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Sediment management decision making of the Sanmenxia reservoir based on RESCON model

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In order to determine whether the existing in water resources system sustainable management solution, we need to develop a tool to provide reasonable and reliable information to decision makers. RESCON project's goal is to use data for reservoir and dam, to provide a toolkit in policy formulation used in decision making. At the same time, it also prompt policymakers stand at the national level to recognize the importance of reservoir protection. Sediment transport rate is an important parameter, which determines the amount of sediment flushed of the reservoir. So its calculating formula based on RESCON Model is revised and validated that it can be used to evaluate sediment management using the data of the Sanmenxia Reservoir in 2003. Among all the five-sediment management solutions RESCON model recommends that, the Flushing is with the highest economic benefit. Also, Flushing as the current sediment management strategy of the Sanmenxia reservoir shows that it is reasonable and effective. Among 15 Flushing solutions, the best one is that while the water level is at 290 m, flushing discharge rate is 1188 m^3/s, dredging every two years with a flushing period of 67 days each time and long-term reservoir storage volume is 16.05 billion m^3 below 323 m water level.

Key word: Reservoir sedimentation, RESCON model, sediment management, scheme comparison, the Sanmenxia reservoir.

INTRODUCTION

Reservoir sedimentation is one of the world's major economic and environmental problems in water conservancy construction. It is estimated that between 0.5 and 1.0% of global water storage volume is lost annually as a result of sedimentation. On the other hand, China has reached 2.3% (Wan, 2005). On average, the loss of reservoir storage volume can be translated into 45 km^3 of storage per year worldwide. Therefore, about $13 billion is needed to construct new reservoirs in compensation for this loss of storage. However, this approximation fails to include the influences of the newly built dams toward the environment and society (Cheng et al., 2004).

According to the National Bureau of Statistics of China (2013), there are 588 large reservoirs and 3271 medium-sized reservoirs and the total amount of water volume is

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3400.7 billion m^3 by the end of 2012. It is important to note that due to sediment deposition, the comprehensive benefits of reservoirs such as flood control ability, storage capacity, water supply capacity, power generation capacity decreased significantly. Similarly, crop yield of land with irrigation facilities, navigation capacity and tourism capability greatly declined. Sediment deposition also induced problems such as increase of dam load, decline of dam safety, abrasion of sluice outlets and power generating equipment, leading to reservoir retirement in the worst cases. According to the data provided by the Ministry of Water Resources regarding twenty reservoirs in the 1980s, most reservoirs have experienced total sediment deposition of 18.6%, in regard to the original designated storage volumes, within twenty years after established (Konrad, 2010).

Basson (Cheng et al., 2004; Ding, 2009), Hotchikiss (Duan et al., 2004) and Zhou (Zhang and Zhang, 1982) have carried out numerous studies about sediment control measures on single reservoir. At the same time, George et al. (2003) proposed a reservoir life-cycle management strategy, which emphasized the concepts of economic evaluation and sustainable development of sediment management, putting forward the concepts of intergeneration equity and conceptual model—RESCON based on principles of sustainable development. Konrad mentioned several issues that should be considered by Ecological reservoir regulation (Han, 2003). Also, others gave some reservoir optimal regulation strategies (Gao et al., 2013).

Various works have been conducted in China on sediment removal and volume recovery of reservoirs, especially in the Sanmenxia reservoir and the Three Gorges reservoir (Konrad, 2010; Mao et al., 1998; Tang, 1964; Tong and Zhou, 2006; Tu et al., 1980; Walling and Webb, 1996; Wan, 2005). George et al. (2003) studied the relationship of sediment delivery ratio under the status of higher water level based on non-equilibrium principle; Tang (1964) and Hu and Wang (2004) put forward an assumption and concept of long-term use of reservoirs. Guo et al. (2003) explicated the principle and foundation of long-term use of reservoirs and gave the calculation method for reserving reservoir storage volume. Many institutions have also done a lot of studies on retaining the effective reservoir storage volume in the Three Gorges and the Sanmenxia reservoir, and discussed its feasibility and effectiveness in technology and economic aspects (George et al., 2003; Tu et al., 1980).

On the basis of reviewing the experiences of reservoir operation on sediment-laden rivers in China, Chinese researchers established about three reservoir operation strategies which are “sediment decreasing regulation operation”, “reservoir operation optimization” and “reservoir ecological operation” (Wu et al., 2004). A reservoir operation strategy called “storing clear water and releasing the mud” was used for solving serious sediment deposition of reservoirs. “Storing clear water and releasing the mud” strategy means discharging sediment by reducing water level in flood period when there is more sand, while storing water in un-flood period. Many practices proved that this is an effective sediment management strategy for solving reservoir sediment deposition. For example, the Heisongling reservoir demonstrated that the amount of deposition was much smaller by using the “storing clear water and releasing the mud” strategy than by using the “impounding water” strategy. In the Sanmenxia reservoir, since using “storing clear water and releasing the mud” strategy from 1973, the amount of sediment deposition has been mostly under control in the reservoir area below Tongguan station and reservoir storage has been partly recovered under the elevation of 330 m. In the meantime, other reservoirs of Naodehai, Honglingjin, Heisongling, Zhiyu reservoirs e.t.c. have also achieved better effects in sediment reduction after adopting the “storing clear water and releasing the mud” strategy (Mao et al., 1998).

In December 1999, the World Bank initiated RESCON (Reservoir Conservation) project to develop an approach to assessment and promotion of sustainable management of reservoirs. Since 2001, RESCON projects have been investigating the sediment deposition problems in three countries: Kenya, Morocco and Sri Lanka, and evaluating selected reservoirs using RESCON, helping these countries to make sustainable reservoir management strategy. At present, RESCON has been applied in many reservoirs of Pakistan, Iran, India, Switzerland, and Japan (Wu and Deng, 2007).

The objectives of this study are applying RESCON approach in the Sanmenxia reservoir to evaluate its feasibility and finding the best sediment management strategy for reserving reservoir storage. It is expected that the studies and practices in sustainable utilization of the reservoirs in the world would be promoted.

METHODOLOGY

The Sanmenxia reservoir and its sediment management

Description of the Sanmenxia reservoir

The Sanmenxia hydropower-complex project is the first large-scale comprehensive project built on the mainstream of the Yellow River after 1949. Areas that dam site controlled is 68.8 million km^2, accounting for 91.5% of the total area of the Yellow River, controlling 89% of water, 98% of sediment of the Yellow River, and the two main flood source of the Yellow River: Hekou town to Longmen interval and Longmen to Sanmenxia interval. The Sanmenxia reservoir is also playing an important role and has comprehensive benefits in flood protection, irrigation, power generation and so on (Guo et al., 2003; Han, 2003; Hu and Wang, 2004; Huang and Zhao, 2000; Konrad, 2010; Tong and Zhou, 2006; Zhang and Wang, 1993; Zhang and Long, 1978). The Sanmenxia main dam is a concrete gravity dam, the length is 713.2 m, maximum height is 106 m, crest elevation is 353 m; the length of the auxiliary dam is 144 m, maximum height of the dam is 24 m. The designed standard of flood frequency is 0.1% and the checking

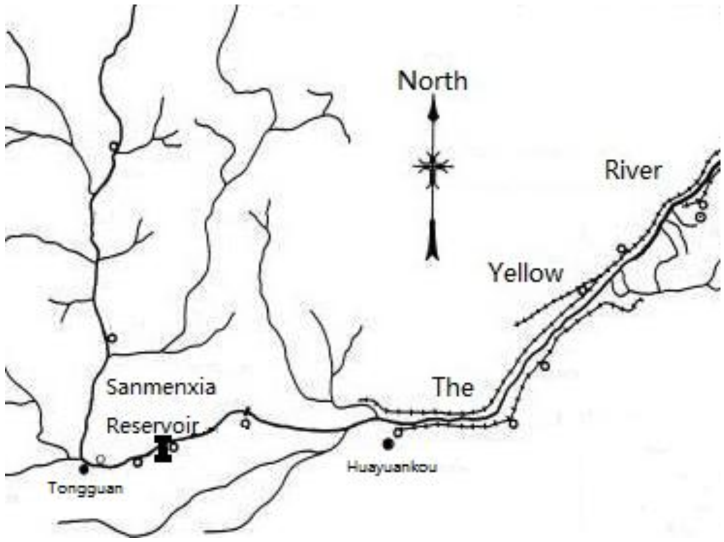

Figure 1. Position of the Sanmenxia reservoir.

standard is 0.01%; the designed highest water level is 340 m, the limited water level of flood storage is 335 m, corresponding reservoir storage volume is 55 million m^3. The measured biggest flood of the Sanmenxia reservoir occurred in 1933, peak discharge was 22000 m^3/s, runoff volume in 5 days was 51.8 billion m^3, while in 12 days the amount of volume was 91.8 million m^3. The historical maximum peak discharge was 36000 m^3/s. Figure 1 illustrates the position of the Sanmenxia reservoir.

Sediment characteristics of the Sanmenxia reservoir

The sediment characteristics of Sanmenxia reservoir are as follows. (1) annual runoff and sediment varies greatly (Tang, 1964; Walling and Webb, 1996); (2) annual distribution of runoff and sediment has changed, especially in flood season, the amount of runoff decreasing obviously; (3) the amount of total flood duration reduces year by year, runoff decreases greatly and the average sediment concentration increases in flood season (Feng et al., 2004; Wu et al., 2010); (4) after 1986, large flow appearance frequency decreases while the small one increases, the amount and days of flow less than 1500 m^3/s both play a dominant role.

Operation and sediment management of Sanmenxia reservoir

From 14 September 1960, the date on which Sanmenxia reservoir began to impound flood and to utilize, such as flood protection, power generation etc. till now, Sanmenxia reservoir has gone through two reconstructions and three different operation stages. ① "water storage and silt detention" (15 September 1960 to 19 March 1962); ② "flood detention-sediment discharging" (20 March 1962 to October 1973); and ③ "storing clear water and releasing the mud" (November 1973 – now) (White, 2001). Since the operation adopting "storing clear water and releasing the mud" strategy has been running in Sanmenxia reservoir, impounding water during non-flood season and controlling water level at 305 m in flood season could mainly keep the balance between scouring and sedimentation. The reservoir storage volume basically maintains at the amount of between 3 billion m^3 and 3.2 billion m^3 below the elevation of 330 m and the elevation of Tongguan mainly alternates between 326.5 and 328.5 m, the sedimentation tail has been effectively controlled (Guo et al., 2003; Konrad, 2010; Tang, 1964).

The sediment desilting methods of the Sanmenxia reservoir are: ①lower water level in front of dam to discharge sediment in flood season; ②Flushing at normal water level between the duration of two flooding events; ③Flushing with small discharge in dry period (which can be also called base flow sediment flushing). The operation of "storing clear water and releasing the mud" in the Sanmenxia reservoir is achieved by controlling the water level according to the principles that "exhausting flood in flood season and controlling water level at 305 m in normal river flow period".

RESCON THEORY AND MODEL

RESCON model and method

The specific objectives planned by RESCON model (Reservoir Conservation) initiated by the World Bank is to put forward the criteria of sediment discharging from the aspect of engineering and develop mathematical models to help decision makers rank the technical feasibility of the sediment discharging schemes from the angle of economics. Figure 2 illustrates the main steps of RESCON.

The overall aim of the RESCON model is to select a sediment management scheme that is technically feasible and also maximizes the net economic benefits. First, enter the technical and economic data on-the-spot; then test the technical feasibility of Flushing and Hydrosuction; If both of them taken through, then calculate their economic benefits and compare them with the Traditional Dredging, Trucking and "Do-nothing" scheme, eventually got the best feasible scheme.

Input and output of the RESCON model

Data input, computing process and result output of RESCON program are all achieved in Excel. Entering related technical parameters, user can get the results computed automatically by Excel. The data input items include technical and economic parameters and social and environmental safety parameters.

Calculation results are displayed mainly as flushing technical calculation, HSRS basic value calculation and economic computing results and conclusions.

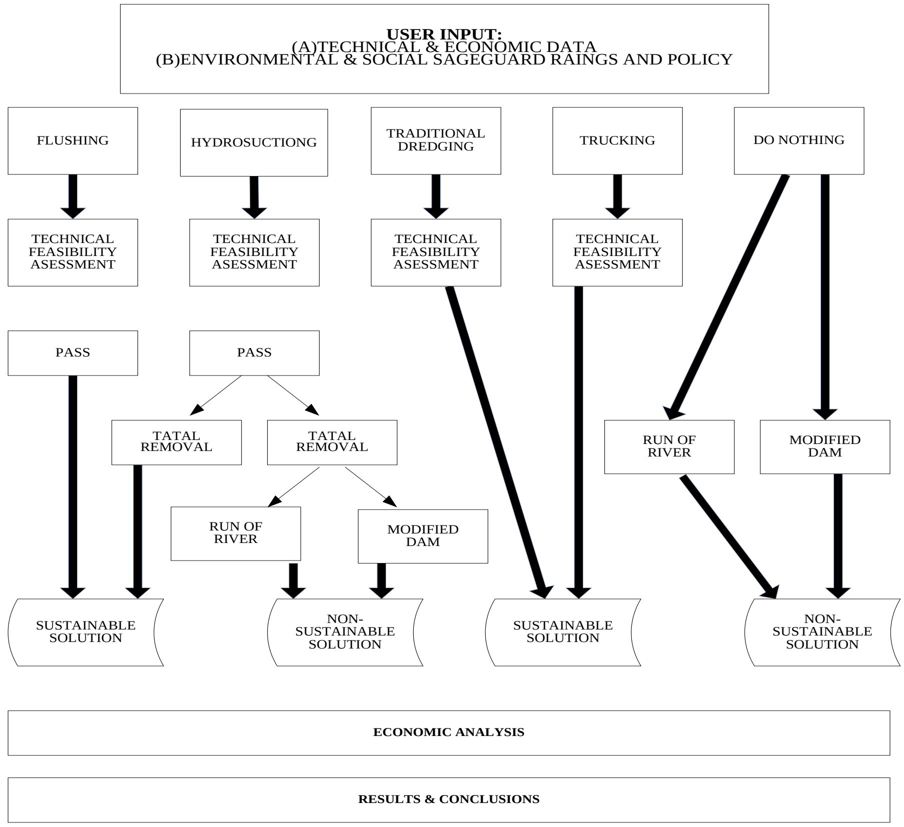

Figure 2. Program structure.

RESCON model parameters and data of the Sanmenxia reservoir

Basic data and parameters collection

RESCON program data input mainly include the following parameters: (1) reservoir geometry; (2) water characteristics; (3) sediment characteristics; (4) removal parameters; (5) economic parameters; (6) flushing benefit parameters; and (7) capital investment. Among them, the core parameter is the sediment parameters.

The parameters using in this research are mainly achieved from the actual measured flow and sediment data of Tongguan station from 1974 to 2004 after investigation and treatment. Model main input data value is shown in input data summary table (Appendix).

Collaborating parameters

In Flushing scheme, the most important parameter in the process of calculating sediment balance is Q_s, namely sediment transport rate during Flushing. According to the relationship between sediment transport rate Q_s and hydraulic factor $Q^{1.6}J^{1.2}S_i^{0.8}$ during Flushing period of Tongguan station in recent several years studied by Duan et al. (2004) and Han (2003), this paper collaborate the suitable calculation formula of sediment transport rate for Sanmenxia reservoir.

$$Q_s = kQ^{1.6}J^{1.2}S_i^{0.8} \tag{1}$$

Q_s = sediment transport rate (t/s), k = coefficient, J = gradient between Tongguan station and Sanmenxia station, S_i = sediment concentration of Tongguan station (kg/m^3), Q = flow in the outlet.

After collaborating the scatter diagram of the relationship between sediment transport rate and hydraulic factor in the Tongguan station, coefficient k is determined as 0.2236. So the sediment transport rate calculation formula is:

$$Q_s = 0.2236Q^{1.6}J^{1.2}S_i^{0.8} \tag{2}$$

In order to verify the accuracy of the amended parameters, we make a related analysis of Q_s calculated according to the revised formula and hydraulic factor of the Sanmenxia station, and it showed that the consistency is higher and the correlation coefficient is 0.92 (Figure 3). So, the amended sediment transport rate calculation formula in the Sanmenxia reservoir was used.

Model validation

The revised RESCON model is validated by using the data of the Sanmenxia reservoir in 2003. The main parameters of the Sanmenxia reservoir in 2003 are shown in Table 1. The simulated results of Flushing and the actual data of the Sanmenxia reservoir in 2003 are shown in Table 2.

It is shown that the consistency between the two results is high. The analysis of the errors indicates that the error of water consumption in Flushing is 6.35%; the error of theoretical sediment mass in Flushing is 2.02%; the error of optimal sediment removed is

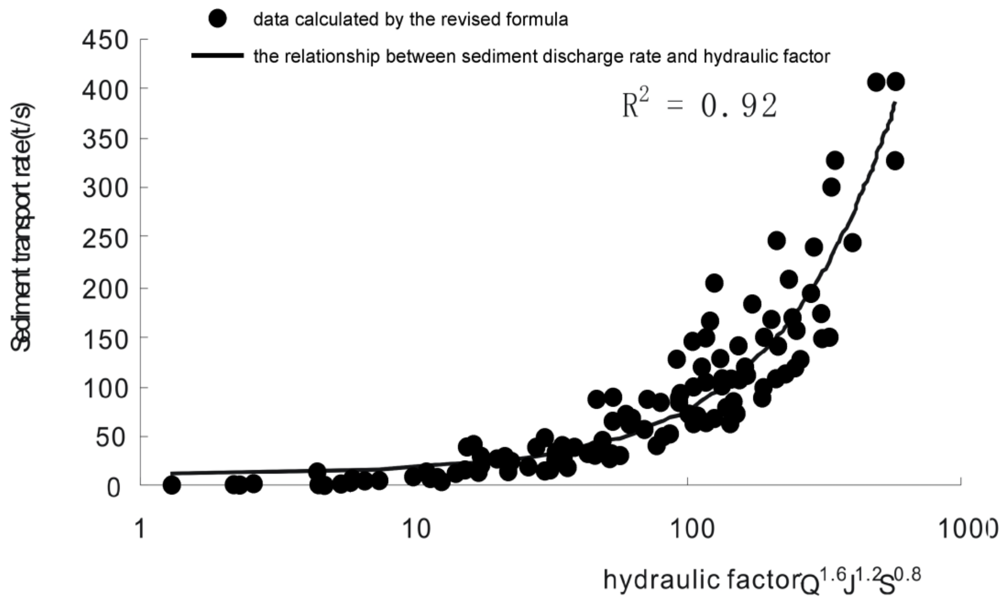

Figure 3. Relationship between Sediment discharge rate and hydraulic factor.

Table 1. Input data of the Sanmenxia reservoir in 2003.

Parameter	Value of parameter	unit
Slope of water level	3.78	‰
water surface elevation of during flushing	292	m
Sediment flow	2000	m^3/s
Days of flushing	60	days
Proportion of days of flushing s1	0.17	
Proportion of days of non-flushing s2	0.83	

Table 2. Flushing and actual data of the Sanmenxia reservoir in 2003.

Parameter	Calculated value	Actual value	Error%
Sediment balance ratio SBR	1.13		
Long term capacity ratio LTCR	0.41		
Theoretical water consumption in a flushing event (million m^3)	83.84	89.53	6.35
Theoretical sediment mass flushed in a flushing event (million tons)	5.81	5.93	2.02
Average sediment concentration (kg/m^3)	69.30	76.50	9.41
Optimal sediment removed circle (year)	1	1	0
Optimal sediment removed (million m^3)	3.63	3.655	0.68
Optimal flushing duration (day)	37	34	8.82

0.68%; and the error of average sediment concentration is 9.41%. It is on the high side due to the theory of water consumption is low. The optimal amount of sediment removed and the duration of Flushing fit the actual value perfectly. So the revised RESCON model can be used in the evaluation of reservoir sediment management.

Table 3. Different sediment management strategies.

Solutions	Aggregate net present value (million Yuan)	Feasibility
Do-nothing	1.85	Not feasible
Flushing	4.08	Feasible
HSRS		Not feasible
Dredging	-3.98	Not feasible
Trucking	-3.26	Not feasible

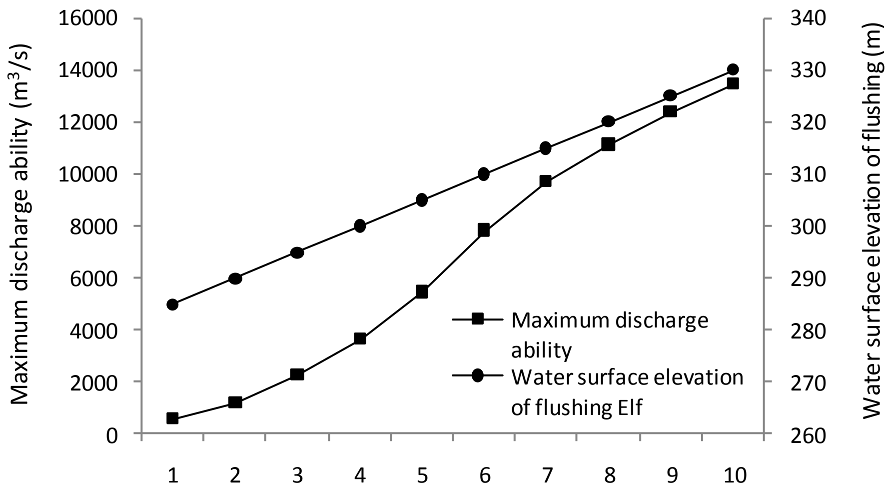

Figure 4. Water level and discharge ability of flushing.

RESULTS AND DISCUSSION

The desilting strategies comparison

On the assumption that the annual average sediment volume flushed is 5.70 billion m^3, the revised RESCON model to simulate and compare with the following 5 kinds of desilting strategies was applied: ①Flushing, ②Hydrosuction, ③Traditional Dredging, ④Trucking and ⑤the "Do-nothing". The "Do-nothing" scheme is a non-sustainable solution that is used as a comparison here. The five solutions simulating results are shown in Table 3.

Of the five removal solutions, Hydrosuction is technically not feasible. As for Traditional Dredging and Trucking, RESCON assumes that they are feasible in techniques. As the sediment volume of 5.69 billion m^3 needs to be flushed annually, up to the present, the biggest Dredging quantity tried in the world is less than a million m^3, the Traditional Dredging and Trucking do not have feasibilities. For reservoir desilting, the RESCON model recommended Flushing is the solution, which is the same as the current operation used in the Sanmenxia reservoir and indicates that the present solution of "storing clear water and releasing the mud" adopted in the Sanmenxia reservoir is reasonable.

Flushing optimization

Reservoir Flushing is inseparable with flushing water level, flushing flow and days of flushing. In order to acquire a rational and effective reservoir optimal Flushing solution, we design different flushing water levels, flushing flows and days of flushing and compose a variety of Flushing solutions. Different flushing water levels and the related flushing flow of the Sanmenxia reservoir are shown in Figure 4.

Based on the average mean annual water level of 304.03 m, average annual inflow which is from 522.8 m^3/s to 4114.2 m^3/s of the Sanmenxia reservoir, the following five groups of data which are feasible for actual operation were selected (Figure 5).

In the meantime, the flood season of the Sanmenxia reservoir each year is from 1 July to 31 October, a total of 123 days normally. As reservoir uses flushing during flood season, the days of flushing are determined (Table 4). Combining flushing water level, flushing flow and days

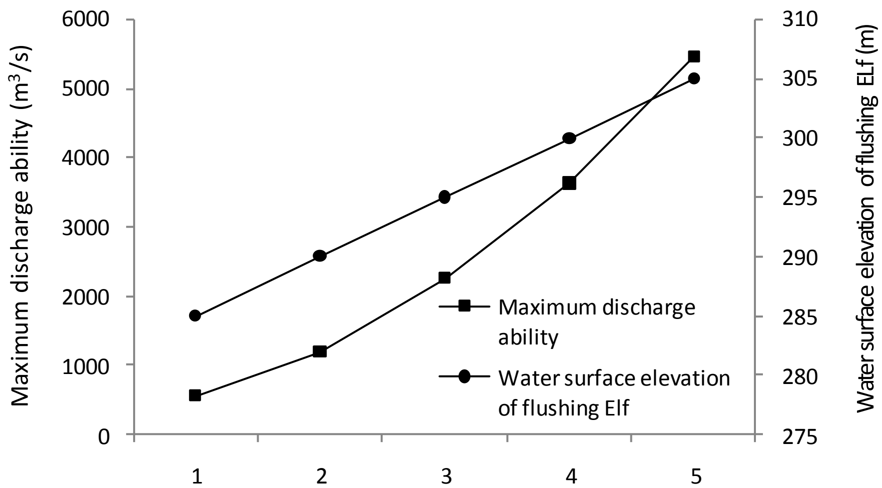

Figure 5. Selected groups of water level and flushing discharge.

Table 4. Selected results of flushing duration.

Days of flushing	Proportion of days of flushing s1	Proportion of days of non-flushing s2
123 (flood season)	0.337	0.663
153 (15 days before and after flood season)	0.419	0.581
184 (30 days before and after flood season)	0.504	0.496

of flushing, 15 kinds of Flushing solutions can be seen in Table 5.

The results of different combination of Flushing solutions calculated by RESCON model are shown in Figure 6. Comparing reservoir long-term capacity and NPV of Flushing solutions, the authors got the best solution that water level is 290 m, flushing discharge is 1188 m^3/s, the flushing duration is 67 days each time, long-term reservoir storage capacity will achieve 16.05 billion m^3 below 323 m water level and dredging every two years.

CONCLUSIONS AND RECOMMENDATIONS

Sediment transport rate during Flushing is an important parameter, which determines the amount of sediment flushed of the reservoir. So its calculating formula was revised as $Q_s = 0.2236Q^{1.6}J^{1.2}S_i^{0.8}$ and it was validated that it could be used to evaluate sediment management using the data of the Sanmenxia Reservoir in 2003.

Among all the five-sediment management solutions, RESCON model recommends that the Flushing is the feasible solution which is with the highest economic benefit. In addition, Flushing as the current sediment management strategy of the Sanmenxia reservoir shows that it is reasonable and effective. The results of different Flushing combinations indicate the best solution as: Water level is at 290 m, flushing discharge is 1188 m^3/s, the flushing duration is 67 days each time, long-term reservoir storage capacity maintained is 16.05 billion m^3 below 323 m water level and dredging every two years.

In the process of research on RESCON model, the following defects have been found:

(1) According to the existing of Sanmenxia reservoir data show that the average amount of coming water and sediment reducing year by year, annual amount of water and sediment changes greatly. But there are some very important in RESCON model parameters, such as average annual incoming water and annual incoming sediment, take the long-time average annual value. It will affect the accuracy of the calculation results in the process to evaluate reservoir, as a direct result of theoretical sediment and dredged sand mass in flushing are on the high side. Suggest improve the advice RESCON model according to the amount of water and sediment characteristics, thus more feasible calculation method is put forward.

(2) The RESCON model is to assess the most appropriate desilting strategy based on the feasibility. But the net income situation by using the model is quite

Table 5. 15 flushing strategies.

Water level of Flushing (m)	Sediment flow of flushing (m^3/s)	Days of flushing	Proportion of days of flushing s1	Proportion of days of non-flushing s2
285	565			
290	1188			
295	2265	123	0.337	0.663
300	3633			
305	5455			
285	565			
290	1188			
295	2265	153	0.419	0.581
300	3633			
305	5455			
285	565			
290	1188			
295	2265	184	0.504	0.496
300	3633			
305	5455			

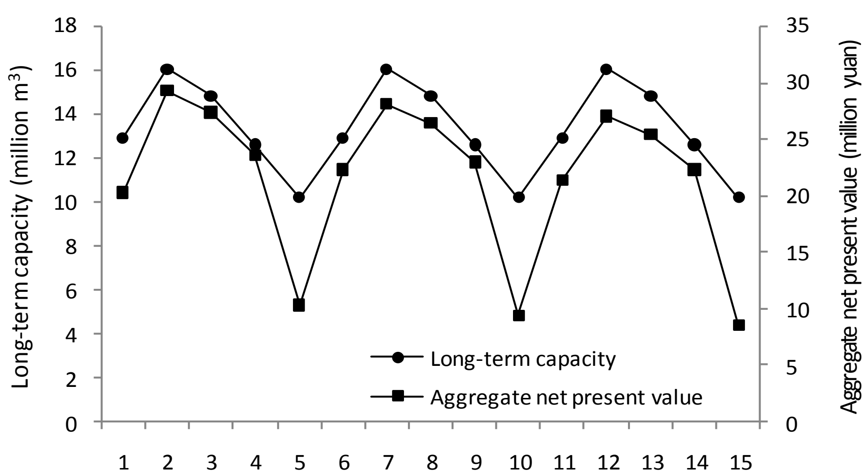

Figure 6. Reservoir long-term capacity and NPV of 15 flushing strategies.

different with the reservoir. In order to make the RESCON model more perfect, suggest cope with its economic parameters. Not only have the effect of sorting the feasibility scheme, at the same time to the income of the reservoir has reference value.

Conflict of Interest

The authors have not declared any conflict of interest.

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Annex Input data summary table.

No.	Parameter			Value	Unit
1	Reservoir geometry	V_o	Original capacity of the reservoir	3644500000	m^3
2		V_e	Existing storage capacity of the reservoir	1124700000	m^3
3		B_{bot}	Representative bottom width for the reservoir	300	m
4		SS_{res}	Representative side slope for the reservoir	1.899	—
5		EL_{max}	Elevation of top water level in reservoir	323	m
6		EL_{min}	Minimum bed elevation	247	m
8		L	Reservoir length at the normal pool elevation	113500	m
9		h	Available head	76	m
10	Water characteristics	V_{in}	Mean annual reservoir inflow	30577000000	m^3
11		Cv	Coefficient of variation of annual run-off volume	0.34	m^3
12		Pr	Supply failure rate of reservoir	0.05	—
13		T	Representative reservoir water temperature	26.1	°C
14	Sediment characteristic	ρ_d	Density of in-situ reservoir sediment	1.44	t/m^3
15		M_{in}	Mean annual sediment inflow mass	831000000	t
16		Y	Constant related to sediment characteristics	1600	—
17		Brune Curve	Brune Curve marks related to sediment characteristics	3	—
18		Ans	This parameter gives the model a guideline of how difficult it will be to remove sediments.	1	—
19		Type	Enter the number corresponding to the sediment type category to be removed by hydrosuction dredging.	3	—
20	Removal parameters	HP	Is this a hydroelectric power reservoir? Enter 1 for yes; 2 for no.	1	—
21		Q_f	Representative flushing discharge	Undetermined	m^3/s
22		T_f	Duration of flushing after complete drawdown	Undetermined	Day
23		N	Frequency of flushing events	1	Year
Number	**Parameter**			**Value**	**Unit**
24	Removal parameters	D	Assume a trial pipe diameter for hydrosuction., Should be between 0-1.2 m.	1	m
25		NP	Number of pipes of for hydrosuction sediment removal	3	—

Contd.

26		YA	Maximum fraction of total yield that is allowed to be used in HSRS operations.	0.2	—
27		CLF	Maximum percent of capacity loss that is allowable at any time in reservoir for Flushing.	99	%
28		CLH	Maximum percent of capacity loss that is allowable at any time in reservoir for Hydrosuvction.	99	%
29		CLD	Maximum percent of capacity loss that is allowable at any time in reservoir for Dredging.	99	%
30		CLT	Maximum percent of capacity loss that is allowable at any time in reservoir for Trucking.	99	%
31		ASD	Maximum percent of accumulated sediment removed per dredging event	100	%
32		AST	Maximum percent of accumulated sediment removed per trucking event	100	%
33		MD	Maximum amount of sediment removed per dredging event.	1000000	m^3
34		MT	Maximum amount of sediment removed per trucking event.	500000	m^3
35		Cw	Concentration by weight of sediment removed to water removed by traditional dredging.	30	%
36		E	If dam being considered is an existing dam enter 0. If the dam is a new construction project enter 1.	0	—
37		c	Unit cost of construction	1.12	¥/m^3
39		r	Discount rate（decimal）	0.12	—
40		Mr	Market interest rate	0.0414	—
41		P1	Unit benefit of reservoir yield	0.2	¥/m^3
42	Economic parameters	V	Salvage value	0	¥
43		omc	Operation and maintenance coefficient	0.01	—
44		PH	Unit value of water released downstream of dam in river by hydro-suction operations.	0.05	¥/m^3
45		PD	Unit value of water used in dredging operations.	0	¥/m^3
46		CD	Unit cost of Dredging	N/A	¥/m^3
47		CT	Unit cost of Trucking	22	¥/m^3
48	Other parameters	FI	Cost of capital investment required for Implementing flushing measures.	0	¥

Contd.

49		HI	Investment cost of the installation of HSRS	7000000	¥
50		DU	The expected life of HSRS	25	year
51		Zpr	Standard normal variable value of Pr	1.64	—
52		Gd	Correction factor of Gould	0.6	—
53		Ma	Types of pipe material	2	—