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Review Article

Review and improvement of conventional models for reservoir sediment trapping efficiency

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ABSTRACT

Sediment accumulation has been the most important factor influencing the comprehensive benefit of reservoirs. A quantitative investigation of the sediment trapping efficiencies of reservoirs is a key to understanding the impact of sedimentation on reservoirs. Generally, the simplest method to assess sediment accumulation ratio is adopting sediment concentration curve with trap efficiency (TE) of the reservoir. Many empirical and semi-empirical models have been proposed to determine this term related to the average annual inflow, features and characteristics of the reservoir watershed area. In this article four different empirical models decided by capacity to inflow ratio (C/I), capacity to watershed ratio (C/W) were used. These different models were summarized and utilized to determine TE of large reservoirs on the Upper Yangtze River for recent decades. Based on these conventional models, an improved model to estimate sediment trapping efficiency is proposed, and experimental data from other 18 reservoirs come from different basins were used to validate the model. The results indicate that the sediment trapping efficiencies that were estimated by the four empirical model were similar to the measured efficiencies for reservoirs on the Upper Yangtze River. Among the the Brune and Siyam empirical models were the most reliable and can be applied to estimate sediment trapping efficiency for reservoirs on the Upper Yangtze River. The improved model takes the capacity/annual inflow ratio and capacity/watershed area ratio into account comprehensively, the effect of particle size and settling velocity of the sediment are also considered, it is more applicable and accuracy to predict large reservoir sediment trapping efficiency. The results of this study provide a valuable reference for predicting large reservoir sedimentation and sediment regulation.

1. Introduction

Reservoir completion results in the rise of water levels within the reservoir, an increase in water depth, a decrease in flow velocity, and a gradual reduction in reservoir capacity due to sediment deposition. In particular, sediment deposition reduces the function of reservoir, which is one of the most important factors and universal problems that influences the benefits gained by use of the reservoir. Globally, the amount of sediment entering the ocean from rivers is about 15–20 Gt per year (Milliman and Meade, 1983; Milliman and Syvitski, 1992). The large-scale transport of sediments to oceans plays a significant role in the biochemical functioning of coastal areas and the evolution of shorelines. However, the loss rate of reservoir capacity caused by reservoir sedimentation is about 1% yearly, which is equivalent to a storage capacity loss of 50 billion m^3 (World Commission of Dams, 2005). The annual average ratio of storage loss in reservoirs of the United States is 0.22%, while that of reservoirs in Turkey is 1.2%. In contrast, the annual average loss rate of reservoirs capacity in Chinese is 2.3%, which is higher than the global average (Jiang and Fu, 1997). In addition, the reservoir sedimentation has an important influence on the safe operation of reservoirs, sediment regulation, riverine sediment transport, and the ecological environment of the downstream river. Some studies have indicated that the suspended sediment discharge (SSD) entering the Yangtze estuary has decreased dramatically (Yang et al., 2002, 2015; Gao and Wang, 2008; Dai et al., 2011, 2014, 2016; Zhao et al., 2017).

A key parameter for evaluating the dam life expectancy is the reservoir sediment trapping efficiency (TE). TE is expressed as the rate of annual sediment deposited in reservoirs to annual sediment load

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incoming to the reservoirs. The TE is determined by several parameters, such as particle size and distribution; the reservoir shape and size; the time and speed of runoff entering the reservoir; the location and depth of outlets, reservoir drainage dispatching mode (Yang, 1996, 2003; Verstraeten and Posen, 2000; Campos, 2001). Many empirical researches on the relationship between water inflow, reservoir capacity, and trap efficiency have been published in the literature (Brown, 1944; Churchill, 1948; Brune, 1953). Most models use curves to determine the relationship between TE and annual average inflow and reservoir capacity parameters.

The first trap efficiency assessment method was first proposed by Brown in 1944. USACE (USACE, 1989) defined the model as capacity to watershed model on account of the Brown curve correlating the rate of the reservoir capacity and the watershed area to trapping efficiency. Following the Brown model, the next model for estimating TE was the Churchill (1948) model. Churchill developed a relationship between the sediment load entering reservoir (100–TE) and the sedimentation index, in percentage also known as discharge efficiency. Churchill established two curves, one is for local sediment, that is, for sediment originated in the watershed area and the other is for fine sediment from the upstream reservoir. The Churchill model is limited to estimate the discharge efficiency in sedimentation tanks, small reservoirs, flood control structures, continuous flushing reservoirs or semi-dry reservoirs (Murthy, 1980; Morris and Fan, 1998). Following the Churchill model, Brune (1953) put forword the next method for predicting TE. This model may be the most widely adopted model for assessing the reservoir trapping efficiency. The Brune curves were drawn from the measured data of 44 normal reservoirs in the US. Brune drew trap efficiency against the reservoir Capacity to annual inflow ratio (C/I). Then, The Brune model was further developed for different regions and different reservoir types, including by Morris (Morris and Fan, 1960), Dendy (Dendy, 1974), Gill (Gill, 1979), and Heinemann (Heinemann, 1981), among others. Siyam (Siyam et al., 2005) proposed another model in 2005 that was based on the trap efficiency of mixed water storage. Further, Jothiprakash (Jothiprakash and Garg, 2008) estimated the trapping efficiency of the Gobindsagar reservoir in 2008 based on the Brune and Brown model and summarized the Jothiprakash empirical model through regression analysis.

The numerical model of water and sediment developed in recent decades has also been applied to compute the reservoir sediment trapping efficiency. Its principle is to simulate the process of drainage and sediment discharge under a certain reservoir operation mode, and then deduce the sediment trapping situation of reservoirs by combining the process of incoming and outcoming water and sediment. One-dimensional unsteady flow sediment computation model, developed by Hu (Hu et al., 2003), was applied to reservoir sediment deposition computation of Xiangjiaba hydropower plant. The concrete computation issues include sediment deposition in the reservoir, reservoir capacity losses, sediment discharge ratio of the reservoir. It can be concluded that the sediment release ratio in the early operation period of the reservoiris comparably larger but gradually decreases year by year, and then increases again until sediment balance in the reservoir. Huang (Huang and Huang, 2009) used one-dimensional unsteady water and sediment numerical model to preliminarily study the incoming water and sediment conditions of the Three Gorges Reservoir in 1961–1970 series and the 100-year scouring and silting prediction calculation under the regulation scheme of the normal storage level of reservoir, and obtained a reasonable calculation result. Although it has certain applicability, there are some blind spots in the study of water-sediment movement law, so the sediment trapping efficiency calculated by numerical model usually deviates from the actual value, and the process is complex. It is not easy to determine the relevant parameters (such as saturation coefficient, roughness, etc.), so the empirical model has obvious advantages in determining the sediment trapping efficiency.

Since the conventional models take the capacity to watershed ratio or capacity to inflow ratio individually in estimating the sediment trapping efficiency (TE), without considering the mutualistic effects of both. This paper compares the results of the Brown, Brune, Siyam, and Jothiprakash model in calculating 20 large reservoirs (more than 1.0×10^9 km^3 storage capacity) in the Upper Yangtze River. Then, proposes an improved model for trap efficiency (TE), which takes the capacity to watershed ratio and capacity to inflow ratio into account comprehensively, and experimental data from other 18 large reservoirs come from different basins were used to validate the improved model.

2. Main text

2.1. Models used to estimate trap efficiency

The reservoir trapping efficiency, refers to the rate of sediment deposition in reservoirs to the amount of incoming sediment in reservoirs at the same period, as follows:

$$TE = \frac{S_{inflow} - S_{outflow}}{S_{inflow}} = \frac{S_{settled}}{S_{inflow}} \tag{1}$$

where S_{inflow} is the incoming sediment amount, $S_{outflow}$ is the outgoing sediment amount, and $S_{settled}$ is the amount of sediment deposition in reservoirs. Formula (1) is the theoretical calculation of reservoir sediment-trapping efficiency, while the actual trap efficiency is affected by numerous factors based on the characteristics of different reservoirs. The complexity of sediment deposition process leads to the diversity of methods for determining the sediment trapping efficiency. Some are direct and some are indirect. The former uses bathymetric and sedimentological data to measure the results, while the latter uses hydrological data and reservoir features to calculate the results (Espinosa-Villegas and Schnoor, 2009; Lewis et al., 2013). These models are widely adopted for engineering purposes. Thus, a large number of empirical models are published, the most common of which are:

1) Brown model:

$$\mathrm{TE} = 100\left[1 - \frac{1}{1 + D\frac{C}{W}}\right] \tag{2}$$

where C, is reservoir capacity in acres/feet; W, is the watershed area above the reservoir in miles^2 or

$$\mathrm{TE} = 100\left[1 - \frac{1}{1 + 0.0021D\frac{C}{W}}\right] \tag{3}$$

where C, is reservoir active storage capacity in m^3; W, is watershed area in km^2, and D is factor determined by detention time and sediment particle size which varies between 1, 0.1 and 0.046 for coarse, medium

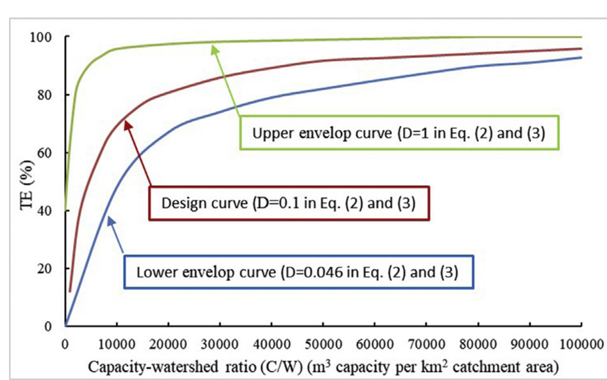

Fig. 1. Trap efficiency related to capacity/watershed ratio.

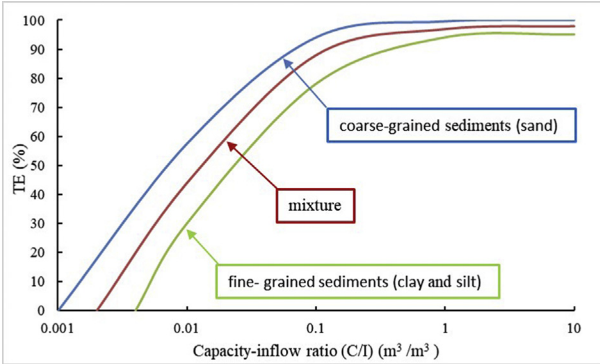

Fig. 2. A modification of the Brune (1953) TE curves for different textures using the relations of the Summit County Soil and Water Conservation District.

and fine sediment respectively (Fig. 1) (Brown, 1944).

2) Brune model:

$$TE = 1 - \frac{0.05\alpha}{\sqrt{\Delta\tau_R}} \tag{4}$$

where α is the correction factor, and $\Delta\tau_R$ is the reservoir water residence time that can be calculated adopting the following equation:

$$\Delta\tau_R = \sum_{1}^{n} C_j / I \tag{5}$$

where C_j is the active (regulation) storage of the j[th] class reservoir expressed in m^3, and I is the average annual runoff of the downstream control section of the dam expressed in m^3. $\Delta\tau_R$ is defined as the detention coefficient that approximates the regulating runoff coefficient of the reservoir (Fig. 2) (Brune, 1953).

3) Siyam model:

$$TE = e^{-\beta \frac{I}{C}} \tag{6}$$

Where, I is the average annual runoff (in m^3) of the downstream control section of the dam, and C is the reservoir active storage capacity (in m^3). β is a correction factor and reservoir sedimentation parameter that reflects the degree of sediment deposition due to the reservoir impoundment detention time. This parameter reflects the hydraulic condition of reservoirs, is variable, and depending on the sedimentation rate of sediment, the reservoir shape and area, and the power-station dispatching. Its value can be estimated by changes of incoming and outcoming sediment transport load.

4) Jothiprakash model:

$$TE = \frac{8000 - 36\left(\frac{C}{I}\right)^{-0.78}}{78.85 + \left(\frac{C}{I}\right)^{-0.78}} \tag{7}$$

where C is the reservoir active storage capacity, and I is the average annual runoff of the downstream control section of the dam.

2.2. Available data and calculation results

2.2.1. Available data

Our analysis focused on 20 large reservoirs of the Upper Yangtze River. Eight of the reservoirs are in the Jinsha River basin, including six cascade reservoirs in the middle-lower reaches, Xiluodu Reservoir, Xiangjiaba Reservoir; two in Yalong River basin; two in Minjiang river basin, including one in Dadu River basin; three in Jialing River basin; four reservoirs in Wujiang River basin, including the Three Gorges Reservoir. The schematic map of the water systems of the Upper Yangtze River and the major reservoirs are shown in Fig. 3, while the relevant characteristic parameters of each reservoir are provided in Table 1.

2.2.2. Correction factor calibration

The known sediment trapping efficiency of Ertan Reservoir on Yalong River was used to calibrate the correction coefficients for the Brune and Siyam model to calculating the sediment trapping efficiency of the Upper Yangtze River reservoirs using the four empirical models. The empirical

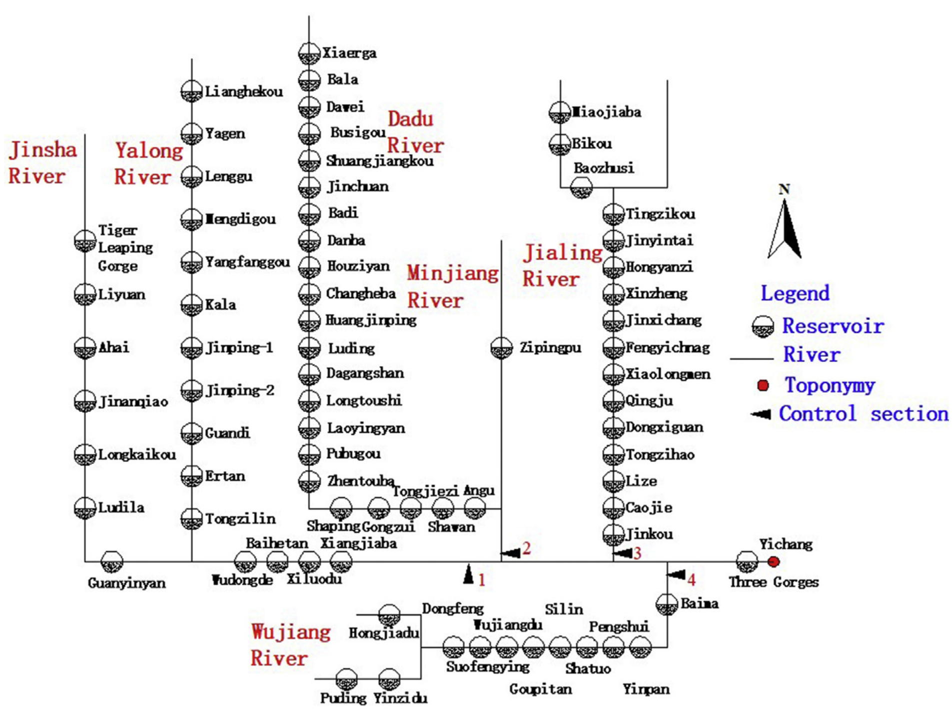

Fig. 3. Schematic map of the water systems of the Upper Yangtze River and the main reservoirs.

Table 1
Characteristic parameters of 20 reservoirs on the Upper Yangtze River.

Reservoir	Watershed area W (10^4 km^2)	Average annual inflow I (10^9 m^3)	Normal water level (m)	Total storage (10^9 m^3)	Active storage C (10^9 m^3)	Time of completion
Liyuan	22	451.9	1618	8.05	1.73	2012
Ahai	23.54	518.3	1504	8.85	2.38	2014
Jinanqiao	23.74	527.7	1418	9.13	3.46	2011
Longkaikou	24	540.4	1298	5.58	1.13	2014
Ludila	24.73	553.1	1223	17.18	3.76	2014
Guanyinyan	25.65	578.3	1134	22.5	5.55	2016
Xiluodu	45.44	1441	600	126.7	64.6	2013
Xiangjiaba	45.88	1460	380	51.6	9.03	2012
Jinping-I	10.26	385	1880	79.9	49.11	2015
Ertan	11.64	527	1200	58	33.7	1998
Zipingpu	2.27	148	877	11.12	7.74	2006
Pubugou	6.85	388	850	53.32	38.94	2009
Bikou	2.6	86.7	704	2.17	1.46	1976
Baozhusi	2.8	90.6	588	25.5	13.4	1996
Tingzikou	6.26	189	458	40.6	17.32	2016
Goupitan	4.33	234	630	64.54	29.02	1995
Silin	4.86	272.16	440	15.93	3.17	2003
Shatuo	5.45	300.54	365	9.21	2.87	2004
Pengshui	6.9	416.28	293	14.56	5.18	2004
TGR	100	4510	175	450.7	165	2003

models were then used to estimate the sediment trapping of other reservoirs that had equivalent scales to the Ertan Reservoir.

The Ertan Reservoir was the first hydropower station to be developed in the Yalong River cascade. Construction began in September 1991, and water storage began in May 1998. The reservoir is classified as a seasonal regulation reservoir with a watershed area of 11.64 10^4 km^2, normal storage level of 1,200 m, total storage of 5.8×10^9 m^3, and a regulation storage of 3.37×10^9 m^3. The main hydrologic control station of the Ertan Reservoir, the Luning station, is located upstream. Additionally, the Zouyu River is the only large tributary between Luning and the dam, with a catchment area of 3,040 km^2. Xiaodeshi is the hydrologic control station at the lower reaches of the Ertan. The sediment load at Xiaodeshi has decreased considerably since the operation of the Ertan reservoir.

The annual sediment discharge at Xiaodeshi station was 31.4×10^6 t between 1961 and 1997 and 7.3×10^6 t between 1998 and 2000, corresponding to a 77% reduction. The annual sediment discharge at Luning station is 20×10^6 t, but it increased to 60.3×10^6 t between 1998 and 2000. When the Ertan station opened in 1998, the sediment discharge at Luning station increased to 74.9×10^6 t. Thus, the annual sediment discharge from Luning to Xiaodeshi was 11.5×10^6 t between 1961 and 1997. Under the assumption that the annual sediment discharge from Luning to Xiaodeshi was 11.5×10^6 t between 1998 and 2000, the annual sediment sediment transport at Ertan station was 71.7×10^6 t between 1998 and 2000; thus, the annual sediment sediment transport at Ertan

Table 2
Average annual trapped sediment load at the Ertan station (in 10^4 t).

Year	Luning station (L)	Xiaodeshi station (X)	Sediment load 1 from L–X	Sediment load 2 from L–X	Sediment trapped load 1	Sediment trapped load 2
1998	7,490	1,600	1,150	3,250	7,040	9,140
1999	6,400	350	1,150	2,830	7,200	8,880
2000	4,200	240	1,150	1,990	5,110	5,950
1998–2000	6,030	730	1,150	2,690	6,450	7,990

Table 3
Trap efficiency of 20 reservoirs on the Upper Yangtze River, as calculated by four empirical models.

Reservoir	C/I	C/W	D_m (mm)	ω(10^{-3} m/s)	Brown	Brune	Siyam	Jothiprakash	Measured TE
Liyuan	0.004	0.079	0.015	0.158	0.268	0.313	0.271	0.703	0.260
Ahai	0.005	0.101	0.014	0.141	0.273	0.373	0.337	0.695	0.260
Jinanqiao	0.007	0.146	0.014	0.129	0.278	0.475	0.466	0.697	0.380
Longkaikou	0.002	0.047	0.013	0.109	0.189	0.071	0.092	0.589	0.040
Ludila	0.007	0.152	0.012	0.097	0.410	0.485	0.479	0.795	0.600
Guanyinyan	0.010	0.216	0.012	0.097	0.467	0.566	0.594	0.825	0.590
Xiluodu	0.045	1.422	0.011	0.085	0.736	0.799	0.837	0.907	0.784
Xiangjiaba	0.006	0.197	0.011	0.085	0.529	0.730	0.724	0.813	0.746
Jinping-I	0.128	4.787	0.01	0.0702	0.886	0.881	0.962	0.958	0.930
Ertan	0.064	2.895	0.01	0.0702	0.833	0.832	0.925	0.924	0.925
Zipingpu	0.052	3.410	0.01	0.0702	0.830	0.814	0.909	0.895	0.800
Pubugou	0.100	5.685	0.01	0.0702	0.886	0.866	0.951	0.937	0.900
Bikou	0.017	0.562	0.009	0.0567	0.455	0.672	0.743	0.762	0.730
Baozhusi	0.148	4.786	0.009	0.0567	0.901	0.889	0.967	0.969	0.939
Tingzikou	0.092	2.767	0.009	0.0567	0.866	0.860	0.947	0.959	0.913
Goupitan	0.124	6.702	0.007	0.0344	0.937	0.879	0.960	0.969	0.869
Silin	0.012	0.652	0.007	0.0344	0.766	0.606	0.651	0.872	0.653
Shatuo	0.010	0.527	0.007	0.0344	0.628	0.565	0.592	0.793	0.540
Pengshui	0.012	0.751	0.007	0.0344	0.678	0.619	0.669	0.811	0.576
TGR	0.037	1.650	0.006	0.0252	0.818	0.778	0.804	0.917	0.740
Average error					**9.2%**	**4.88%**	**4.97%**	**18.1%**	

station was 64.5 × 10^6 t. According to the relationship between the annual sediment discharge at Xiaodeshi station and the Luning station between 1961 and 1997, the annual sediment load of Luning to Xiaodeshi can be estimated as 26.9 × 10^6 t between 1998 and 2000. Moreover, the incoming sediment discharge increased to 32.5 × 10^6 t in 1998. Therefore, the average annual incoming sediment discharge at Ertan station was 87.2 × 10^6 t between 1998 and 2000, and the average annual trapped sediment load is 79.9 × 10^6 t (Table 2).

In conclusion, the average annual trapped sediment load of the Ertan Reservoir was 72.2 × 10^6 t between 1998 and 2000, and the average annual incoming sediment load was about 78.5 × 10^6 t. Thus, the measured sediment trapping efficiency of the Ertan Reservoir was 92.5%. Substituting the measurement data for the Ertan Reservoir into Eqs. (3) and (5), the modified coefficients can be obtained as $\alpha = 0.85$ and $\beta = 0.005$, respectively.

2.2.3. Calculation results

The four conventional empirical models were then used to calculate the trap efficiency of 20 large reservoirs in the Upper Yangtze River.

The sediment trapping efficiencies calculated by the four different empirical models were obviously different. The average error between the calculated trap efficiencies and measured trap efficiencies were smallest using the Brune model (4.88%) followed by the Siyam model (4.97%). In contrast, the average error between the calculated and measured trap efficiencies when using the Brown model and Jothiprakash model were higher, at 9.2% and 18.1%, respectively. The Brown model and Brune model exhibited consistent deviations in results, which were either larger or smaller than measured values. When using the Jothiprakash and modified Siyam model to estimate efficiencies, the values were generally larger than the measured values. However, the standard errors using the Siyam model were relatively small, while estimations with the Jothiprakash model exhibited large deviations

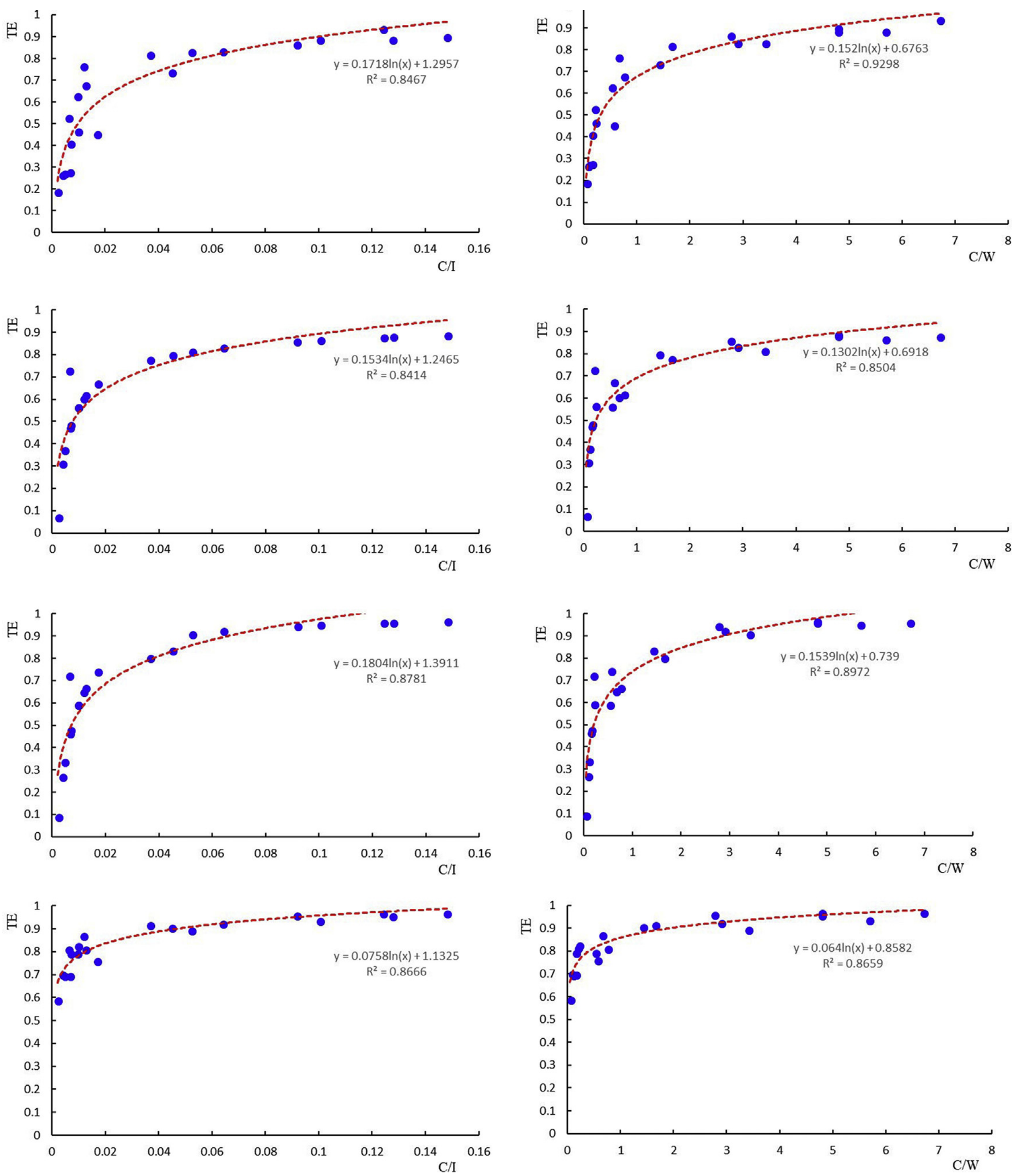

Fig. 4. Relationship between calculated Trap Efficiency (TE) and C/I and C/W ratios for the four empirical formulae that were used to analyze sediment-trapping.

(Table 3).

The calculated capacity to inflow ratio and capacity to watershed ratio for each reservoir were compared with the four empirical model for estimating sediment trapping efficiency (Fig. 4). From top to bottom are Brown, Brune, Siyam, Jothiprakash, respectively.

The reservoir sediment trapping efficiency was closely related to capacity to inflow ratio and capacity to watershed ratio. The correlation between the Brown model and the capacity-watershed area ratio was the highest (0.93), while the correlation between the Siyam model and capacity-inflow ratio was the highest (0.88).

Since the conventional models take the capacity-watershed ratio or capacity-inflow ratio individually in estimating the sediment trapping efficiency (TE), this article takes the capacity to inflow ratio and capacity to watershed ratio into account comprehensively, the effect of particle size and settling velocity of the sediment are also considered. Accordingly, the improved model for the sediment trapping efficiency in the Upper Yangtze River is as follows:

$$\mathrm{TE} = \gamma \mathrm{Ln}\left(D_m \frac{C}{W}\right) + \delta \mathrm{Ln}\left(\omega \frac{C}{I}\right) + \varepsilon \tag{8}$$

Where D_m is the medium particle size of the sediment, the medium particle size indicates that the weight of sediment larger than or smaller than this particle size is just equal in all the sand samples. ω is the settling velocity of the sediment deposits, it refers to the velocity of sediment settling at constant speed in stationary clear water. It is mainly affected by the shape of sediment, flocculation, low sediment concentration. Normally, the settling velocity corresponding to different sediment particle sizes at room temperature (25 degrees Celsius) is taken.γ, δ and ε are the related parameters.

Therefore, the improved model to calculate the sediment trapping efficiency can be obtained as:

$$\mathrm{TE} = 0.174 \mathrm{Ln}\left(D_m \frac{C}{W}\right) - 0.022 \mathrm{Ln}\left(\omega \frac{C}{I}\right) + 1.371 \tag{9}$$

The data measured for 18 large reservoirs, including the Guandi reservoir, Dagangshan reservoir, Wujiangdu reservoir, Xiaolangdi reservoir, Ankang reservoir and Yantan reservoir which come from different basins, were used to validate the accuracy of the improved model (Table 4).

The average error between the calculated trap efficiencies and measured trap efficiencies were relatively small by using the Brune model (8.2%) followed by the Siyam model (8.4%). In contrast, the average error between the calculated and measured trap efficiencies when using the Brown model and Jothiprakash model were higher, at 12.9% and 14.7%, respectively. While, the average error between the estimated trap efficiency using the improved model and the measured trap efficiency was 4.1%, which was minimal. Thus, the improved model has better applicability and accuracy in the calculation of large reservoirs sediment trapping efficiency than other empirical models.

2.3. Results and discussion

The reservoir sediment trapping efficiency was closely related to the capacity to inflow ratio (C/I) and capacity to watershed ratio (C/W). The correlation between the Brown model and the capacity to watershed ratio was the highest (0.93), while the correlation between the Siyam model and capacity to inflow ratio was the highest (0.88).

The average error between the calculated trap efficiencies and measured trap efficiencies were relatively small by using the Brune model and the Siyam model, which was 8.2% and 8.4% respectively. In contrast, the average error between the calculated and measured trap efficiencies when using the Brown model and Jothiprakash model were higher, at 12.9% and 14.7%, respectively. While, the average error between the estimated trap efficiency using the improved model and the measured trap efficiency was minimal.

When using the improved trap efficiency model, it should be noted that the independent parameters (C/I, C/W) of each reservoir are dynamic. With the occurrence of sedimentation, the active storage capacity decreases, the capacity to inflow ratio and capacity to watershed ratio decrease accordingly. The trap efficiency of rapid-silting reservoirs will therefore decline through time (Butcher et al., 1992). Rowan et al. (1995) noticed that if sediment in a reservoir or lake is used to reconstruct sedimentation, trap efficiency should be considered as a dynamic term.

It should be emphasized that traditional empirical models stated above are based on a limited number of reservoir data in designateed areas. Therefore, it may be inappropriate to use these models to predict sediment trapping efficiency in areas with other features, such as sediment yield, runoff response and rainfall regime. In addition, since most empirical curves are designed for large reservoirs, the improved model is not suitable for smaller reservoirs and ponds. Because these reservoirs and ponds usually have a low capacity to inflow ratio or capacity to watershed ratio.

3. Conclusion

In this study, four different empirical models decided by capacity to inflow ratio, capacity to watershed ratio were summarized and utilized to determine TE of large reservoirs in the Upper Yangtze River for recent

Table 4
Comparison of calculated trap efficiency by four empirical model and an improved model against measured trap efficiency.

Basin	Reservoir	D_m (mm)	ω (10^{-3} m/s)	Brown	Brune	Siyam	Jothiprakash	Improved model	Measured TE
Yalongjiang	Guandi	0.01	0.0702	0.362	0.387	0.353	0.699	0.422	0.37
Daduhe	Dagangshan	0.01	0.0702	0.553	0.302	0.260	0.759	0.409	0.43
Daduhe	Gongzui	0.01	0.0702	0.289	0.176	0.153	0.478	0.378	0.26
Wujiang	Puding	0.007	0.0344	0.972	0.842	0.934	0.912	0.903	0.89
Wujiang	Yinzidu	0.007	0.0344	0.985	0.853	0.945	0.929	0.937	0.91
Wujiang	Dongfeng	0.007	0.0344	0.973	0.793	0.893	0.898	0.818	0.85
Wujiang	Suofengying	0.007	0.0344	0.847	0.453	0.453	0.616	0.507	0.48
Wujiang	Wujiangdu	0.007	0.0344	0.885	0.896	0.942	0.935	0.917	0.929
Yellow River	Qingtongxia	0.04	0.112	0.184	0.947	0.614	0.723	0.475	0.496
Yellow River	Xiaolangdi	0.04	0.112	0.646	0.949	0.817	0.971	0.576	0.763
Qingjiang	Geheyan	0.028	0.0612	0.959	0.954	0.972	0.968	0.996	0.968
Hanjiang	Ankang	0.023	0.0323	0.879	0.951	0.910	0.936	0.840	0.904
Hangjiang	Huanglongtan	0.0057	0.0248	0.913	0.952	0.950	0.954	0.939	0.938
Lancangjiang	Manwan	0.0035	0.00118	0.446	0.945	0.472	0.753	0.477	0.46
Lancangjiang	Dachaoshan	0.0035	0.00118	0.437	0.946	0.570	0.742	0.525	0.513
Yuanshui	Fengtan	0.005	0.00175	0.888	0.951	0.928	0.907	0.910	0.914
Zhujiang	Yantan	0.0066	0.00324	0.709	0.949	0.837	0.848	0.735	0.716
Zhujiang	Lubuge	0.008	0.00449	0.601	0.947	0.705	0.735	0.647	0.660
Average error				**12.9%**	**8.2%**	**8.4%**	**14.7%**	**4.1%**	

decades. Based on these conventional models, an improved model to estimate sediment trapping efficiency is proposed, and experimental data from other 18 reservoirs come from different basins were used to validate the model. The main conclusions from this study are as follows:

(1) The sediment trapping efficiencies that are estimated by four different conventional models are similar to the measured trapping efficiencies for large reservoirs in the Upper Yangtze River. Among these, the average error exhibited by the Brune and Siyam models were the smallest, and these empirical models have applicability towards estimating the sediment TE of reservoirs in the Upper Yangtze River.
(2) The improved model takes the capacity to watershed ratio into and capacity to inflow ratio account comprehensively, and the average error between the estimated trap efficiency using the improved model and the measured trap efficiency was minimal in estimating 18 large reservoirs come from different basins. Thus, it is more applicable and accuracy to predict large reservoir sediment trapping efficiency.
(3) Through comparison of conventional empirical models, and the proposal of an improved model for predicting sediment trapping efficiency, the present study verifies and furthers existing theory and methods for calculating such efficiencies. Moreover, this study provides an important reference for reservoir sedimentation and the assessment of ecological impacts.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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