APPLICATIONS OF NUMERICAL SIMULATION IN SOLVING KEY SEDIMENT PROBLEMS OF THE YELLOW RIVER

Qingchao Guo[1], Chunhong Hu[2], and Jianguo Chen[3]

ABSTRACT

The insufficient water and excessive sediment, along with the non-harmonious combination of their processes, cause a lot of problems for the Yellow River and its reservoirs, including the severe sedimentation in Sanmenxia reservoir, the rising of Tongguan elevation, the perched river in the lower Yellow River. How to lower the Tongguan elevation and alleviate the sedimentation in the lower Yellow River becomes one of the most important issues in managing the Yellow River. This paper gives an overall summary of the recent researches on the key problems of sediment in the Yellow River by the authors and tries to form a comparatively complete conception of managing sedimentation in the Yellow River and reservoirs. The paper is firstly to give a brief introduction to the numerical model and its calibration and verification. Its applications in solving the key sediment problems in the Yellow River are then illustrated, which include the relationship between the operational modes of Sanmenxia reservoir and the change of Tongguan elevation, the effect of large-scale hydraulic projects on the sedimentation reduction in the lower Yellow River, and the critical equilibrium index of sedimentation in the lower Yellow River.

1. INTRODUCTION

The Yellow River, originating from the northern part of the Bayankela Mountains on the Tibet plateau at elevation 4,500m, is flowing through nine provinces, with a total length of 5,464km and a basin area 795,000km^2, and finally empties itself into the Bohai Sea (see Fig. 1). The insufficient water and excessive sediment, along with the non-harmonious combination of flow and sediment processes, cause a lot of problems for the Yellow River and its reservoirs. For example, the severe sedimentation in Sanmenxia reservoir and the obvious rising of Tongguan elevation have resulted in the decrease of the flood control ability of the lower Weihe River and the deterioration of eco-environment in the Sanmenxia reservoir area. At the same time, the long-term sedimentation in the lower Yellow River have made a continuous rising of river bed and a so-called "perched river" has

[1] Professor, Department of Sedimentation, China Institute of Water Resources and Hydropower Research, 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R. Phone: 86-10-68786632 Fax: 86-10-68416371 Email: guoq@iwhr.com
[2] Professor & Secretary-General, International Research and Training Center on Erosion and Sedimentation, 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R. Phone: 86-10-68413372 Fax: 86-10-68411174 Email: chhu@iwhr.com
[3] Professor, Vice director, Department of Sedimentation, China Institute of Water Resources and Hydropower Research, 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R.. Phone: 86-10-68786639 Fax: 86-10-68416371 Email: chenjg@iwhr.com

been formed in the lower Yellow River. This makes the lower Yellow River has to face more austere situation of flood control. Therefore, how to lower the Tongguan elevation and alleviate the sedimentation in the lower Yellow River becomes one of the most important issues in managing the Yellow River.

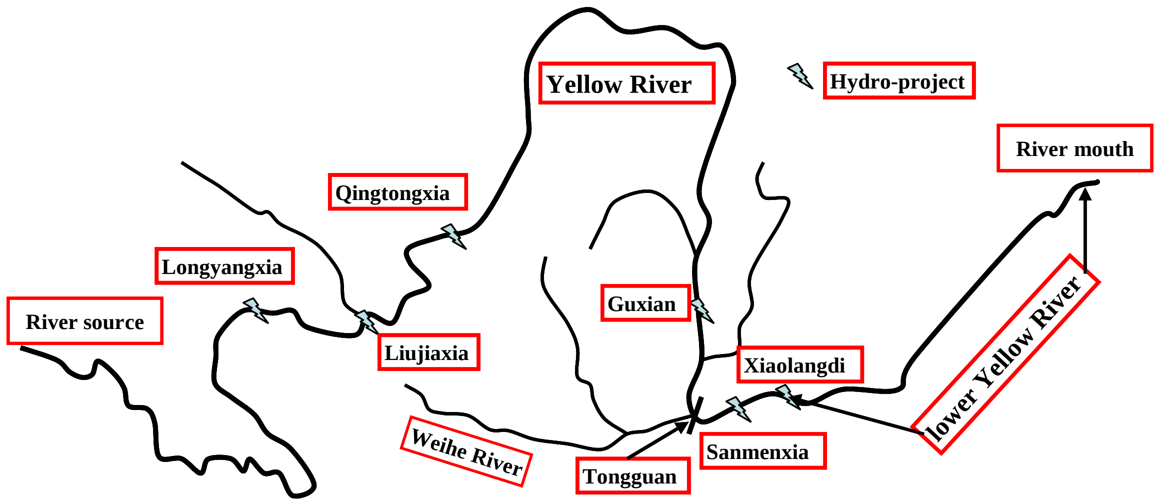

Fig. 1 Sketch map of the Yellow River and related Hydro-projects

Sanmenxia reservoir is the first large-scale hydro-project on the Yellow River for flood control, sedimentation reduction of the lower river, power generation, water supply and other purposes. It controls 91.5% area of the Yellow River basin, 89% runoff and 98% sediment yield. Due to the underestimation to sediment problem during the period of planning and design, severe sedimentation has happened since the operation of the Sanmenxia reservoir in Sept. 1960. Correspondingly, the Tongguan (TG in short) elevation, the water level at flow discharge of 1000m^3/s, has risen by about 5m. As the erosion base level of Weihe River and Beiluohe River, the change of TG's elevation has a big influence to the sedimentation upstream. This rising of TG resulted in the continuous rising of Weihe river channel, the worse situation of flood control, the rising of ground water level in the central Shaanxi plain, soil salinization, and the reduction of agricultural production. To alleviate the negative effects of TG elevation on Weihe River basin, deep investigation on the factors to influence TG elevation and the measures to lower it is urgently needed.

The lower Yellow River (LYR in short) starts from Xiaolangdi and enters into the Bohai Sea. The upper reach of LYR wanders with a shallow main channel and broad flood plains. The lower reach has a relatively narrow and deep main channel and less broad plains. According to the observed data at Xiaolangdi station from 1950 to 2000, the mean sediment concentration is 31.2kg/m^3, the annual runoff and sediment load are 36.68 billion m^3 and 1.145 billion tons respectively. The accumulative amount of sedimentation ("sedimentation" used here includes processes of deposition, erosion, and equilibrium) in the LYR from 1952 to 1999 is about 5.64 billion m^3 (Long et al. 2002), and the channel bed generally raised over 4.0m which resulted in that in some reaches, the flow-conveying capacity of the main channel reduced greatly from about 6000m^3/s to around 3000m^3/s and channel bed elevation is 3m to 5m higher than the ground level outside the levees. With the rapid development of economy in the Yellow River basin in recent years, the problem of the river bed rising in the LYR becomes more protruding. To restrain the continuous rising of river bed, it is strongly needed to alleviate deposition in the LYR. Up to date, building large-scale hydraulic projects is one of the most effective and feasible approaches which can not only optimize the combination between water and sediment to reduce deposition but also create more temporal space for soil-and-water conservation. However, the sequences resulting from the operation of hydraulic projects still remain unclear, such as the response of river channel to the new flow-sediment condition, sedimentation processes in the LYR, the sedimentation reduction efficiency, the non-deposition period, etc.

Therefore, after a brief introduction of the sediment mathematical model developed by Hu and Guo (2004) and its calibration and verification, this paper presents the calculation of the relationship between the Sanmenxia reservoir operation and the Tongguan elevation, as well as the relationship between the sedimentation in the LYR and different water-sediment combinations from Xiaolangdi reservoir for different options including sole reservoir operation (Sanmenxia), two-reservoir combined operation (Sanmenxia plus Xiaolangdi) and three-reservoir combined operation (Sanmenxia, Xiaolangdi and Guxian). The simulation results properly answer such questions as the relationship between lowering Tongguan elevation and Sanmenxia reservoir operation modes and the effects of the combined operation of hydro-projects on the sedimentation in the LYR.

2. NUMERICAL MODEL OF SEDIMENT IN THE YELLOW RIVER

The numerical model for the sediment transport in the Yellow River developed by the authors is a 1-D model based on the non-equilibrium theory of non-uniform sediment transport (Han 2003). The model properly considers the effect of water diversion and flow entering on flow movement, and the flow momentum equation is improved by adding an extra slope caused by the longitudinal change of the flow. As for the hyper-concentration, a universal valid sediment-carrying formula for both low and high sediment concentrations is used. The coefficient of sediment-carrying capacity and the restoring saturation coefficient can be estimated from semi-theoretical expressions, so the uncertainty to select values for these coefficients could be avoided.

To test the applicability of the above model in simulating the processes of sedimentation in Sanmenxia reservoir and in the LYR, large quantity of observed data from Sanmenxia reservoir (1960 to 2000) and the LYR (1974 to 1997) are utilized to rate the model.

Fig. 2 shows the measured and calculated sedimentation processes in Sanmenxia reservoir from 1960 to 2000. It can be seen that the model can give a good simulation not only for the accumulated sedimentation but also for the annual sedimentation. It also indicates the sedimentation in Sanmenxia reservoir experienced three different periods (Guo et al 2002): (1) the rapid accumulative deposition, from 1960 to 1964; (2) the accumulative erosion period from 1965 to 1973; and (3) nearly equilibrium of sedimentation period from 1974 to 2000. Further investigation shows that these three different sedimentation periods are just consistent with the three different operation modes of Sanmenxia reservoir.

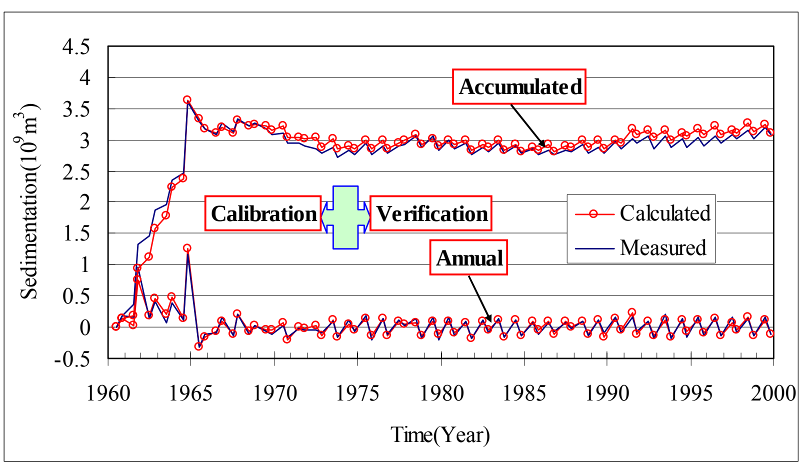

Fig. 2 Comparison between the measured and calculated sedimentation in Sanmenxia resrvoir

Fig. 3 shows the observed annual and accumulated sedimentation of LYR from 1974 to 1997 and rating results of the model. Among them the first 15-year data are used to calibrate the model and the other 10-year data are utilized to verify the model. It can be found the rating calculation results are in conformity with the observed data well, especially the strong silting processes which happened in 1977. The 7.6% relative error of the first 15-year accumulated amount shows that the model can simulate the sedimentation character of LYR.

After the calibration by 1974-1988 data, the model is verified by observed data from 1989-1997. In general, the calculated results conform to the field data well except some individual time periods. For example, the error between the measured and calculated in 1996 flood period reaches 0.34 billion tons because the calculated value is 0.5 billion tons and observed value is 0.84 billion tons. Such a big error may come from both the model's error and the observed data's error.

The rating and verification of sedimentation processes by 40-years measured data from the Sanmenxia reservoir and nearly 30-years data from the LYR show the math model can simulate sediment transport characteristics in Sanmenxia reservoir and the LYR very well. It can be used to analyze the relationship between the Sanmenxia reservoir operation and the change of Tongguan elevation, the effect of large-scale hydro-projects on the sedimentation reduction in the LYR, and the critical equilibrium index of sedimentation in the lower Yellow River.

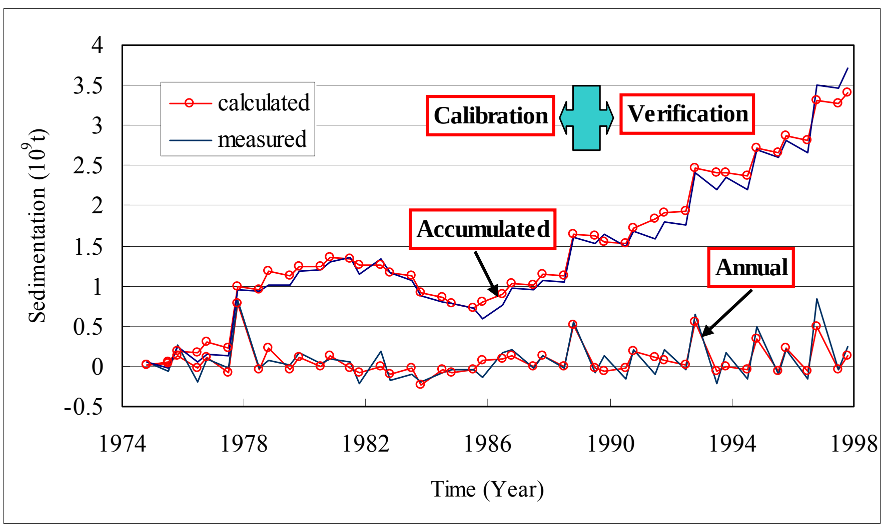

Fig. 3 Calibration and verification of sedimentation processes in the Lower Yellow River

3. APPLICATIONS OF THE MODEL IN SOLVING SEDIMENT PROBLEMS IN THE YELLOW RIVER

3.1 Sanmenxia Reservoir Operation and Tongguan Elevation

Before the construction of Sanmenxia reservoir, TG reach is in the natural state. Its variation was mainly controlled by the natural incoming flow and sediment upstream. Due to the lack of measured data of TG elevation in history, different knowledge to the variation of TG elevation is co-existent. However, from a long history term the TG reach was in a slight deposition state. Since the operation of Sanmenxia reservoir in Sept. 1960, a great change has happened to TG elevation, which basically includes four stages: rapidly rising (1960-1969)—lowering (1969-1973)—stable (1973-1985)—slowly rising again (after 1985), see Fig. 4.

During the first stage from Sept. 1960 to the end of 1969 flood season, TG elevation rose by 5.25m due to the operation of "storing water and detaining sediment" and "detaining flood and discharging sediment" under the insufficient flow discharge capacity. In the second stage from Nov. 1969 to Oct. 1973, with the increase of flow and sediment discharge capacity, the obvious erosion happened in the reservoir and TG elevation lowered by 2.01m from 328.65m to 326.64m. During the third stage form Nov. 1973 to Oct. 1985, the operation of "storing clear water and discharging muddy water" made the reservoir in a dynamic equilibrium condition, i.e. the erosion in flood season traded off the deposition in a non-flood season, and correspondingly the TG elevation varied in a limit range, nearly stable. After Oct. 1985, due to the dual effects of continuous low annual runoff and the operation of Liujiaxia reservoir upstream, TG elevation started to rise again and reached even 329m until 2002.

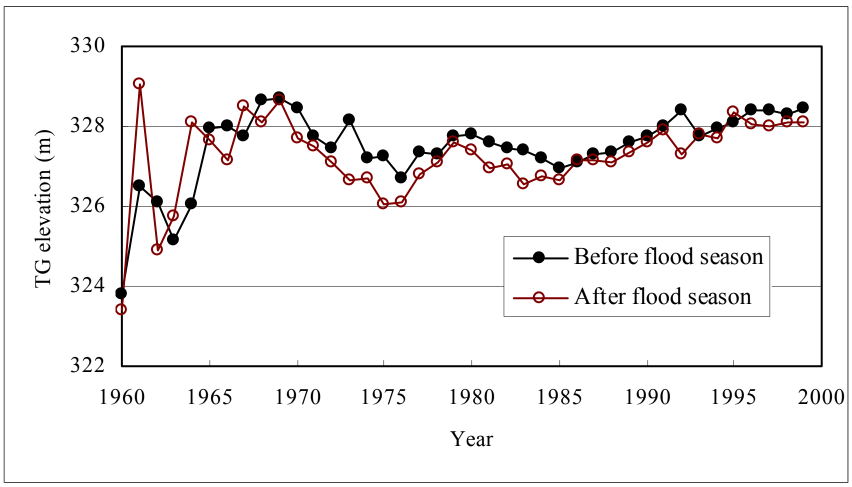

Fig. 4 Change of water level at Tongguan for discharge of 1000m^3/s

There are two major approaches to lower TG elevation: one is the low water level operation of SMX reservoir and the other is the good incoming flow/sediment condition. To investigate the effects of these two ways to lower TG elevation, the above calibrated and verified mathematical model is used to simulate the change of TG elevation under two different flow/sediment series and eight different reservoir operation modes.

The two flow/sediment series with 14 years duration named as Series I and Series II are used. Series I is composite of the actual time series of flow/sediment from 1978 to 1983 and 1987 to 1996, whereas series II is from 1987 to 2001. The annual runoff and sediment loads for series I and II are 30.4 billion m^3/0.95 billion tons and 26 billion m^3/0.86 billion tons, respectively. Series I can represent the average time series and series II is apt to the dry time series.

Eight reservoir operation modes (OM in short)are taken accounted of in the numerical simulation, which include the present operation mode, the un-gated operation, the un-gated operation in flood seasons and control operation in dry seasons, etc. the details for the eight operation modes are illustrated in Table 1.

The simulated TG elevations under the two flow/sediment series and eight reservoir operation modes based on the initial channel bed condition in September 2001 are listed in Table 2. "The lowest", "End value", and "Change" in the table respectively represent the lowest TG elevation during the 14 years, the TG elevation at the end of computation time duration, and the difference between the "End value" and the initial TG elevation. TG elevation will rise comparing with the present TG elevation if the change value is positive, vice versa.

Table 1 Eight reservoir operation modes used in numerical simulation

Operation mode	Operation modes of Sanmenxia reservoir
OM 1	Present OM: storing clear water and discharge muddy flow.
OM 2	Un-gated OM all year around: discharging flows as possible as the reservoir can.
OM 3	Flood season: un-gated OM. Dry season: the highest water level is less than 318m.
OM 4	Flood season: un-gated OM if Q>1500m^3/s, otherwise 305m. Dry season: water level ≤318m.
OM 5	Flood season: un-gated OM. Dry season: the highest water level is less than 315m.
OM 6	Flood season: un-gated OM if Q>1500m^3/s, otherwise 305m. Dry season: water level ≤315m.
OM 7	Flood season: un-gated OM. Dry season: the highest water level is less than 310m.
OM 8	Flood season: un-gated OM if Q>1500m^3/s, otherwise 305m. Dry season: water level ≤310m.

From Table 2, the following knowledge can be summarized.

(1) The change of TG elevation is affected by both reservoir operation and the incoming flow/sediment condition from the upstream of TG cross section. Low operation water level of Sanmenxia reservoir and good incoming flow/sediment condition can result in an obvious lowering of TG elevation; otherwise TG elevation is hard to be lowered.

(2) If the present operation mode, storing clear water and discharging muddy flow, is continuously used, TG elevation will maintain around the initial value after 14 years, just a slight lowering in good flow/sediment conditions and a slight rising in the case of disadvantage flow/sediment condition.

(3) The un-gated operation mode all year round will result in an obvious lowering of TG elevation. Series I and series II may lower TG elevation by 1.64m and 1.09m respectively. The averaged is about 1.36m. The partial un-gated and partial controlled operation modes(OM 3 to OM 8) may also lower TG elevation and the lower the operation water level, the better for TG elevation lowering, but smaller than OM 2. The averaged lowering value of TG elevation is about 1.0m.

(4) Simulated results of all eight operation modes and two different flow/sediment series show that even under the disadvantage flow/sediment condition and partial un-gated operation during the flood seasons, TG elevation can still be lowered by 0.7m. Therefore, for general case, it is possible that the un-gated operation for whole flood season can lower TG elevation by around 1.0m and the un-gated operation all year round can lower TG elevation by 1.4m or so.

Table 2 Simulated TG elevation for different series and operation modes (unit:m)

Series / Operation mode	Flow/sediment Series I			Flow/sediment Series II		
	The lowest	End value	Change	The lowest	End value	Change
Present	/	328.23	/	/	328.23	/
Operation mode 1	327.35	328.12	-0.11	327.65	328.33	0.10
Operation mode 2	325.82	326.59	-1.64	325.90	327.14	-1.09
Operation mode 3	326.01	326.86	-1.37	326.06	327.44	-0.79
Operation mode 4	326.07	326.97	-1.27	326.11	327.53	-0.70
Operation mode 5	325.95	326.75	-1.48	326.00	327.34	-0.89
Operation mode 6	326.03	326.85	-1.38	326.08	327.45	-0.78
Operation mode 7	325.89	326.63	-1.60	325.95	327.22	-1.01
Operation mode 8	325.98	326.74	-1.49	326.04	327.35	-0.88

3.2 Effect of Large-scale Hydro-projects on Sedimentation Reduction in the LYR

To investigate the effects of combined operation among different reservoirs (including Xiaolangdi, Sanmenxia, and Guxian reservoirs, see Fig. 1) on the sedimentation reduction in the LYR, numerical simulations for sedimentation processes in the future 80 years for different combined operation have been conducted, including the sole operation of Sanmenxia reservoir, the two-reservoir combined operation of both Sanmenxia and Xiaolangdi, and the three-reservoir combined operation of Sanmenxia, Xiaolangdi, and Guxian. The simulation results provide a technical basis for assessing the efficiency of sediment reduction by using the regulation operation of reservoirs for flow and sediment.

The designed 18 calculation options are shown in Table 3 and all calculation conditions are provided by the Yellow River Conservancy Commission. There are three series of incoming flow-sediment with numbers of 3393, 5031, 8768 respectively and a temporal span of 80 years and the first 20 years conditions of 3 series are the same with the process structure 1978-1983+1987-1997+1971-1976 while the following 60 years consist of 1933-1993 (Series 3393), 1950-1998+1919-1931 (Series 5031) and 1987-1998+1919-1968 (Series 8768), respectively. The simulated river reach is from Tiexie to Lijin with a length of 728.4km. The initial channel bed boundary is the measured cross-sections before the flood period of 2000 with 135 cross-sections and a mean section interval of 5.4km.

According to Table 3, the annual incoming runoffs of different series are varied, and Series 3393 has a largest annual runoff of 30.7 billion m^3 and Series 5031 and 8768 have the similar runoffs of 28.1 billion m^3 and 27.9 billion m^3 respectively. In the same series, different options have a similar runoff but different annual sediment load. For the annual mean sediment concentration, Series 8768 is the highest and Series 5031 is the lowest. Among which, the mean sediment concentration in the 3 options of S only exceeds 30kg/m^3, the mean sediment concentration in the 3 options of S+X exceeds 25kg/m^3, and the mean sediment concentration in the other 12 options of S+X+G are smaller than 25kg/m^3.

The calculation results of 18 options listed in Table 3 show that the sedimentation reduction of Series 5031 is the best due to its lowest incoming sediment concentration. The results of different series and operations are summarized in Table 3.

Table 3 Calculation conditions and results of options

Option		Annual incoming runoff (10^9m^3)	Annual incoming sediment (10^9t)	Sediment concentration (kg/m^3)	80-year Sediment-ation (10^9t)	Non-silting period (years)		Silting reduction comparing with 'S only' (10^9t)
Series	Operation ways					Process method	E/D method	
3393	1-S only	30.864	0.983	31.849	22.51	/	/	
	2-S+X	30.714	0.859	27.968	16.07	36	23	6.44
	3-S+X+G/640m/H	30.687	0.719	23.43	10.05	54	44	12.46
	4-S+X+G/640m/M	30.638	0.726	23.696	10.38	54	43	12.13
	5-S+X+G/645m/H	30.689	0.707	23.038	9.58	54	46	12.93
	6-S+X+G/645m/M	30.628	0.707	23.083	9.25	54	47	13.26
5031	7-S only	28.239	0.889	31.481	19.92	/	/	
	8-S+X	28.122	0.755	26.847	13.22	37	27	6.70
	9-S+X+G/640m/H	28.105	0.612	21.775	6.32	63	55	13.60
	10-S+X+G/640m/M	28.052	0.613	21.852	6.28	64	55	13.64
	11-S+X+G/645m/H	28.109	0.595	21.168	5.48	66	58	14.44
	12-S+X+G/645m/M	28.053	0.596	21.245	5.46	66	58	14.46
8768	13-S only	28.072	0.949	33.806	21.99	/	/	
	14-S+X	27.944	0.827	29.595	16.14	45	21	5.85
	15-S+X+G/640m/H	27.89	0.696	24.955	9.71	62	45	12.28
	16-S+X+G/640m/M	27.839	0.703	25.252	10.11	63	43	11.88
	17-S+X+G/645m/H	27.894	0.687	24.629	9.35	65	46	12.64
	18-S+X+G/645m/M	27.835	0.691	24.825	9.46	65	46	12.53

Notes: 1. S-Sanmenxia Reservoir; G-Guxian Reservoir; X-Xianlangdi Reservoir; 2. H-High initial operation water level of G; M-Middle initial operation water level of G; 3. 640m, 645m- Normal operation water level of G; 4. E/D method = the ratio of the total silting reduction to the annual sedimentation rate of option S only.

3.2.1 Options under same incoming flow and sediment series

Series 3393 is regarded as a sample for analyzing and its 6 options results shown in Fig 5 and Table 3 are analyzed as follows:

(1) Sedimentation reduction effect: The sedimentation reduction caused by Xiaolangdi Reservoir only and by both Xaolangdi and Guxian Reservoir is very remarkable. If there is only Sanmenxia reservoir in operation, the sedimentation in the LYR would be very serious. For example, the accumulated sedimentation amount is about 22.5 billion tons for the period of 80 years. If Sanmenxia and Xiaolangdi reservoirs are jointly operated, the sedimentation amount is 16.1 billion tons for the period of 80 years in the LYR, 6.4 billion tons less than the former option. When the three reservoirs (S+X+G) operate jointly, the sedimentation amount is 9.25-10.4 billion tons for the period of 80 years in the LYR, 5.69-6.82 billion tons less than the case with S+X. Of course, the different operational water levels of Guxian reservoir have a slight influence on sedimentation in the LYR. Generally, the higher the normal operational water level, the better the sedimentation reduction effect in the LYR.

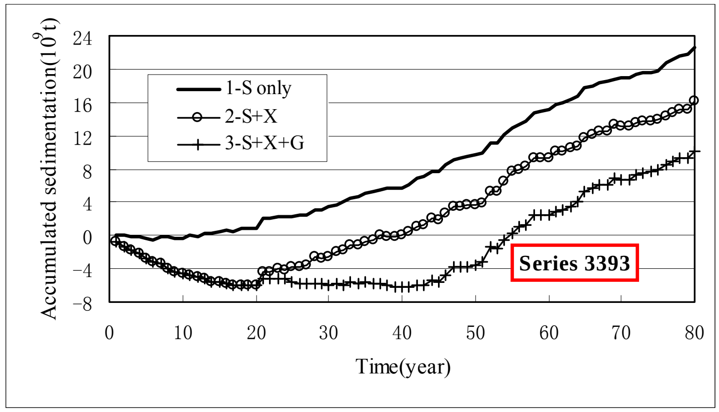

Fig. 5 Sedimentation processes in the LYR under Series 3393

(2) Sedimentation processes: Different combined operation ways of the three reservoirs affect not only the sedimentation amount, but the sedimentation processes as well. When the Sanmenxia reservoir operates solely, an almost constant sedimentation in the LYR can be observed, except the quasi-equilibrium sedimentation in the first 10 years due to sediment concentration of 5 years of this 10 years less than 20kg/m^3, and then the accumulative deposition occurs at an annual deposition rate of 0.327 billion tons. If Sanmenxia and Xiaolangdi reservoir are jointly operated, there is erosion first and followed by deposition. During the first 20 years, Xiaolangdi Reservoir may trap a lot of sediment so that the sediment concentration of the overflow is decreased sharply and the lower channel is eroded with an annual erosion intensity of 0.295 billion tons, and then the accumulative deposition appears with an annual intensity of 0.366 billion tons due to the consumption of the reservoir's sediment-storing capacity. If Guxian reservoir joins after 20 year-operation of Sanmenxia plus Xiaolangdi reservoirs, the sedimentation processes in the LYR show three different phases, erosion-equilibrium-deposition. During the first 20 years, the processes are the same as that of option S+X because Guxian Reservoir has not been functioned yet. After operation of Guxian Reservoir, the channel bed is in equilibrium for nearly 22 years but not eroded, and then at the end of the 42nd year, deposition appears with an annual intensity of 0.405 billion tons due to the decrease of ability to trap sediment of Guxian Reservoir. According to the above analysis, it can be found that the sedimentation intensity in the option of S+X+G is greater than that of S+X, and the sedimentation intensity of S+X is greater than that of S only. This characteristic demonstrates such a channel evolution regularity that the more the erosion intensity is, the faster the re-deposition.

(3) Non-deposition period: from the sedimentation processes in Fig. 5, it can be seen that the non-deposition periods for the option of S+X and option of S+X+G are 36 years and 54 years, respectively, i.e. the riverbed in the LYR can be maintained no rising in the future 36 years or 54 years with Series 3393. The non-deposition period obtained from E/D method are also listed in Table 3 and the difference between the two methods is quite big. It is suggested that the two methods should comprehensively considered for one to determine the non-deposition period in practical application.

3.2.2 Options under same reservoir operation

(1) Sole Sanmenxia reservoir operation

Fig. 6 shows the sedimentation processes in the LYR under 3 different water-sediment series with sole Sanmenxia reservoir operation. Accumulated deposition occurs in all series, the biggest in Series 3393 and the smallest in Series 5031. The sedimentation processes of 3 series are not parallel but intersectant and separate sometimes, and are related to incoming flow-sediment processes. The lower the sediment concentration, the smaller the deposition, especially showed in Series 5031. The series process curve of 5031 sometimes intersects the curve of Series 3393 upwards such as the shape from the 20th to 50th year due to higher sediment concentration and sometimes intersects the curve of Series 8768 downwards at the following 10 years due to lower sediment concentration. Also, the lower Yellow River channel is nearly in equilibrium state during the first 10 years due to 3 series' lower sediment concentration of about 20kg/m^3. However, the very high sediment concentration which is more than 100 kg/m^3 in the 21st year of Series 3393 and the 46th year of Series 8768 causes an annual silting of even more than 1 billion tons in the lower Yellow River.

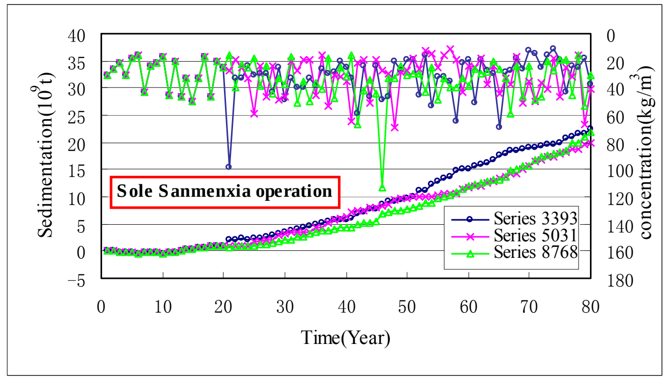

Fig. 6 Sedimentation processes in the LYR under sole Sanmenxia operation

(2) Joint operation of Sanmenxia and Xiaolangdi reservoirs

Generally, sedimentation processes in the LYR under different water-sediment series are nearly the same when Sanmenxia and Xiaolangdi reservoirs are jointly operated, i.e. first erosion and then deposition. However, the scour and deposit processes from different series shown in Fig. 7 are not parallel but intersectant and separate in different years. The erosion occurs in the LYR during the first 20 years due to lower sediment concentration of less than 20kg/m^3, and then the continuous deposition occurs due to the increase of sediment concentration. The rate of deposition is subject to the sediment concentration of the overflow from Xiaolangdi reservoir.

The sedimentation amount of Series 3393 and 8768 are nearly the same and that of Series 5031 is relatively smaller due to the lower incoming sediment concentration, and the total deposition amounts in the future 80 years of the 3 series are 16.07 billion tons, 13.22 billion tons and 16.14 billion tons respectively, with non-deposition periods of 23 years, 27 years and 21 years. It shows that the more the total deposition, the shorter the non- deposition period, but sometimes not. For example, non-deposition period of Series 5031 is not the shortest though the total deposition amount in the LYR is smallest. The reason may be explained as that the sedimentation amount is mainly determined by the annual mean incoming water and sediment, but the sedimentation processes are influenced not only by the annual mean incoming water and sediment, but also by the incoming flow-sediment processes. Therefore, the phenomena that Series

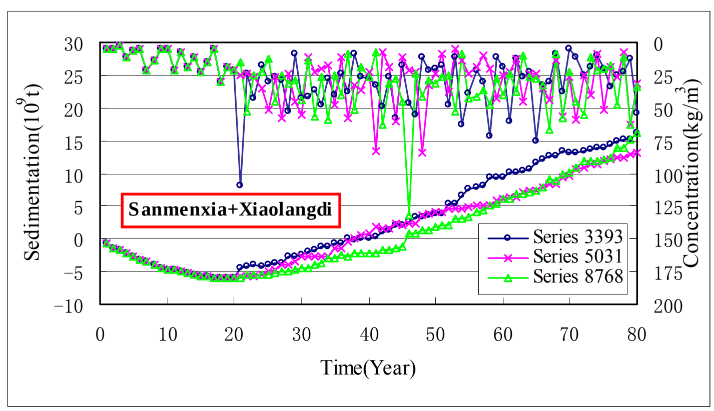

Fig. 7 Sedimentation processes in the LYR under Sanmenxia plus Xiaolangdi

8768 results in a relatively more deposition and longer non-deposition period comparing with the other two Series can be easily understood due to the higher annual mean sediment concentration of 29.6kg/m^3 and the lower concentration of 22kg/m^3 for the first 45 years.

(3) Combination of Sanmenxia, Xiaolangdi and Guxian reservoirs

Fig 8 shows the comparison of the sedimentation processes in the LYR under 3 flow-sediment series when the three reservoirs are operated jointly, among which Guxian Reservoir has four operation modes of high initial water stage of 640m, middle stage of 640m, high stage of 645m, and middle stage of 645m. Because different operation modes of Guxian Reservoir produce nearly the same sedimentation processes in the LYR, only operation mode of high initial stage of 640m is used to specify the influence while combining Sanmenxa, Xiaolangdi and Guxian reservoirs. Firstly, the total sedimentation amounts of Series 3393 and 8768 in the future 80 years are obviously more than that of Series 5031 because of the higher incoming sediment supply of Series 3393 and 8768. Then, the sedimentation processes of 3 series are not parallel but intersect and separate sometimes. During the first 20 years, all the three series exhibit the accumulative erosion because of the same incoming flow and sediment processes. In the following 25 years, the LYR experiences a nearly equilibrium state. Then the accumulative deposition occurs for all 3 series and the three process curves start to separate. For example, first fast deposition and then slow deposition for Series 3393, even silting for Series 5031, slow then fast silting for Series 8768. Their characteristics are subject to the sediment concentration of the overflow from Xiaolangdi reservoir according to their process curves.

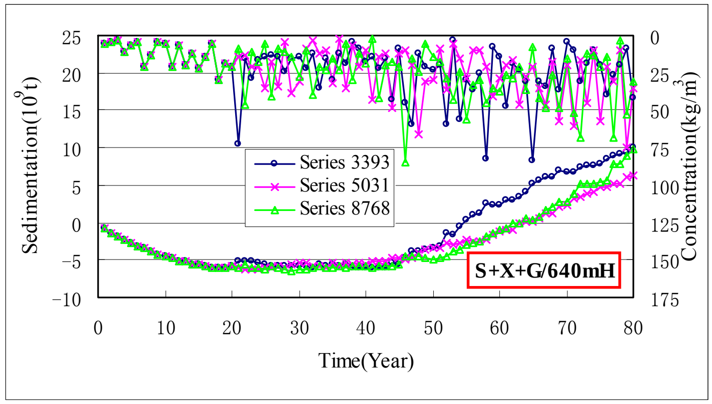

Fig. 8 Sedimentation processes in the LYR under Sanmenxia + Xiaolangdi +Guxia

4. CONCLUSIONS

(1) Low operation water level of Sanmenxia reservoir and good incoming flow/sediment conditions may result in an obvious lowering of TG elevation; otherwise TG elevation is hard to be lowered.

(2) Simulated results of all eight operation modes and two different flow/sediment series show that the un-gated operation for the whole flood season can lower TG elevation by around 1.0m and the un-gated operation for all year round can lower TG elevation by 1.4m or so.

(3) The operation of Xiaolangdi Reservoir has a clear effect on the sedimentation reduction in the LYR. Compared with sole Sanmenxia reservoir operation, the joint operation of Sanmenxia and Xiaolangdi reservoirs may reduce deposition 5.85~6.7 billion tons in the future 80 years under Series 3393, 5031, and 8768 and keep riverbed no rising for 21~27 years.

(4) Compared with sole Sanmenxia reservoir operation, the operation of Guxian Reservoir after the 20-year joint operation of Sanmenxia and Xiaolangdi reservoirs plays a notable role in reducing sedimentation in the lower Yellow River channel. The study shows that the two reservoirs may reduce sediment deposition 11.9-14.5 billion tons for the period of 80 years and keep riverbed no rising for about 43~55 years under the flow-sediment processes of Series 3393, 5031 and 8768.

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