Case Study: Delayed Sedimentation Response to Inflow and Operations at Sanmenxia Dam

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Abstract: This paper presents a study on the reservoir sedimentation processes in response to changes in incoming flow at the upstream and changes in the pool level at the downstream for Sanmenxia Reservoir, which is located on the middle reach of the Yellow River in China and has experienced serious sedimentation problems even since its impoundment in 1960. The hysteresis effect in reservoir sedimentation was used as the basis for analysis and its behavior was fully investigated throughout this study. The research found that the rise in the elevation of Tongguan, which is located in the backwater region at a distance of 113.5 km upstream of the Sanmenxia Dam, had a time delay of about 2 years compared with the sediment deposition in the reservoir area downstream of Tongguan. Moreover the accumulated sediment deposition in the reservoir area was closely related not only to the current year's flow and dam operational conditions, but also to the preceding 3–4 years' flow and dam operational conditions. Likewise the variation of Tongguan's elevation was a function of 6 years' linearly superimposed runoff, and the channel bed slope in the vicinity of Tongguan was determined by a moving average pool level over a 7 year period. The research results are of practical importance in particular for optimizing the operation of Sanmenxia Dam, and the finding of the hysteresis phenomenon in the sedimentation process of the reservoir is of merit to the advancement of sedimentation science.

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Introduction

Reservoir sedimentation problems have been experienced at sites worldwide and sedimentation management has become a contemporary problem that needs to be thoroughly investigated (Mahmood 1987; Morris and Fan 1997; White 2001; Palmieri et al. 2003; Piccinni 2004). In addition to storage loss, aggradation in the upstream reach may occur over long distances above a reservoir and increase the risk of flooding, as demonstrated by the upstream extension of sediment deposition that has occurred at the Sanmenxia Reservoir (Wu et al. 2004; Wang et al. 2005). Reservoir sedimentation is a complex process that varies with watershed sediment production and mode of deposition, and therefore managing reservoir sedimentation is extremely difficult due to the location and nature of the sediment deposits (Julien 1995; Hotchkiss 2004).

The Sanmenxia Dam, located on the lower part of the middle reach of the Yellow River (Fig. 1), was completed in 1960. It is a multipurpose project including flood control, hydropower, irrigation, navigation, and ice jam control. The dam is 713.2 m long, with the crest at an elevation of 353 m, a maximum dam height of 106 m, and a maximum pool level of 340 m. An elevation of 335 m has been used as the maximum pool level for flood control in order to avoid rapid upstream extension of backwater sediment deposition; under this pool level the reservoir has a total storage capacity of about 9.75×10^9 m^3.

The drainage area above the dam is 688,400 km^2, which is 92% of the total drainage area of the Yellow River and supplies 89% of the runoff and 98% of the sediment load to the river. According to data measured at Sanmenxia Station between 1919 and 1960 before dam construction, the mean annual runoff was 42.3×10^9 m^3, with a maximum value of 65.9×10^9 m^3 occurring in 1937 and a minimum value of 20.1×10^9 m^3 occurring in 1928. The mean annual discharge was 1,342 m^3/s, whereas the maximum historical flood records at the dam site were 22,000 m^3/s in 1933 and 36,000 m^3/s in 1843 (Yang et al. 1995; Morris and Fan 1997). The sediment load at the dam site is extremely high due to severe soil erosion from the loess plateau located in the middle reaches above the dam. According to data measured at Sanmenxia Station between 1919 and 1960, the long-term average annual sediment load was 1.57×10^9 t and the average concentration was 49.8 kg/m^3. The sediment load was during this period composed of mainly suspended load with very fine sand and silt sizes and had an average median diameter of about 0.028 mm.

As shown in Fig. 1, the dam site is situated at a gorge section downstream of Tongguan, which is located immediately downstream of the confluence of the Yellow and Wei Rivers. The river is constricted from a width of more than 10 km to less than 1 km at Tongguan, forming a naturally constricted river reach which acts as a hydraulic control section for the reaches of both the Yellow and Wei Rivers upstream of Tongguan. Therefore the elevation of Tongguan is extremely critical for limiting the impacts

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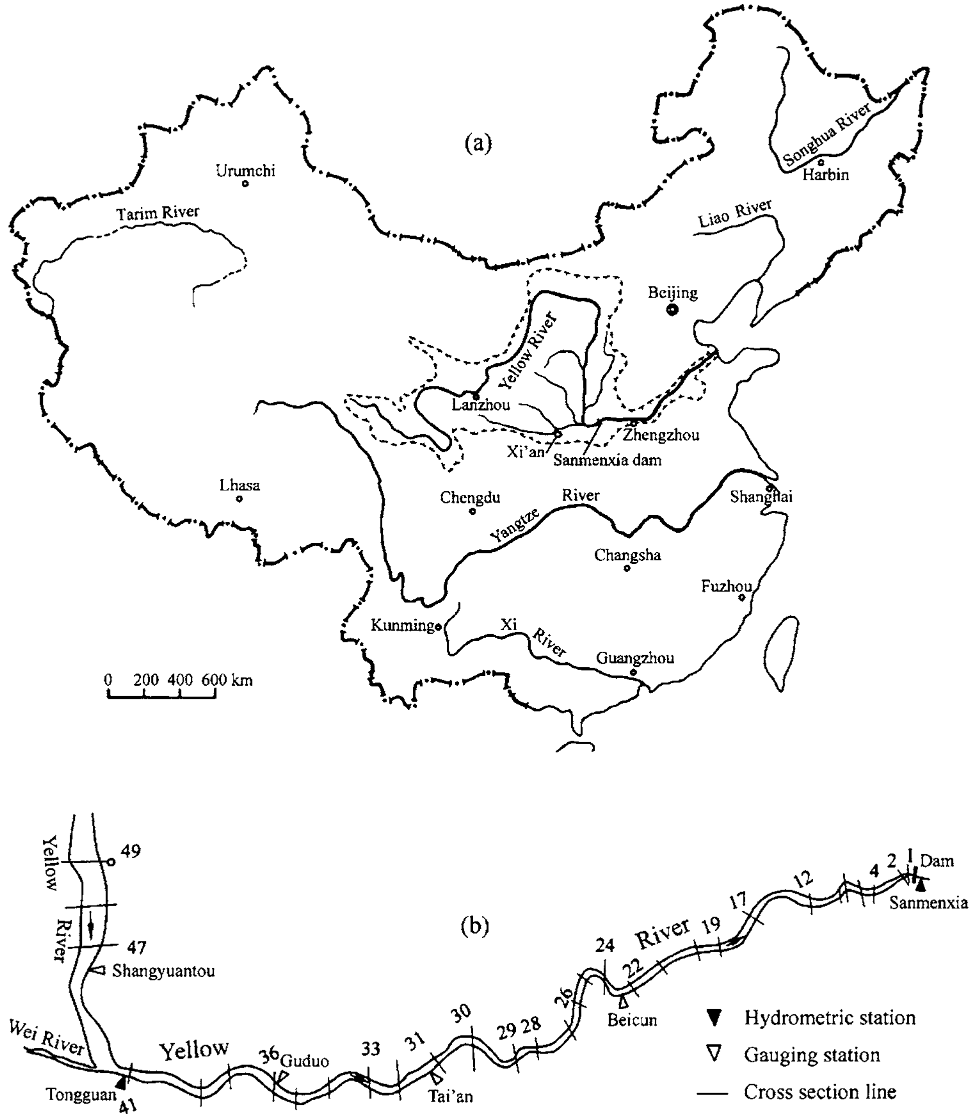

Fig. 1. Sketch map showing the plan view of the Sanmenxia Reservoir: (a) locations of the Yellow River Basin and the Sanmenxia Dam; (b) reservoir area below Tongguan (the number next to the line is the cross section number)

of sedimentation in the farther upstream area of the reservoir. The reservoir area downstream of Tongguan is a strip-shaped channel-type reservoir reach, having a valley pattern typically encountered in mountain rivers, with a length of 113.5 km, valley width of 1–6 km, channel width of 500 m, and average channel slope of 0.00035.

The Sanmenxia Reservoir is well known worldwide because of sedimentation problems caused by the extremely high incoming sediment load. Since 1960 when the operation of Sanmenxia Dam was started, much research has been conducted concerning the reservoir sedimentation and the water surface elevation at Tongguan Station (for simplicity and comparison purposes, it is called the elevation of Tongguan and is defined as the water stage corresponding to a discharge of 1,000 m^3/s at Tongguan Station), which is a measure for the severity of the backwater effect of the reservoir. However, there are different views on how each dominant factor, such as inflow discharge or pool level, affects the elevation of Tongguan. An important reason is that none of the past research (Sanmenxia Reservoir Operation Review Group 1994; Yang et al. 1995; Chen et al. 1999; Shanxi Provincial Management Bureau of the Sanmenxia Reservoir Region 2000; Yellow River Conservancy Commission 2001; Wang et al. 2005) recognized the phenomenon of delayed response in the sedimentation process in the reservoir area to the incoming flow and pool level conditions. Therefore, it has been difficult to have a thorough understanding of the inherent relationships of the reservoir sedimentation and the elevation of Tongguan.

The fundamental factors that affect the reservoir sedimentation and the elevation of Tongguan include the inflows of water and sediment at the upstream and the pool level of the dam at the downstream. Based on analysis of the hysteresis phenomenon in the fluvial processes of the reservoir, this paper will investigate the reservoir sedimentation process and the variation of Tongguan's elevation in response to changes in water runoff and the pool level of the dam, focusing on the time period when the controlled release scheme has been used for dam operation, which begun in 1974. The research results are of practical importance in particular for optimizing the operation of Sanmenxia Dam. They are also of theoretical merit in general to the study of reservoir sedimentation and fluvial processes of rivers with high sediment loads. In particular, the finding of the hysteresis phenomenon in

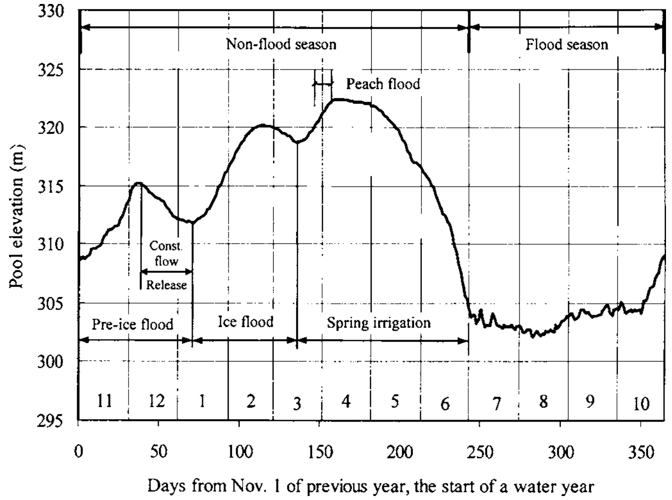

Fig. 2. Average operational pool level in the period of controlled release

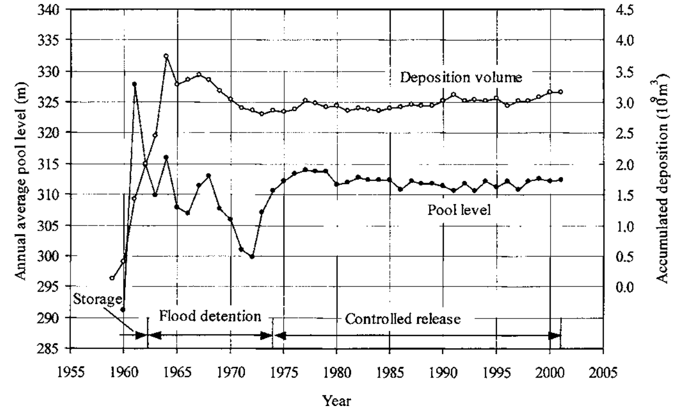

Fig. 3. Annual variations of the accumulated deposition volume and the annual pool level of the Sanmenxia Dam

the fluvial processes of the reservoir is an important contribution to the development of reservoir sedimentation theories.

Sedimentation Process in the Reservoir

Following completion of the dam, the reservoir began to function as a storage basin from September 1960 to March 1962. Severe sedimentation problems became evident immediately after beginning impoundment (Long and Chien 1986; Long 1996; Wu and Wang 2004). During this impounding period, the elevation of Tongguan was raised 4.5 m, reaching 327.2 m in March 1962. Backwater sediment deposition extended over Chishui in the lower Wei River, about 187 km upstream of the dam, and extended 152 km in the Yellow River. This threatened the industrial and agricultural bases, and more importantly Xi'an, the capital city of Shanxi province, in the lower reaches of the Wei River. In addition, an additional one million people potentially needed to be relocated.

To mitigate the sedimentation, including the quick loss of reservoir storage capacity and the rapid upstream extension of backwater sediment deposition, the operation scheme of the dam was changed to detain only floodwater in flood seasons, and the dam was reconstructed to provide outlet structures with high capacity for releasing sediment during the period from 1965 to 1973. The elevation of Tongguan was decreased from 328.65 m at the end of the flood season in 1969 to 326.64 m at the end of the flood season of 1973.

Reconstruction of outlet structures has significantly increased the discharge capacity, providing the dam with the necessary facility for avoiding significant detention of floodwater, which is important for maintaining sediment balance across the impounded reach in the reservoir. On top of this, the operation scheme was further changed to controlled release, beginning in November 1974 (Yang et al. 1995; Wang et al. 2005). As shown in Fig. 2, the dam is operated at a higher pool level in nonflood seasons (November to June). During this time period, relatively clear water entering the reservoir with an average suspended sediment concentration of 12.1 kg/m^3 (measured at Tongguan Station between 1960 and 2000) is stored to meet the need of spring irrigation and to control the ice flood, when sediment is trapped in the reservoir due to the reduced flow velocity caused by backwater deposition. In flood seasons (July–October), the pool level is lowered to flush the sediment deposited in the earlier non-flood season and to dispose of the muddy water entering the reservoir with an average suspended sediment concentration of 47.5 kg/m^3 (measured at Tongguan Station between 1960 and 2000), in which 54.2% by weight has particle sizes small than 0.025 mm and 81.3% smaller than 0.05 mm. As a result, a sediment balance in the reservoir can be maintained within a water year (the 12-month period from November through October) or over a period of several water years. As shown in Fig. 3 and Table 1, the accumulated volume of sediment deposition has changed little since 1974, indicating that a sediment balance has been achieved on the whole in the reservoir area.

Because the channel bed elevation of the Tongguan reach serves as the base level of erosion for the lower reaches of the Wei River, its variation has significant effects on the channel bed aggradation and flood control of the lower Wei River. Fig. 4 shows the annual variation of the elevation of Tongguan in response to the dam reconstructions and the changes in dam operation since the impoundment of the reservoir. It can be seen from Fig. 4 that the elevation of Tongguan increased in some years, whereas it decreased in other years, indicating that there was no tendency such as rising or falling from 1974 to 1985. In other words, the sediment temporarily deposited on the channel bed in the vicinity of Tongguan at a time can be eroded at another time, resulting in a zero value of net accumulated deposition or zero variation in the elevation of Tongguan over a long time period. This means in general a sediment balance was achieved during this time period in the sense that the amount of sediment discharged from the reservoir equaled the amount of sediment entering the reservoir. However, after 1986 the elevation of Tongguan started to rise, and has remained high since 1995. In summary, the sediment deposition in the backwater zone and the associated rise of the elevation of Tongguan in the earlier period of time were caused by inappropriate dam operation and the limits of the dam's release capacity. Since 1974 when the controlled release operation was used, the sedimentation process in the reservoir and the variation of Tongguan's elevation has been primarily controlled by the incoming flow conditions. Especially after 1986, the rising in the elevation of Tongguan has been mainly caused by the reduced annual runoff.

Table 1. Summary of Data Used for the Analysis of Sedimentation at the Sanmenxia Reservoir

Period	Year	W_a (10^9 m^3)	W_s (10^9 t)	Z_d (m)	V_s (10^9 m^3)	Z_{tg} (m)	$S_{t\text{-}g}$ (10^{-4})	$\tilde{W}_6$ (10^9 m^3)	$\hat{Z}_d$ (m)	$\tilde{Z}_{d5}$ (m)	$\bar{Z}_{d7}$ (m)
Nature	1960	30.67	0.97	291.09	0.41	323.40	—	40.38	—	—	—
Storage	1961	46.79	1.12	327.78	1.43	329.06	—	41.81	325.55	—	—
	1962	41.31	0.95	314.71	1.99	325.11	—	41.87	317.02	—	—
Flood detention	1963	44.68	1.25	309.83	2.46	325.76	—	42.76	312.54	—	—
	1964	67.54	2.42	316.00	3.72	328.09	—	49.54	319.68	—	—
	1965	36.31	0.52	307.78	3.27	327.64	—	46.78	309.54	314.91	—
	1966	40.49	2.07	306.95	3.35	327.13	—	45.62	312.48	313.45	—
	1967	61.91	2.17	311.50	3.43	328.35	—	50.12	314.21	313.43	—
	1968	52.24	1.52	313.01	3.35	328.11	—	51.13	312.88	313.17	—
	1969	28.79	1.21	307.72	3.17	328.65	2.01	44.92	308.89	311.54	310.65
	1970	34.00	1.91	305.80	3.05	327.71	2.49	40.95	306.57	309.87	310.07
	1971	29.44	1.28	300.89	2.91	327.50	2.77	37.28	302.75	307.11	307.79
	1972	30.33	0.67	299.81	2.87	327.55	2.77	34.19	300.69	304.32	306.65
	1973	30.80	1.61	307.17	2.80	326.64	2.81	31.72	303.95	303.52	306.68
Controlled release	1974	27.53	0.75	310.67	2.86	326.70	2.75	29.79	308.45	304.81	306.56
	1975	46.05	1.24	312.30	2.85	326.04	2.40	34.33	308.11	306.02	306.34
	1976	53.88	1.06	313.44	2.88	326.12	2.32	40.29	310.60	307.96	307.15
	1977	33.41	2.24	314.01	3.02	326.79	2.43	39.46	311.99	309.84	308.33
	1978	34.51	1.36	313.73	2.98	327.09	2.27	38.75	308.74	309.88	310.16
	1979	36.69	1.10	313.81	2.93	327.62	2.35	38.46	309.27	309.77	312.16
	1980	27.65	0.60	311.59	2.95	327.38	2.09	35.31	309.00	309.53	312.79
	1981	45.26	1.17	312.01	2.86	326.94	2.00	37.18	307.13	308.60	312.98
	1982	36.54	0.58	312.80	2.89	327.06	2.15	36.60	309.61	308.73	313.06
	1983	49.54	0.76	312.39	2.89	326.57	2.00	40.56	307.96	308.46	312.91
	1984	49.24	0.90	312.34	2.87	326.75	1.94	43.67	308.11	308.26	312.67
	1985	40.80	0.82	312.46	2.91	326.64	2.00	43.66	308.90	308.45	312.49
	1986	30.56	0.42	310.87	2.92	327.18	2.05	40.54	308.38	308.47	312.07
	1987	19.31	0.32	312.17	2.97	327.16	1.93	34.06	311.37	309.19	312.15
	1988	30.92	1.36	311.76	2.94	327.08	2.01	32.13	306.58	308.45	312.11
	1989	37.68	0.85	311.76	2.95	327.36	2.01	32.40	309.17	308.67	311.96
	1990	35.10	0.76	311.46	3.02	327.60	1.96	32.50	310.53	309.26	311.83
	1991	24.84	0.62	310.55	3.11	327.90	2.03	30.34	312.80	310.50	311.58
	1992	25.13	0.99	311.79	3.02	327.30	1.99	29.03	308.42	309.99	311.48
	1993	29.47	0.60	310.65	3.05	327.78	2.19	29.21	308.59	309.69	311.45
	1994	28.66	1.21	312.24	3.03	327.69	2.16	28.68	310.26	309.81	311.46
	1995	25.46	0.87	311.28	3.07	328.28	2.24	27.34	309.21	309.50	311.39
	1996	25.54	1.16	312.12	2.94	328.07	2.26	26.60	308.48	309.04	311.44
	1997	16.03	0.53	310.92	3.02	328.05	2.10	23.61	311.44	309.86	311.36
	1998	19.19	0.64	312.26	3.03	328.28	2.32	21.94	310.28	310.09	311.61
	1999	21.75	0.54	312.52	3.08	328.12	2.14	21.28	310.86	310.40	311.71
	2000	18.78	0.35	312.13	3.16	328.33	2.04	20.14	312.11	311.08	311.92
	2001	15.80	0.34	312.47	3.15	328.23	2.00	18.62	311.35	311.32	311.96

Note: W_a=annual runoff measured at Tongguan Station; W_s=annual suspended sediment load measured at Tongguan Station; Z_d=annual average pool level of the dam; V_s=accumulated sediment volume from Tongguan to the dam; Z_{tg}=elevation of Tongguan measured at the end of flood season; $S_{t\text{-}g}$=channel bed slope from Tongguan to Guduo; $\tilde{W}_6$=6 years' linearly superimposed runoff defined by Eq. (18); $\hat{Z}_d$=discharge-weighted average pool level defined by Eq. (6); $\tilde{Z}_{d5}$=linearly superimposed pool level for 5 consecutive years defined by Eq. (7); and $\bar{Z}_{d7}$=moving average value of the annual mean pool level for 7 years.

Phenomenon of Delayed Response

In principle, the rise of Tongguan's elevation is a result of continuous upward propagation of sediment deposition in the reservoir area because the Tongguan reach is located in the backwater zone. Fig. 5 shows the relationship between the elevation of Tongguan and the accumulated deposition volume in the reservoir area. The data from 1961 to 1968 were highly scattered, indicating there was no obvious correlation between the elevation of Tongguan and the accumulated deposition volume in the reservoir area. This was because, in the initial period of dam operation, a large portion of sediment deposition occurred in the wide valley plains. After 1969, a channel-shaped cross section with a deep main channel and high floodplains was formed in the reservoir area. Since then, the erosion and deposition of sediment in the reservoir area has occurred mainly in the channel, and the reser-

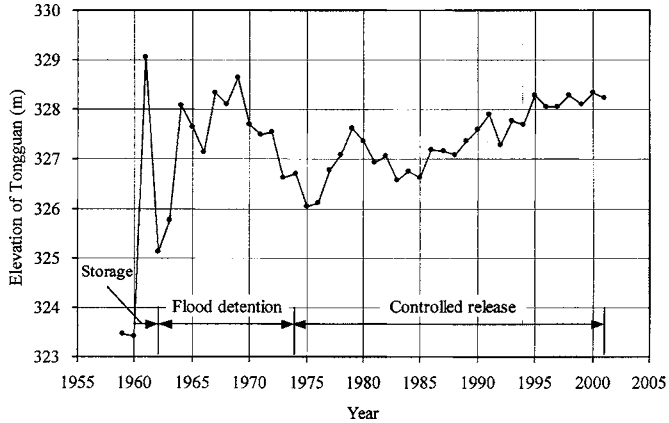

Fig. 4. Annual variation of the elevation of Tongguan, which is the water stage corresponding to a discharge of 1,000 m^3/s measured at Cross Section No. 41 next to the Tongguan Station. Due to the difficulty in determining the average channel bed elevation caused by the strong variability and irregular configuration of the cross section, this water surface elevation is used as an indication of the channel bed elevation for the purpose of comparison in order to avoid any arbitrary result. The selected discharge of 1,000 m^3/s is because the channel width under this discharge is close to the bankfull width for the river reach in the vicinity of Tongguan.

voir behaves like a regular river channel. Therefore, there is a definite relationship between the elevation of Tongguan and the accumulated deposition volume in the reservoir area, which can be expressed as

$$Z_{tg} = 0.0546V_s + 311.17 \quad (R^2 = 0.65) \tag{1}$$

where Z_{tg}=elevation of Tongguan measured at the end of the flood season (m) and V_s=accumulated volume of sediment deposited in the reservoir area from Tongguan to the dam (10^9 m^3). The deposited volume of sediment was determined based on range surveys conducted at the end of each flood season for the 41 range lines along the 113.5 km river reach from Tongguan to Sanmenxia Dam. According to a detailed analysis by Chen et al. (1999), the accuracy of the measured volume of deposited sediment is over 90%, and additionally, no accumulative error can be observed in the range survey.

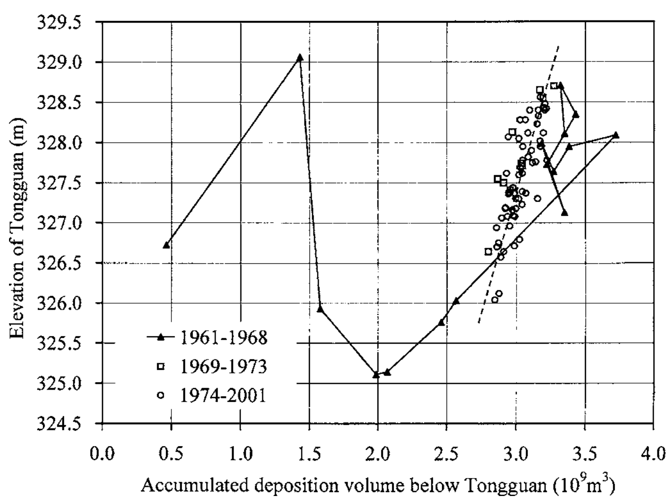

Fig. 5. Relationship between the elevation of Tongguan and the accumulated deposition volume in the reservoir area (the range survey was carried out twice a water year, once at the end of the nonflood season and again at the end of the flood season; data correspond to the results measured at the end of flood seasons)

Past research (Sanmenxia Reservoir Operation Review Group 1994; Yang et al. 1995; Chen et al. 1999; Shanxi Provincial Management Bureau of the Sanmenxia Reservoir Region 2000; Yellow River Conservancy Commission 2001) indicated that the elevation of Tongguan is closely related to the accumulated amount of sediment deposition at the reach in the vicinity of Tongguan, such as the reach from Tongguan to Tai'an. A regression equation based on data from 1969 to 2001 is as follows

$$Z_{tg} = 0.1419V_{s31-41} + 315.27 \quad (R^2 = 0.73) \tag{2}$$

where V_{s31-41}=accumulated volume of sediment deposited between Cross Sections 41 and 31, which is also denoted as between Tongguan and Tai'an (10^9 m^3).

Likewise, based on the data of 1969–2001, relationships between the increment of Tongguan's elevation and the same year's volume of sediment deposited in the reservoir area from Tongguan to the dam, as well as the same year's volume of sediment deposited between Tongguan and Tai'an can be obtained:

$$\Delta Z_{tg} = 0.0297\Delta V_s \quad (R^2 = 0.58) \tag{3}$$

$$\Delta Z_{tg} = 0.0925\Delta V_{s31-41} \quad (R^2 = 0.70) \tag{4}$$

where ΔZ_{tg}=increment of Tongguan's elevation (m); ΔV_s=same year's volume of sediment deposited in the reservoir area from Tongguan to the dam (10^9 m^3); and ΔV_{s31-41}=same year's volume of sediment deposited between Tongguan and Tai'an (10^9 m^3). It can be seen that the correlation coefficients of the relationships between Z_{tg} and V_s expressed by Eqs. (1) and (2) are higher than the relationships between ΔZ_{tg} and ΔV_s expressed by Eqs. (3) and (4). The occurrence of this phenomenon is not by accident, but has an inherent physical basis; that is, the resultant values of Z_{tg} and V_s themselves integrate the influence of the previous channel boundary conditions.

To further investigate the hysteresis phenomenon in the elevation of Tongguan in response to the sediment deposition in the reservoir area, variations of the elevation of Tongguan measured at the end of the flood season and the accumulated deposition volume in the reservoir area are plotted in Fig. 6(a). Three distinct time periods are indicated in Fig. 6(a); for each period Tongguan's elevation was either continuously rising or continuously descending. These three periods are a continuous descent from 1969 to 1975, a continuous rise from 1976 to 1979, and another continuous descent from 1980 to 1983. Correspondingly, there were three time periods in which the accumulated volume of sediment deposition in the reservoir area was either continuously increasing or continuously decreasing. These three time periods are a continuous erosion period from 1967 to 1973, a continuous deposition period from 1974 to 1977, and another continuous erosion period from 1978 to 1981. Similar rising or decreasing trends between Tongguan's elevation and the accumulated sediment deposition in the reservoir can be observed. The only difference lies in the fact that the rise or descent of Tongguan's elevation was delayed, occurring about 2 years after the deposition or erosion of sediment in the reservoir area. After 1983, however, the time delay between Tongguan's elevation and the accumulated sediment deposition in the reservoir became almost invisible or even disappeared. This is because after 1983 the channel bed had a relatively small deviation from its equilibrium state when it was gradually rising on the whole. More importantly, there was an

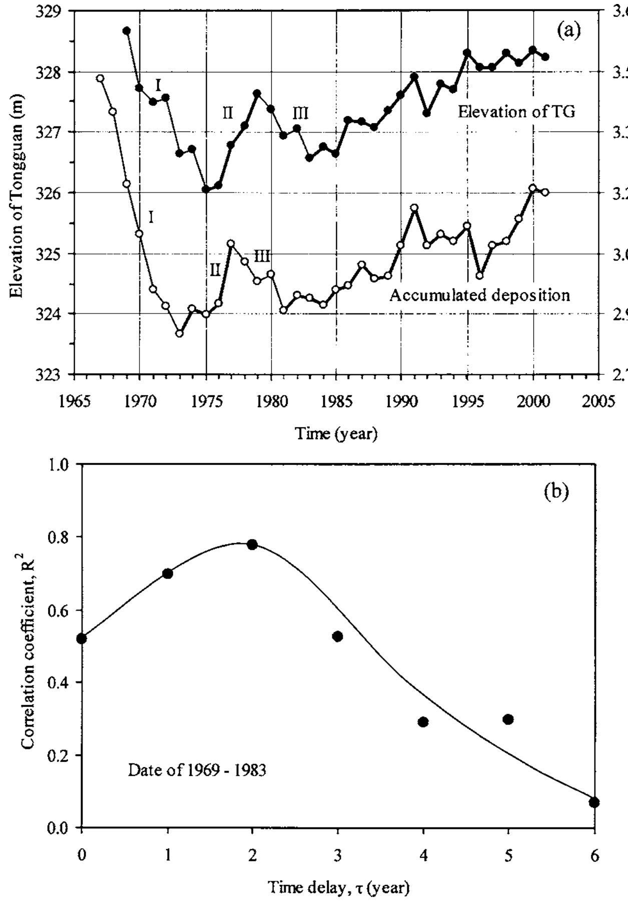

Fig. 6. Hysteresis phenomenon in Tongguan's elevation in response to the sediment deposition in the reservoir area: (a) variation with time; (b) hysteresis correlation coefficient

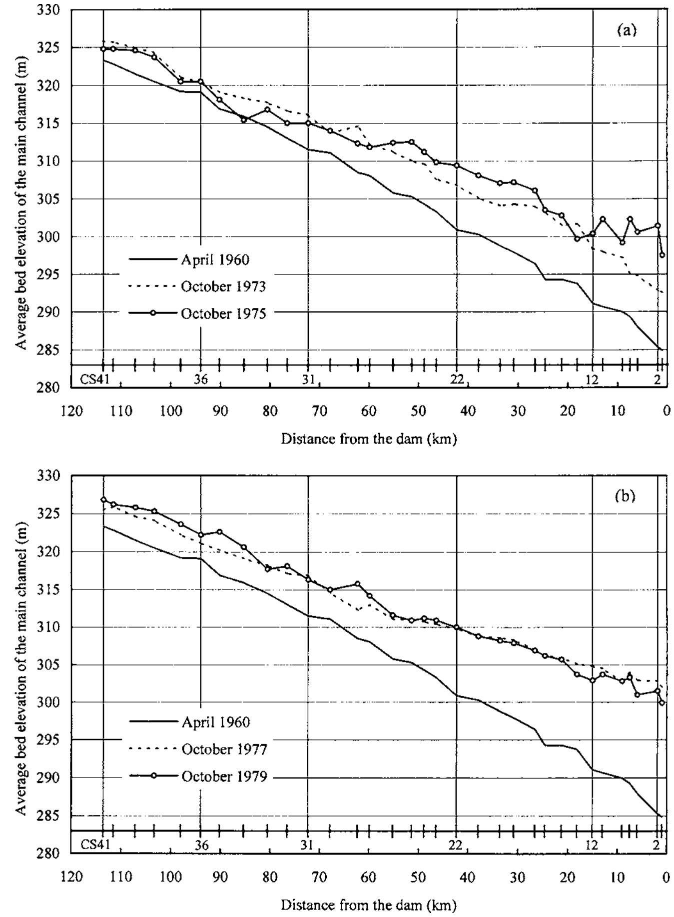

Fig. 7. Typical channel bed profiles in Sanmenxia Reservoir below Tongguan: (a) channel bed adjustment in the early time of a continuous deposition period, after the accumulated sediment deposition reached a minimum value following the continuous erosion between 1967 and 1973; (b) channel bed adjustment in the early time of a continuous erosion period, after the accumulated sediment deposition reached a maximum value following the continuous deposition between 1974 and 1977

absence of large-scale consecutive erosion or deposition phenomenon, and because of the lack of consecutive changes in opposite directions, the time delay could not be easily observed.

Assuming the elevation of Tongguan has a time delay τ, then the delay relationship between Z_{tg} and V_s can be expressed as

$$Z_{\mathrm{tg}}(t) \sim V_s(t-\tau) \tag{5}$$

The correlation coefficient between $Z_{\mathrm{tg}}(t)$ and $V_s(t-\tau)$ was computed based on Eq. (5), and the computed result is shown in Fig. 6(b). The correlation coefficient has the highest value of $R^2=0.78$ when $\tau=2$. This indicates that the elevation of Tongguan has a time delay of about 2 years in response to the sediment deposition in the reservoir area, which is consistent with the hysteresis phenomenon shown in Fig. 6(a).

The slope is one of the most active factors in fluvial processes. The delayed response of Tongguan's elevation to the sediment deposition in the reservoir area was mainly caused by the delayed adjustment of the channel bed slope. The dashed line in Fig. 7(a) is the longitudinal profile measured at the end of the flood season of 1973, which corresponds to a minimum volume of accumulated sediment deposition in the reservoir area being reached after a period of continuous erosion from 1967 to 1973, as shown in Fig. 6(a). Then there was a period of continuous deposition of sediment from 1974 to 1977, which is indicated by the continuous increase in the accumulated sediment deposition in the reservoir area, as revealed in Fig. 6(a). In the first two years of this continuous deposition period, contrary to the sediment deposition that occurred in the lower part, the channel bed erosion at the upper part continued for 2 more years and caused Tongguan's elevation to continue to drop during 1974 and 1975. This fact can be seen from a comparison of the longitudinal bed profile measured in 1975 to the one of 1973 as shown in Fig. 7(a). Following the continuous deposition between 1974 and 1977, a continuous erosion period occurred from 1978 to 1981 [Fig. 6(a)]. In the first 2 years of this continuous erosion period, even though sediment erosion occurred in the lower part of the reservoir, the channel bed deposition at the upper part continued for 2 more years and caused Tongguan's elevation to continue to rise during 1978 and 1979. This fact can be seen from a comparison of the longitudinal bed profile measured in 1979 to the one of 1977 as shown in Fig. 7(b).

Accumulated Deposition in Response to Pool Level

Generally speaking, the sediment transport capacity of a river is related to the stream power γQS. It can be expressed as $\gamma Q[(Z_{\mathrm{tg}} - Z_d)/\Delta L]$ or $\gamma Q Z_{\mathrm{tg}}/\Delta L - \gamma Q Z_d/\Delta L$, where Q=flow discharge; γ=specific weight of water; S=slope; ΔL=channel length; and

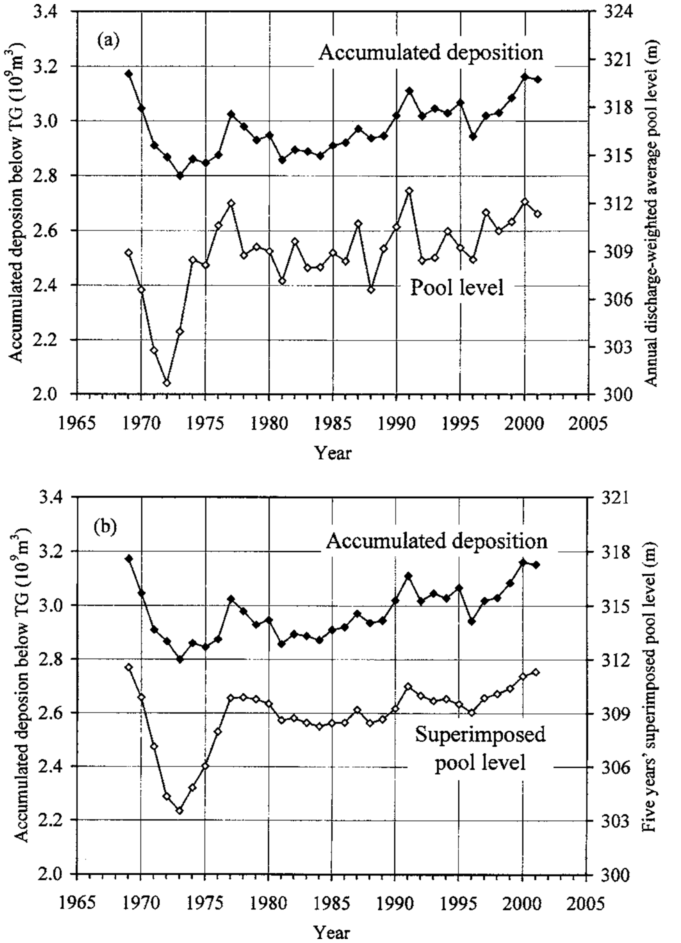

Fig. 8. Annual variations of accumulated sediment deposition volume and the superimposed pool level with time [the annual discharge-weighted average pool level ($\hat{Z}_d$ or $\widetilde{Z}_{d1}$) was computed using Eq. (6); the 5 years' superimposed pool level ($\widetilde{Z}_{d5}$) was computed using Eq. (7); and TG on the y-axis is the abbreviation for Tongguan]

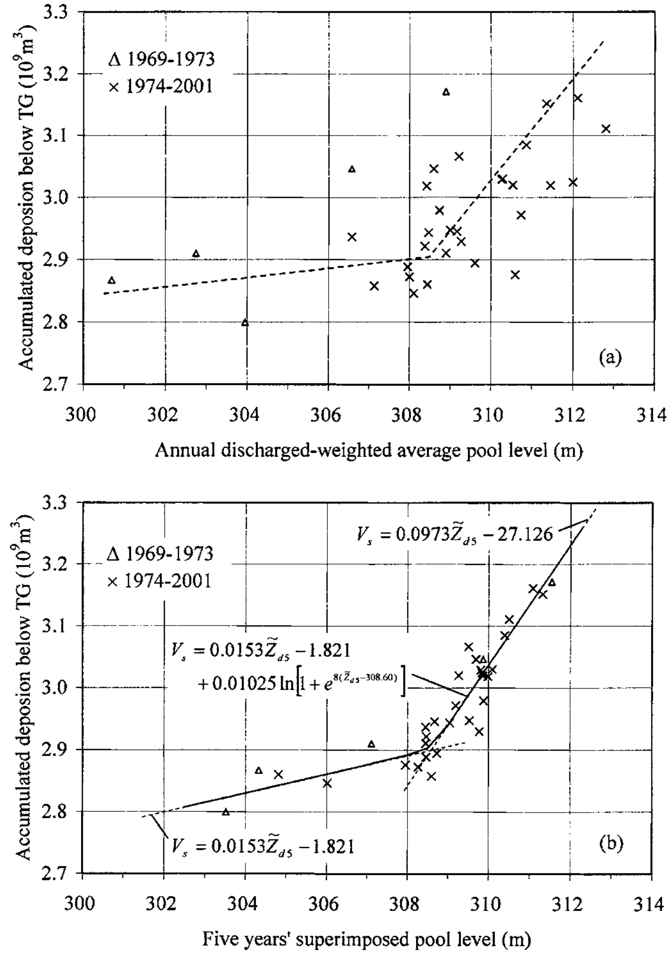

Fig. 9. Relationship between the accumulated sediment deposition volume and the linearly superimposed pool level [the annual discharge-weighted average pool level ($\hat{Z}_d$ or $\widetilde{Z}_{d1}$) was determined by Eq. (6); the 5 years' linearly superimposed pool level ($\widetilde{Z}_{d5}$) was computed using Eq. (7); and TG on the y-axis is the abbreviation for Tongguan]

Z_d=pool level of the dam (water surface elevation measured at Cross Section 2, which is 1.9 km from the dam, see Fig. 1). Compared with the pool level Z_d that has a large variability, the water stage Z_{tg} at the Tongguan section has a relatively small variation and can be treated as a constant; and this treatment is also necessary to facilitate the analysis of the two dominant factors including the inflow discharge and downstream pool level. In the meantime, ΔL can also be treated as a constant, so the change in stream power is mainly attributed to the change in QZ_d. For the convenience of application, QZ_d can be represented by a more general term $Q^{\alpha}Z_d$. Then the weighted average pool level can be expressed as

$$\hat{Z}_d = \sum \left(\frac{Q_{tg} + Q_{out}}{2}\right)^{1.5} Z_d \Bigg/ \sum \left(\frac{Q_{tg} + Q_{out}}{2}\right)^{1.5} \tag{6}$$

where $\hat{Z}_d$=discharge-weighted average pool level (m) and Q_{tg} and Q_{out}=daily mean discharges at the Tongguan and Sanmenxia Stations, respectively (m^3/s). Liang et al. (2001) demonstrated that the sediment transport rate Q_s in the Sanmenxia Reservoir is proportional to parameter $Q^{1.8}S^{1.2}$ or $(Q^{15}S)^{1.2}$. Using Liang et al.'s relationship as a reference and to best fit the data (as demonstrated in Figs. 8 and 9, the exponent in Eq. (6) was determined to be 1.5 for this paper.

The current year's channel boundary and the sedimentation state are the result of the cumulative effect of some previous years' reservoir operations. They are related not only to the current year's dam operation conditions, but also to some of the preceding years' dam operation conditions. The integrated effect of several consecutive years' reservoir operations may be represented by the following linearly superimposed pool level:

$$\widetilde{Z}_{di} = \sum_{k=1}^{i} a_k \hat{Z}_{dk}, \quad a_k = \frac{i-k+1}{N_i}, \quad N_i = \sum_{j=1}^{i} j \tag{7}$$

where i=total number of years included; k=year number counted from the same year (k=1 for the current year); and a_k=weighting factor of the kth year. The principles for determining a_k are the longer the time interval to the same year, the smaller the a_k; the sum of a_k has a value of 1 unit. For example, when i is taken to be 3, we have weighting factors $a_1 = 3/6 = 0.50$, $a_2 = 2/6 = 0.33$, and $a_3 = 1/6 = 0.17$.

Similar to the superposition method of Eq. (7), Zhou and Lin (2003) used the geometric mean of 3 consecutive years' pool level to reflect the effect of the preceding operational conditions of the

Table 2. Summary of Comparison between Computed and Measured Values of Accumulated Sediment Deposition Volume Including Different Numbers of Years in the Computation of the Superimposed Pool Level

i (year)	Formula for low pool levels ($\tilde{Z}_{di}<308.60$)	Formula for high pool levels ($\tilde{Z}_{di}\geqslant 308.60$)	R^2	RMSE (10^9 m^3)	MAE (10^9 m^3)	MNE (%)	CE
1	$V_s=0.0074\tilde{Z}_{d1}+0.622$	$V_s=0.090\tilde{Z}_{d1}-24.880$	0.362	0.0966	0.0714	2.38	0.276
2	$V_s=0.0095\tilde{Z}_{d2}-0.039$	$V_s=0.090\tilde{Z}_{d2}-24.874$	0.615	0.0667	0.0491	1.64	0.452
3	$V_s=0.0098\tilde{Z}_{d3}-0.129$	$V_s=0.088\tilde{Z}_{d3}-24.248$	0.734	0.0508	0.0408	1.37	0.488
4	$V_s=0.0127\tilde{Z}_{d4}-1.016$	$V_s=0.0877\tilde{Z}_{d4}-24.147$	0.845	0.0386	0.0313	1.06	0.596
5	$V_s=0.0153\tilde{Z}_{d5}-1.821$	$V_s=0.0973\tilde{Z}_{d5}-27.126$	0.889	0.0321	0.0260	0.87	0.672
6	$V_s=0.0170\tilde{Z}_{d6}-2.345$	$V_s=0.1020\tilde{Z}_{d6}-28.568$	0.857	0.0375	0.0303	1.02	0.624
7	$V_s=0.0176\tilde{Z}_{d7}-2.525$	$V_s=0.1153\tilde{Z}_{d7}-32.676$	0.789	0.0507	0.0376	1.26	0.565
8	$V_s=0.0219\tilde{Z}_{d8}-3.874$	$V_s=0.1241\tilde{Z}_{d8}-35.409$	0.728	0.0627	0.0463	1.54	0.507

Note: V_s=accumulated sediment deposition volume in the reservoir area (10^9 m^3); $\tilde{Z}_{di}$=superimposed pool level given by Eq. (7) (m); i=number of years included in $\tilde{Z}_{di}$; RMSE=root mean square error defined by Eq. (13); MAE=mean absolute error defined by Eq. (14); MNE=mean normalized error defined by Eq. (15); CE=coefficient of efficiency defined by Eq. (16); and R^2=squared correlation coefficient.

dam. Another option is to use an equal weighting factor in Eq. (7), then the superimposed pool level becomes a moving average value of the discharge-weighted average pool level. Both of them were tested during the analysis and the results revealed that the linear superposition method was superior to the geometric mean and the moving average values. One of the reasons is that the linear superposition method uses a varying weighting factor based on the length of the time interval to the same year, which is more in accord with the reality that earlier years' reservoir operation, compared with the current year's reservoir operation, should have lesser effect on the current sedimentation state in the reservoir.

Fig. 8 is a plot of the variations of accumulated sediment deposition volume V_s and the superimposed pool level $\tilde{Z}_{di}$ with time. Fig. 9 shows the relationship between V_s and $\tilde{Z}_{di}$. It can be seen that because $\tilde{Z}_{d1}$ changed frequently to a large extent, the change in V_s could not fully follow the change in $\tilde{Z}_{d1}$, and therefore the correlation between these two variables was poor. A careful examination of 1–8 consecutive years' superimposed pool level reveals that when the superimposed pool level includes 4 or 5 consecutive years, the trends of V_s and $\tilde{Z}_{di}$ variation were identical, resulting in the highest correlation between them (see Table 2).

Fig. 9 reveals that the trend line between V_s and $\tilde{Z}_{di}$ had a turning point at $\tilde{Z}_{di}=308.6$ m. The data follow two different trend lines on the left- and the right-hand sides of the turning point, and they can be represented by two separate straight lines. For 5 consecutive years' superimposed pool level, these two straight lines can be expressed as:

$$V_s=\begin{cases}0.0153\tilde{Z}_{d5}-1.821 & \text{(for low pool levels)} \qquad (8a)\\ 0.0973\tilde{Z}_{d5}-27.126 & \text{(for high pool levels)} \qquad (8b)\end{cases}$$

where V_s has a unit of 10^9 m^3 and $\tilde{Z}_{d5}$ has a unit of meters.

Eqs. (8a) and (8b) may be merged into a single composite equation according to Guo (2002). Suppose we have two linear asymptotic equations:

$$y=\begin{cases}K_1x+C_1 & \text{for } x\ll x_0 \qquad (9a)\\ K_2x+C_2 & \text{for } x\gg x_0 \qquad (9b)\end{cases}$$

where x=independent variable; y=dependent variable; K_1 and K_2=two slopes; C_1 and C_2=two intercepts; and x_0=reference of x, which is given by

$$x_0=(C_1-C_2)/(K_2-K_1) \tag{10}$$

The single composite equation can be expressed by

$$y=K_1x+C_1+\frac{K_2-K_1}{\beta}\ln[1+e^{\beta(x-x_0)}] \tag{11}$$

where β=transitional shape parameter that needs to be determined by data fitting.

Comparing Eqs. (9a) and (9b) with Eqs. (8a) and (8b) gives $K_1=0.0153$, $K_2=0.0973$, $C_1=1.821$, $C_2=27.126$, and $x_0=(C_1-C_2)/(K_2-K_1)=308.60$. Applying Eq. (11) to the data shown in Fig. 9, a value of 8 for β was obtained by trial and error method given the smallest mean square error between the measured and computed values of V_s. This results in the following single composite equation:

$$V_s=0.0153\tilde{Z}_{d5}-1.821+0.01025\ln[1+e^{8(\tilde{Z}_{d5}-308.60)}] \tag{12}$$

To illustrate the goodness-of-fit when including a different number of consecutive years in the analysis of the cumulative effect, in addition to the correlation coefficient (R^2), several other statistical parameters and the results are reported in Table 2. These statistical parameters include the root-mean-square error (RMSE), the mean absolute error (MAE), the mean normalized error (MNE), and the coefficient of efficiency (CE); and they can be expressed as

$$\text{RMSE}=\sqrt{\frac{1}{N}\sum_{n=1}^{N}(V_{scn}-V_{smn})^2} \tag{13}$$

$$\text{MAE}=\frac{1}{N}\sum_{n=1}^{N}|V_{scn}-V_{smn}| \tag{14}$$

$$\mathrm{MNE}=\frac{100}{N}\sum_{n=1}^{N}\left|\frac{V_{scn}-V_{smn}}{V_{smn}}\right| \tag{15}$$

$$\mathrm{CE}=1.0-\frac{\sum_{n=1}^{N}|V_{scn}-V_{smn}|}{\sum_{n=1}^{N}|V_{scn}-\bar{V}_{sm}|} \tag{16}$$

where the subscripts c and m denote the computed and measured values of accumulated sediment deposition volume, respectively; the subscript n represents the data number; N=total number of data points or years; and the overbar denotes the mean for all the data used. The first two parameters are absolute error measures that provide an evaluation of the error in the units of V_s, whereas the latter two are relative error measures that offer a relative assessment of the performance of the fitting equations. The reader is referred to the article by Legates and McCabe (1999) for a complete discussion of these goodness-of-fit measures.

The statistical results in Table 2 indicate that RMSE, MAE, and MNE decreased as the number of years increased, and they reached a minimum value when the number of superimposed years equals 5 years. Then RMSE, MAE, and MNE became larger instead as the number of superimposed years further increased. The reason is that the effect of the past conditions far way from the same year on the present fluvial processes had already disappeared. Therefore, including additional years in the superimposed pool level would incorporate extra information that is not relevant or has little relevance to the present fluvial processes. Likewise, the statistical parameters of CE and R^2 listed in Table 2 reached a maximum value when the number of superimposed years equaled 5 years, which is consistent with the result of the other three parameters, including RMSE, MAE, and MNE.

The previous results demonstrate that the sediment deposition in the reservoir area was closely related not only to the current year's flow and dam operation conditions, but also to the preceding 3–4 years' flow and dam operation conditions. In addition, Fig. 9 reveals that there is a turning point on the relation line between V_s and $\tilde{Z}_{di}$ when $\tilde{Z}_{di}$=308.6 m, corresponding to V_s $=2.9\times10^9$ m^3. This means that when V_s is reduced to 2.9 $\times10^9$ m^3, further reduction in V_s requires a large extent of reduction in $\tilde{Z}_{di}$. In other words, when the accumulated sediment deposition in the reservoir area downstream of Tongguan is reduced to 2.9×10^9 m^3, it becomes harder to further flush the previously deposited sediment out of the reservoir. This is because the turning point in Fig. 9 corresponded to the transition from delta erosion to general channel erosion. Below this turning point, further erosion needs to gradually downcut the whole channel bed through retrogressive erosion or progressive erosion.

Variation of Tongguan's Elevation in Response to Runoff

Fig. 10 is a plot showing the annual water runoff, annual average pool level, and the elevation of Tongguan at the end of the flood season. It needs to be pointed out that the annual average pool level in the figure is the arithmetic mean of daily mean pool levels for a water year, which is different from the discharge-weighted average pool level $\hat{Z}_d$ defined by Eq. (6). Under normal reservoir operation conditions, the annual average pool level is generally larger than the corresponding value of $\hat{Z}_d$. This is because the pool level was normally kept low at high flows during the flood season, and therefore the low pool levels usually had a larger weight, resulting in a lower value of $\hat{Z}_d$. The use of an annual average pool level, rather than the discharge-weighted pool level, in Fig. 10 is to demonstrate the changes in reservoir operation conditions during different time periods.

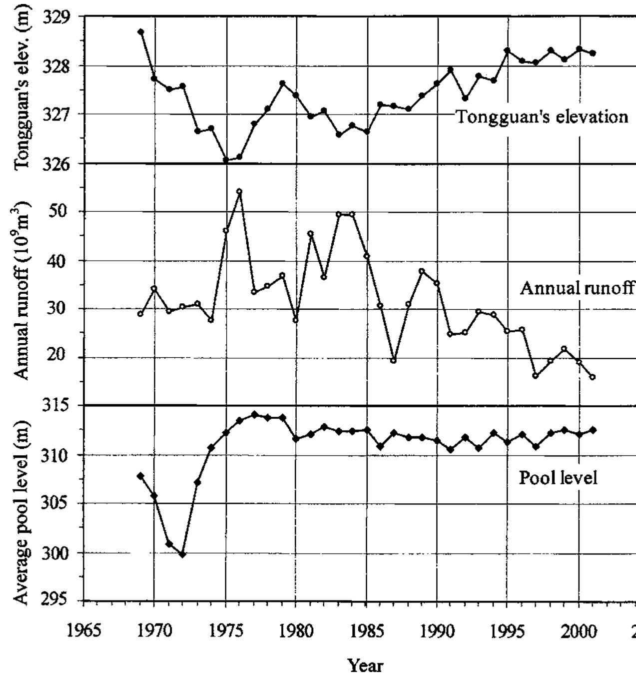

Fig. 10. Annual variations of Tongguan's elevation measured at the end of the flood season, annual water runoff measured at Tongguan Station, and annual average pool level (arithmetic mean of daily pool levels for a year)

It can be seen from Fig. 10 that even though the annual average pool level remained almost constant, the elevation of Tongguan increased or decreased as the annual runoff decreased or increased, and there was an inverse correlation between them. Since 1974, the annual average pool level has varied in the range of 310.6 and 314.0 m, with a mean annual pool level of 312.09 m. Though a certain degree of variability in the annual average pool level was observed, the range of variation was relatively small. On the other hand, the range of variation in the annual runoff was large, with a minimum value of 15.81 $\times10^9$ m^3 and a maximum value of 53.88×10^9 m^3. Similarly, since 1974 the annual average pool level in the flood season has varied in a small range between 310.6 and 306.7 m, while the annual runoff in the flood season has varied in a large range between 5.56×10^9 and 33.83×10^9 m^3. As a result, the elevation of Tongguan has been mainly affected by the inflow to the reservoir, and the pool level has had little effect.

Earlier research (Wu et al., 2004) indicated that the elevation of Tongguan Z_{tg} was closely related to the annual incoming runoff W_a as the use of the controlled release operation in 1974. The correlation coefficient R^2 between Z_{tg} and W_a reached 0.65. To reflect the effect of previous years' runoff on the elevation of Tongguan, similar to Eq. (7), a 6 years' linearly superimposed runoff (weighted-average runoff) was used:

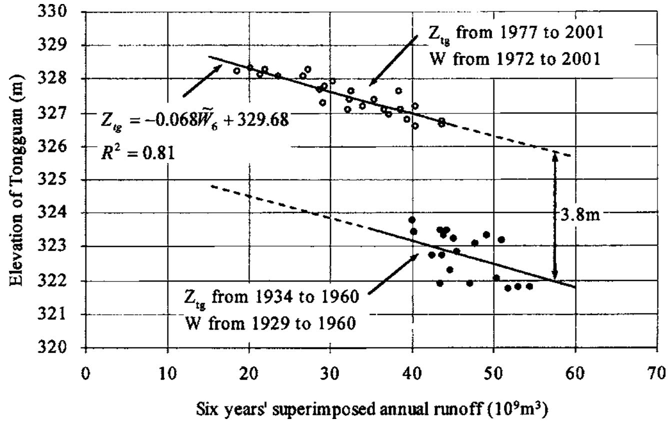

Fig. 11. Relationship between Tongguan's elevation at the end of the flood season and the 6 years' superimposed annual runoff

$$\widetilde{W}_6 = \sum_{k=1}^{6} a_k W_{ak} \quad (17)$$

Fig. 11 is a plot showing the variation of Z_{tg} versus $\widetilde{W}_6$. Considering that the elevation of Tongguan was in the process of adjusting in response to the new pool level conditions utilized in the controlled release operation from 1974 to 1976, these 3 years' data points were not included in Fig. 11. A regression relationship based on the data in Fig. 11 is as follows:

$$Z_{tg} = -0.068\widetilde{W}_6 + 329.68 \quad (R^2 = 0.81) \quad (18)$$

where Z_{tg} is in meters and $\widetilde{W}_6$ is in 10^9 m^3.

The correlation coefficient R^2 was as high as 0.81, which was a big improvement compared with the correlation coefficient of 0.65 obtained by using the current year's runoff as an independent variable. This indicated that the idea of including the effect of previous years' runoff is physically sound and the method of using a decreasing weight when integrating the earlier years' runoff is appropriate.

Referring to the analysis of Zhang et al. (2005), data before the dam construction were also included in Fig. 11. Comparing the trend line for data of controlled release since 1974 and the trend line under the natural conditions before the dam construction, the figure clearly demonstrates that the dam operation caused a rise of 3.8 m in the elevation of Tongguan. The long-term average pool level from 1974 to 2001 was 321 m, and it was 286 m before the dam construction. This means that due to dam operation, the water level at the dam site rose about 26 m on average, which caused the channel bed at Tongguan to rise by about 3.8 m.

It can also be seen from Fig. 11 or Eq. (18) that the elevation of Tongguan can rise about 1.36 m when the runoff decreases from a level of 40×10^9 m^3 to a level of 20×10^9 m^3. The results in Figs. 10 and 11 indicated that the continuous decrease of runoff was the main reason for the rise in the elevation of Tongguan after 1986.

Channel Slope in Response to Pool Level

Channel slope is one the most active factors that adjust in response to the upstream and downstream controls in a reservoir. Fig. 12 is a plot of the typical longitudinal channel bed profiles

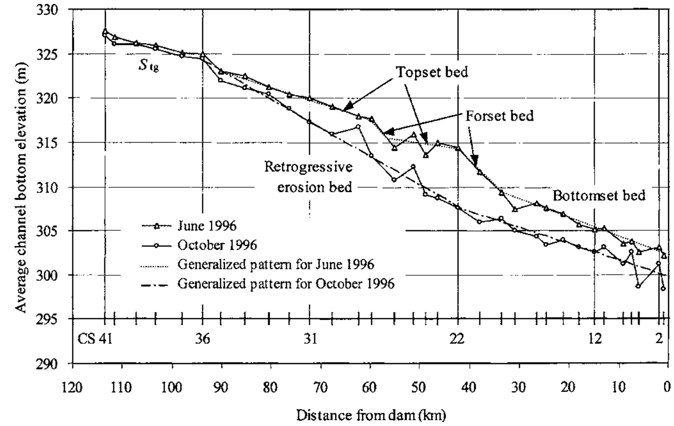

Fig. 12. Typical channel bed profile adjustments in Sanmenxia Reservoir below Tongguan within a water year in the time period of controlled release (topset beds correspond to the delta deposits on the top surface of an advancing delta; foreset beds represent the face of the delta advancing into the reservoir and are differentiated from the topset beds by an increase in slope and decrease in grain size; bottomset beds consist of fine sediments which are deposited on the bottom beyond the delta; retrogressive erosion bed is a zone of high slope with rapid erosion, moving upstream along the channel)

formed in the reservoir area in the period when the controlled release scheme has been used since 1974. The longitudinal channel bed profile has basically been composed of superimposed deltas in the nonflood season. When the reservoir stage was lowered in the flood season, the deposits in the main channel were eroded along with the drawdown of the reservoir. If the oncoming flow in the flood season was too small, and/or the operational stage in the nonflood season was relatively too high, deposition that took place at the head reach may not have been entirely eroded and thus would not be carried out of the reservoir in the same year. The residue would continue to be eroded until a large flood came the next year. In this case, the equilibrium of the deposition and erosion in the reservoir could not then be maintained within an operational year.

The channel bed slope $S_{t\text{-}g}$ from Tongguan (Cross Section 41) to Guduo (Cross Section 36) at the tail of the reservoir was relatively stable because it was outside of the direct backwater region of the reservoir under the operational conditions that were applied in the period of controlled release. However, it was still closely related to the pool level, rather than the upstream controls such as flow discharge or water runoff. Fig. 13 shows the annual variations of $S_{t\text{-}g}$ at the end of the flood season and the annual average pool level. At the end of the flood season of 1969, $S_{t\text{-}g}$ was about 0.0002. In the flood seasons between 1969 and 1973, the pool level remained at a relatively low level, with a long-term average value of 304.28 m, because all the outlets were kept fully open. The low pool level caused the channel bed slope from Tongguan to Guduo to increase, reaching a value of about 0.00028 between 1971 and 1973. In the time period from 1969 to 1973, the annual runoff had a relatively small variation, with a long-term average value of 30.67×10^9 m^3, which was a moderate amount of runoff for the reservoir. After the controlled release scheme was used in 1974, the channel bed slope from Tongguan to Guduo decreased gradually year by year, and reached a value of 0.0002 in 1981. $S_{t\text{-}g}$ remained around 0.0002 in the time period from 1981 to 1992, in which the annual runoff between 1981 and 1985 was on the high side, with a long-term average value of 44.3×10^9 m^3, and the

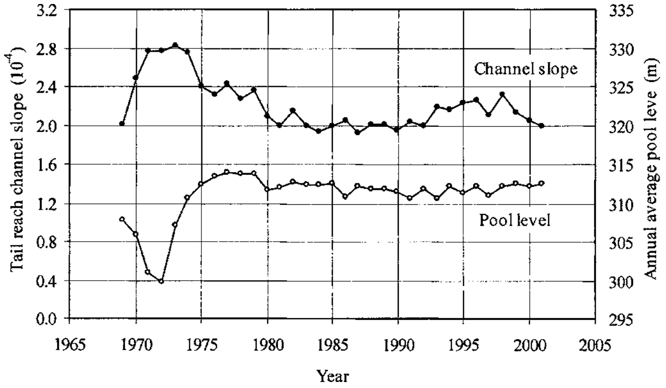

Fig. 13. Variations of channel slope at the tail reach from Tongguan to Guduo and annual average pool level

water runoff between 1986 and 1992 was on the low side, with a long-term average value of 29.1×10^9 m^3. Since 1993, S_{t-g} has slightly recovered. In this time period, the annual runoff decreased dramatically, with a long-term average value of only 22.3×10^9 m^3. But the number of days with a daily mean pool level higher than 322 m in the nonflood season decreased from 50 days to zero. The relatively low pool level in the nonflood season was the reason that the channel bed slope at the tail of the reservoir increased.

In principle, the longitudinal channel profile of an alluvial river is proportional to the flow discharge. Therefore, a decrease in runoff can usually result in an increase in the channel slope. However, the variation of the channel bed slope from Tongguan to Guduo did not follow this principle, and also there is no correlation between S_{tg} and the annual runoff W_a. In fact, the value of $S_{t\text{-}g}$ was determined by the magnitude of pool level because the flow and the channel bed near Tongguan were affected, directly or indirectly, by the upstream extension of sediment deposition caused by backwater of the reservoir. As shown in Fig. 14, the value of $S_{t\text{-}g}$ increased with the decrease in pool level, and it decreased as the pool level increased. So there was an inverse correlation between them.

As demonstrated earlier, the morphological configuration of the reservoir is not only determined by the current year's flow and dam operational conditions, but is also affected by the previous years' conditions. Therefore, the moving average $\bar{Z}_{di}$ of the annual mean pool level was used here to reflect the cumulative effect of the previous years' dam operational conditions. Then the correlation coefficients between S_{t-g} and $\bar{Z}_{di}$ for including different numbers of years were calculated for data of 1969–2001, and the results were plotted in Fig. 14(a). It can be seen from the figure that the correlation coefficient increased rapidly at the beginning as the number of years included in $\bar{Z}_{di}$ increased. Then the speed of increase in R^2 gradually became slow, and it reached a maximum at around 7 years. After that, the correlation coefficient decreased quickly as the number of years increased. The results in Fig. 14(a) indicated that the channel bed slope from Tongguan to Guduo was related to 7 consecutive years' dam operational conditions, in which the most recent three consecutive years had a greater effect than other more earlier years.

Fig. 14(b) is a plot showing the relationship between the channel bed slope from Tongguan to Guduo and the 7 years' moving average pool level. The value of S_{t-g} from 1969 to 2001 was in the range of 0.000193–0.000281. The 7 years' moving average pool level from 1969 to 2001 was in the range of 306.34–313.06 m, which corresponds to annual average pool levels in the range of 299.81–316.87 m for the time period from 1963 to 2001. The linear regression relationship between the channel bed slope from Tongguan to Guduo and the 7 years' moving average pool level for data shown in Fig. 14 can be expressed as follows:

$$S_{t-g} = -0.1043\bar{Z}_{d7} + 34.63 \quad (R^2 = 0.71) \tag{19}$$

where S_{t-g}=channel bed slope from Tongguan to Guduo ($\times10^{-4}$) and $\bar{Z}_{d7}$=moving average pool level of the dam over a 7-year period (m).

The previous analysis indicated that the channel bed slope from Tongguan to Guduo was mainly determined by the downstream dam operational conditions, rather than by the upstream inflow conditions. Though S_{t-g} remained almost constant after 1980, it was not a dynamic equilibrium slope normally required by the inflow conditions. As a matter of fact, the reason for a constant S_{t-g} was because the pool level had no tendency of variation, and the magnitude of S_{t-g} was controlled by the upstream extension of backwater deposition.

Conclusions

The effect of the variations of runoff and pool level on the reservoir sedimentation and Tongguan's elevation was extensively investigated in this paper. The hysteresis effect in reservoir sedimentation was used as the basis for analysis throughout this study. The delayed response in reservoir sedimentation revealed in the study implies that the erosion and sedimentation as well as the adjustment in channel morphology to a new equilibrium state

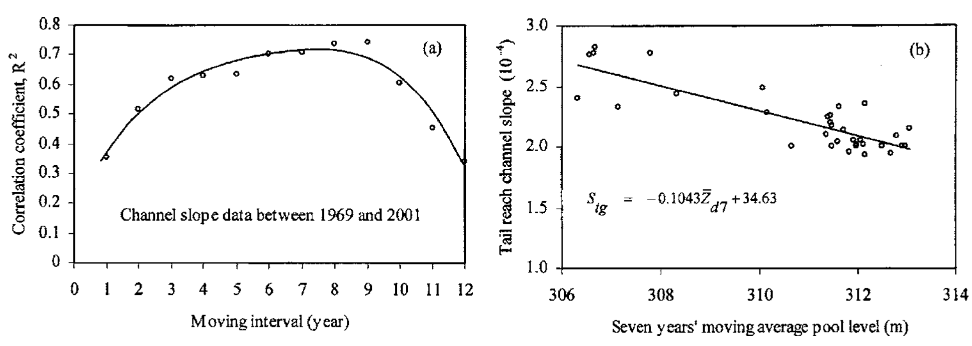

Fig. 14. Correlation between the channel slope at the tail reach from Tongguan to Guduo and the moving average annual pool level

require a certain length of time, and this phenomenon must be considered in the study of sedimentation. The following conclusions can be drawn from the study:

1. Each period of continuous rise or descent in Tongguan's elevation corresponded to a period of continuous deposition or erosion in the reservoir area downstream of Tongguan, but with the variation of Tongguan's elevation having about 2 years' delay compared with the sediment deposition in the reservoir area. The delayed response of Tongguan's elevation to the sediment deposition in the reservoir area was mainly caused by the delayed adjustment of the channel bed slope.
2. The accumulated sediment deposition in the reservoir area was related not only to the current year's flow conditions and the pool level of the dam, but also to the preceding 3 to 4 years' flow conditions and the pool level of the dam. This is well demonstrated by the good correlation between the accumulated sediment deposition in the reservoir area V_s and the 5 years' linearly superimposed pool level $\tilde{Z}_{d5}$.
3. Since 1974, under the operational conditions of the controlled release scheme, the variation of Tongguan's elevation was mainly related to the 6 years' linear superimposed runoff. The continuous decrease of runoff was the main reason for the rise in the elevation of Tongguan after 1986. The dam operation caused a rise of 3.8 m in the elevation of Tongguan, and the runoff decrease from a level of 40×10^9 m^3 to a level of 20×10^9 m^3 caused the elevation of Tongguan to rise by about 1.36 m.
4. The channel bed slope from Tongguan to Guduo at the tail of the reservoir was mainly determined by the downstream dam operational conditions. This slope was not a dynamic equilibrium slope normally required by the inflow conditions; instead it was controlled by the upstream extension of backwater deposition. The channel bed slope from Tongguan to Guduo was related to the moving average pool level over a 7-year period, and it was mainly determined by the pool level in the most recent 3 years.

To stop the rise in the elevation of Tongguan is an urgent need for the sustainable use of the Sanmenxia dam. As indicated in the analysis, the rise in Tongguan's elevation after 1986 was mostly caused by the decrease in inflow runoff resulting from unrealistic basin development and the situation of water shortage is not likely to change in the near future. Therefore, lowering the pool level becomes the most appropriate way to stop and lower Tongguan's elevation. The plan is to allow all flows to pass through the dam without any control in flood seasons, while lowering the maximum pool level from 322 to 318 m in nonflood seasons, and in addition the average pool level in the non-flood season should not exceed a value of 315 m (Research Group for Tongguan's Elevation Control and Sanmenxia Dam Operation, 2005). This strategy of pool level adjustment is under implementation and will be tested for a time period of 5 years because it will take at least 5 years for the reservoir sedimentation to reach a new balance. The effectiveness of the adjustment of the pool level will be continuously monitored and carefully evaluated to meet the goal of lowering the current Tongguan's elevation by 1 to 2 m.

Acknowledgments

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Notation

The following symbols are used in this paper:

a_k = weighting factor of the kth year;
C_1, C_2 = intercepts;
CE = coefficient of efficiency defined by Eq. (16);
c = subscript denotes the computed value;
i = total number of years included in the calculation of moving average or superimposed value;
K_1, K_2 = slopes;
k = year number counted from the same year;
MAE = mean absolute error defined by Eq. (14);
MNE = mean normalized error defined by Eq. (15);
m = subscript denotes the measured value;
N = total number of data points or years;
n = subscript represents the data number;
Q = flow discharge;
Q_{tg}, Q_{out} = daily mean discharges at Tongguan and Sanmenxia Stations, respectively;
RMSE = root-mean-square error defined by Eq. (13);
S = channel slope;
$S_{t\text{-}g}$ = channel bed slope from Tongguan (Cross Section No. 41) to Guduo (Cross Section No. 36);
V_s = accumulated volume of sediment deposited in the reservoir area from Tongguan to the dam;
V_{s31-41} = accumulated volume of sediment deposited between Tongguan and Tai'an;
W_a = annual runoff at Tongguan Station;
W_s = annual sediment load at Tongguan Station;
$\tilde{W}_6$ = 6 years' linearly superimposed runoff or weighted-average runoff defined by Eq. (17);
x, x_0 = independent variable and reference value of x, respectively;
y = dependent variable;
Z_d = pool level of the dam;
$\hat{Z}_d$ = discharge-weighted average pool level defined by Eq. (6);
$\tilde{Z}_{di}$ = linearly superimposed pool level for i consecutive years defined by Eq. (7);
$\bar{Z}_{di}$ = moving average value of the annual mean pool level for i years;
Z_{tg} = elevation of Tongguan measured at the end of flood season;
β = transitional shape parameter;
γ = specific weight of water;
ΔL = channel length;
ΔV_s = same year's volume of sediment deposited in the reservoir area from Tongguan to the dam;
ΔV_{s31-41} = same year's volume of sediment deposited between Tongguan and Tai'an;
ΔZ_{tg} = increment of Tongguan's elevation; and
τ = time delay.

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