station finished in 2012, the sedimentation of Jinghong reservoir was relieved. Thereafter, the annual sedimentation volume has dropped to about 1.4 million t, resulting in an annual loss of 0.12% of total storage capacity.

With the operation of the Lancang cascade reservoirs, it is essential to study the situation of reservoir siltation and get a good knowledge of the current status of the reservoirs. Only in this way can managers make better decisions when taking measures to ensure the sustainable development of reservoirs as well as the rational use of water resources in the river basin. Then the people and nation can greatly benefit from the Lancang river and reservoirs. The results of this study show that the siltation of Manwan and Jinghong reservoirs has been relatively serious. Although the construction of Xiaowan and Nuozhadu hydropower stations has relieved a certain amount of pressure, it can be seen that the overall siltation of the reservoirs still needs to be paid more attention to. Due to the limitation of hydrological and sediment data, this paper only uses the available information to carry out the empirical estimation and theoretical calculation, but it is sufficient to illustrate the problem and its severity. Future research can be carried out with more detailed calculations, but more importantly, it should focus on how to innovate measures for dredging reduction, and apply effective methods and devices for silt reduction in Lancang reservoirs. Ensuring the sustainability of Lancang reservoirs should be the focus of research, but little research has been done in this area.

5. CONCLUSIONS

Based on reservoir information and sediment data, this paper uses empirical and theoretical methods to illustrate the siltation status of the Manwan and Jinghong reservoirs in the Lancang river, and the siltation situations of Xiaowan and Nuozhadu reservoirs are also reflected from the side. Results show that since Manwan reservoir was put into use, the storage capacity has lost 51.4% in just two or three decades, and the trapping efficiency has reached 69%. The siltation of Manwan reservoir is quite serious. The capacity loss of Jinghong reservoir reached 1.54% as of 2019 and the situation is much better. With the completion of Xiaowan and Nuozhadu reservoirs, the pressure on Manwan and Jinghong reservoirs has been relieved to some extent. The quantitative information this paper provided can enable managers to accurately grasp the current state of Lancang cascade reservoirs and provide scientific guidance for them to make relevant decisions. For Manwan and other reservoirs, practical and effective measures should be taken in time to ensure their sustainable development and prevent the sedimentation problems of other reservoirs from being more serious.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES

ADB 2004 *Cumulative Impact Analysis and Nam Theun 2 Contributions*. Final Report. Prepared by NORPLAN and EcoLao for Asian Development Bank (ADB), Vientiane, Laos, p. 143.

Binh, D. V., Kantoush, S. & Sumi, T. 2020 Changes to long-term discharge and suspended loads in the Vietnamese Mekong delta caused by upstream dams. *Geomorphology* **353**, 1–14.

Brown, C. B. 1943 Discussion of Sedimentation in Reservoirs. by B. J. Witzig. In: *Proceedings of the American Society of Civil Engineers*, Vol. 109, American Society of Civil Engineers, New York, pp. 1047–1106.

Brune, G. M. 1953 Trap efficiency of reservoirs. *Transactions of the American Geophysical Union* **34**, 407–418.

Code for measurement of suspended load in open channels 2015 GB/T 50159–2015. (in Chinese).

Dai, S. B., Yang, S. L. & Cai, A. M. 2008 Impacts of dams on the sediment load of the Pearl River, southern China. *Catena* **76**, 36–43.

Dendy, F. E. 1974 *Transactions of the ASAE*. American Society of Agricultural Engineers, St. Joseph, MI, pp. 898–908.

Dickey, D. A. & Fuller, W. A. 1979 Distribution of the estimators for autoregressive time series with a unit root. *Journal of American Statistical Association* **74**, 427–431.

Fan, H., He, D. M. & Wang, H. L. 2015 Environmental consequences of damming the mainstream lancang-Mekong river: a review. *Earth-Science Reviews* **146**, 77–91.

Fu, K. D. & He, D. M. 2007 Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the lancang river. *Chinese Science Bulletin* **52**, 134–140. https://doi.org/10.1007/s11434-007-7026-0.

Fu, K. D., He, D. M. & Lu, X. X. 2008 Sedimentation in the manwan reservoir in the upper Mekong and its downstream impacts. *Quaternary International* **186**, 91–99.

Fu, K. D., Yang, W. H., Su, B., Li, D. X., Li, M. Y., Zhang, J. L. & Song, J. Y. 2015 Response of river sediments to basin environmental changes: a case study of the Lancang River. *Progress in Geography* **34** (9), 1148–1155. doi:10.18306/dlkxjz.2015.09.007. (in Chinese).

Fuller, W. A. 1976 *Introduction to Statistical Time Series*. Wiley, New York, p. 373.

Han, Z. Y., Long, D., Fang, Y., Hou, A. Z. & Hong, Y. 2019 Impacts of climate change and human activities on the flow regime of the dammed Lancang River in Southwest China. *Journal of Hydrology* **570**, 96–105.

Harbor, J., Bhaduri, B., Angelakis, L. & Snyder, J. 1997 *Sediment Basins, Using Modified Storm Water Management Basins and Sediment Basins to Reduce Water Pollution From Construction Sites in Ohio*. Department of Geology, Kent State University, Kent, OH.

He, D. M. 2004 *Research on Transboundary Impact of Lancang River Cascades Development and its Countermeasures*. Asian International Rivers Center, Yunnan University, and Yunnan Huaneng Lancang River Hydropower Co. Kunming, Yunnan. (in Chinese).

He, D. M., Wu, S. H., Peng, H. & Yang, Z. F. 2005 A study of ecosystem changes in longitudinal range-gorge and transboundary eco-security in southwest China. *Advances in Earth Science* **20**, 338–344. (in Chinese with English abstract).

Hecht, J. S., Lacombe, G., Arias, M. E., Dang, T. D. & Piman, T. 2019 Hydropower dams of the Mekong River basin: a review of their hydrological impacts. *Journal of Hydrology* **568**, 285–300.

Heinemann, H. G. 1981 A new sediment trap efficiency curve for small reservoirs. *Water Resources Bulletin* **17**, 825–830.

Heinemann, H. G. 1984 Reservoir trap efficiency. In: *Erosion and Sediment Yield: Some Methods of Measurement and Modelling* (Hadley, R. F. & Walling, D. E. eds.). Geo Books, Norwich, pp. 201–218.

Hou, S. Y., Tian, F. Q. & Ni, G. H. 2020 Review of sediment yield, transportation, and trap in reservoirs in Lancang-Mekong River Basin. *Advances in Water Science* **31** (04), 619–628.

Jiang, Y., Gao, J. X. & Ou, X. K. 2006 Change of land use pattern and analysis of environment impact of LancangWatershed in Yunnan. *Research of Environmental Sciences* **19** (3), 46–51. (in Chinese).

Kummu, M. & Varis, O. 2007 Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* **85** (3–4), 275–293.

Kummu, M., Lu, X. X., Wang, J. J. & Varis, O. 2010 Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. *Geomorphology* **119** (3–4), 181–197. https://doi.org/10.1016/j.geomorph.2010.03.018.

Liu, H., Liu, J. F. & Tang, H. X. 1998 Present and future of water resources development in the Lancang River Basin in Yunnan Province. *Advances in Water Science* **9**, 70–76. (in Chinese with English abstract).

Liu, C., He, Y., Walling, D. E. & Wang, J. J. 2013 Changes in the suspended load of the Lancang-Mekong River over the period 1965–2003. *Science China-Technological Sciences* **56** (4), 843–852.

Milliman, J. D. & Meade, R. H. 1983 World-wide delivery of river sediment to the oceans. *Journal of Geology* **91**, 1–21.

Morris, H. M. 1963 *Applied Hydraulics in Engineering*. The Ronald Press Co., New York, New York, p. 339.

Morris, G. L. & Fan, J. 1998 *Reservoir Sedimentation Handbook*. McGraw-Hill, New York.

Räsänen, T. A., Koponen, J., Lauri, H. & Kummu, M. 2012 Downstream hydrological impacts of hydropower development in the Upper Mekong Basin. *Water Resources Management* **26** (12), 3495–3513.

Roberts, T. 2001 *Downstream Ecological Implications of China's Lancang Hydropower and Mekong Navigation Project*. International Rivers Network.

Siyam, A. M., Yeoh, J. S. & Loveless, J. H. 2001 Sustainable reservoir sediment control. In *XXIX IAHR Congress*, Beijing.

Sun, Z. L., Zheng, H. L. & Sun, L. X. 2021 Analysis on the characteristics of bed materials in the Jinghong Reservoir on the Lancang River. *Sustainability* **13** (12), 1–9.

USDA-NRCS 1983 Section 3: 'Sedimentation'; Chapter 8 'Sediment storage design criteria'. In: *National Engineering Handbook*, 2nd edn. US Department of Agriculture, National Resources Conservation Service eDirectives, Washington, DC.

Vorosmarty, C. J., Sharma, K., Fekete, B., Copeland, A. H., Holden, J., Marble, J. & Lough, J. A. 1997 The storage and aging of continental runoff in large reservoir systems of the world. *Ambio* **26**, 210–219.

Vorosmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P. & Syvitski, J. P. M. 2003 Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change* **39**, 169–190.

Walling, D. E. 2006 Human impact on land–ocean sediment transferred by the world's rivers. *Geomorphology* **79** (3–4), 192–216.

WCD. 2000 *Dams and Development: A New Framework for Decision Making*. Earthscan, London and Sterling, VA.

Xu, K., Milliman, J. D., Yang, Z. & Wang, H. 2006 Yangtze sediment decline partly from Three Gorges Dam. *Eos, Transactions, American Geophysical Union* **87** (19), 185–196.

Zhai, H. J., Hu, B., Luo, X. Y., Qiu, L., Tang, W. J. & Jiang, M. 2016 Spatial and temporal changes in runoff and suspended loads of the Lancang River over the last 50 years. *Agricultural Water Management* **174** (SI (1)), 74–81.

Zhang, P. F. & Xu, J. C. 2003 Analysis of spatial- temporal characteristics of land use change and its driving forces in the Lancang basin of Yunnan Province. *Advance in Earth Sciences* **18** (6), 947–953. (in Chinese).

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