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Dam Operation for Mitigating Ice Jam Flooding Risks under the Adjustment of River Channel-Forms: Implications from an Evaluation in the Ningxia-Inner Mongolia Reach of the Upper Yellow River, China

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Abstract: Dam operation has been widely deployed to mitigate the risks of ice jam flooding, but it may result in a decrease in the discharging capacities of downstream river channels. The Ningxia-Inner Mongolia reach of the Huanghe River (Yellow River) has historically suffered numerous disasters caused by ice jam flooding, and three large dams have been jointly operated to mitigate such risks since 1968. Whilst the resultant significant increases in both the annual runoff and mean water temperature during the ice jam flooding seasons helped to shorten the freezing-up duration and reduce the thickness of the ice cover, a significant channel shrinkage occurred in the reach when the dam operation took place under the input of a relatively larger amount of sediment from the upstream. In the new flow regime that commenced in 2008, a detailed examination of the river channel-form adjustments and the resultant changes to the discharging capacities identified a slight increase in the discharging capacity of the channel along the entire study reach. This was mainly due to a significantly smaller amount of sediment load being carried by a slightly increased annual runoff. Whilst it was demonstrated that the dam operation was still an effective means for mitigating the risk of ice jam flooding in the Ningxia-Inner Mongolia reach under the new flow regime, care needs to be taken when the favorable flow-sediment condition changes. Furthermore, the effectiveness of the dam operation appeared to vary significantly at the channel sections of different planforms; thus, more detailed studies are required.

Keywords: ice jam flooding; dam operation; risk mitigation; river channel-form adjustment; Upper Yellow River

1. Introduction

Ice jam flooding normally occurs in rivers that encounter ice jams or a wide range of downstream ice cover [1,2]. Long-term temperatures below 0 °C and a change in the river flow direction from a low latitude to a high latitude are the two main factors causing the occurrence of ice jam flooding [3–5]. During the freezing-up and breaking-up periods of river flow, disasters to local communities from ice jam flooding are prone to appear [6–8]. Many large rivers in cold regions, such as the Yellow River (Huanghe River), Vistula River, all Siberian Rivers, and so on, frequently experience ice jam flooding because these rivers are located in high latitude areas and they flow northward in many reaches [9–11].

Significant mitigation of the risks from ice jam flooding can be achieved by the construction and operation of dams to alter the hydrological process and thermal conditions of river flow [12–14].

Reservoirs have been operated to increase the velocity of the flow released to a river channel downstream when the ice-run appears, such that ice stagnation in the channel is avoided, and consequently, the freezing-up dates are delayed [14]. During the freezing-up period, flow discharge released from the reservoir is decreased gradually for the formation of a stable ice cover [14]. Furthermore, the reservoirs can raise the temperature of the water remaining within [15] or the water that is released from the thermal power plant to the river channel downstream [16], such that the ice cover in the channel can be significantly reduced. However, these changes to the hydrological process of river flow from the operation of dams can exert considerable influence on the downstream river channel-forms, most typically during the summer flooding seasons when powerful floods play a predominant role in shaping the river channel-forms [17–19]. The adjustments in the river channel-forms can influence the capacity of discharging ice and summer floods, the breaking-up water level, as well as the channel impoundage [20].

Over the last decades, a hot topic has been the response of river channel-form to the altered flow conditions due to dam operation, since a large number of dams have now been constructed world-wide [21–27]. However, it has been demonstrated that the response of river channel-form to the change in hydrological processes induced by dam operation occurs in a very complex form. Friedman et al. analyzed the response of channel geometry to 35 dams in the Great Plains and Central Lowlands of the USA and found that the response of a braided channel to altered flow and sediment processes occurred in the form of channel-narrowing, whilst a meandering channel exhibited a reduction in the channel migration rate [28]. However, along the lower Trinity River in Texas, USA, Phillips et al. identified a general phenomenon of incision, widening, coarsening of bed sediment, and a decrease in the channel slope, following a detailed examination of the downstream channel cross-sectional changes post operation of the Livingston Dam [24]. The Yellow River in China has experienced dramatic variations in the runoff and sediment input since 1950, owing to climatic and anthropogenic changes. After a detailed evaluation of the Lower Yellow River's channel cross-sectional geometry response to such variations, Hu et al. found that the depositional and shrinking trends were more severe in the wandering reach than in the meandering reach [17]. Even though a longer period was considered, nevertheless, Ma et al. still found that the changes in the at-a-station hydraulic geometry and bankfull channel-forms were different across different periods, with the altered flow conditions in the wandering reach of the Lower Yellow River [18].

The Ningxia-Inner Mongolia reach of the Upper Yellow River in China is an area that has historically suffered numerous disasters caused by floods, particularly from ice jam flooding [29]. In this reach, ice jam flooding usually occurs in late November or in late March, during which the river flow freezes up for about 120 days from early December to late March of the following year [30]. To mitigate the risks of ice jam flooding and to satisfy the demand for increased water resources for use in agricultural irrigation and urban expansion; during the 1960s, a large reservoir was constructed at Qingtongxia on the upper trunk of the reach. In 1968 and 1986, two large reservoirs were constructed at Liujiaxia and Longyangxia, respectively, on the further upper trunk of the Yellow River. The joint operation of the three large reservoirs significantly altered the flow and sediment regime into the downstream Ningxia-Inner Mongolia reach [31–33]. As a result, the resultant ice jam flooding in the reach considerably changed the characteristics. On one hand, the frozen days reduced due to the delay of the freezing-up dates whilst the breaking-up dates occurred earlier. On the other hand, the runoff in the freezing-up periods increased, reducing the frequency of ice jams and making ice cover melt occurred locally instead of cracking during the breaking-up periods [34,35].

Whilst the joint operation of the Qingtongxia, Liujiaxia, and Longyangxia Reservoirs has significantly reduced the magnitude and frequency of ice jamming floods in the Ningxia-Inner Mongolia reach downstream of the Qingtongxia Dam, there were considerable adjustments in the downstream river channel-forms. It has been shown that the channel over the entire reach has shrunk significantly, with the joint reservoir operation being regarded as the major cause [32,33]. Meanwhile, in a more detailed examination of the variation in sediment erosion/deposition along the Inner Mongolia reach during the period from 1955–2003, Shi demonstrated that the channel in the reach had been successively subjected to aggradation, degradation, and aggradation over three periods, with the years of 1961 and 1987 serving as the approximate break-points [36]. Whilst the break-points were very close to the time when the Qingtongxia and Longyangxia Reservoirs were constructed, Shi et al. argued that the successively changing pattern in erosion/deposition was caused by several factors, including natural river runoff, sediment retention behind dams, and sediment supply from the tributaries [37].

Together with the implementation of continuous land and water conservation practices, and grassland restoration policy in the drainage basin of the Yellow River, the source and the upper reach of the Yellow River have experienced dramatic changes in both runoff and sediment supply [37,38]. Knowledge is required on how the joint dam operation helps in mitigating the risks of ice jam flooding in the Ningxia-Inner Mongolia reach of the Upper Yellow River under the new flow regime. For the purpose, this study presented a detailed investigation of the characteristics of river flow in the ice jam flooding seasons during the period from 2008–2015, as well as the accompanying adjustments in the river channel-forms and channel-bed elevation. Consequently, a detailed evaluation was provided on the effectiveness of dam operation in mitigating the risks of ice jam flooding by accounting for the effects of river channel-form adjustments on the channel's discharging capacity.

2. Materials and Methods

The Ningxia-Inner Mongolia reach of the Yellow River, i.e., the Huanghe River, is the lower part of the upper reach of the river, located at the northernmost part of the whole drainage basin (Figure 1). The Huanghe River flows from Xiaheyan Town in Zhongwei County of the Ningxia Hui Autonomous Region of China to Tuoketuo Town in the Inner Mongolia Autonomous Region. Over its entire length of 1217 km, the river changes its flow direction several times. Initially it flows northeastwardly from Zhongwei to Dengkou, and then it turns southeastward from Dengkou to Lamawan. Finally, it flows southward downstream from Lamawan until Tuoketuo. This reach is called the Ningxia-Inner Mongolia reach, and it is located in a continental Monsoon climate zone, with a mean annual precipitation of only 150–400 mm, which falls predominantly in the short period from June to September of each year [39]. In contrast, the winter in the region has a temperature below 0 °C in approximately 4–5 months of each year [40]. As a result, the water surface of the river flow is covered with ice from December each year to March in the following year, with spring ice jam flooding commonly occurring when the ice begins to melt in late March of each year [41].

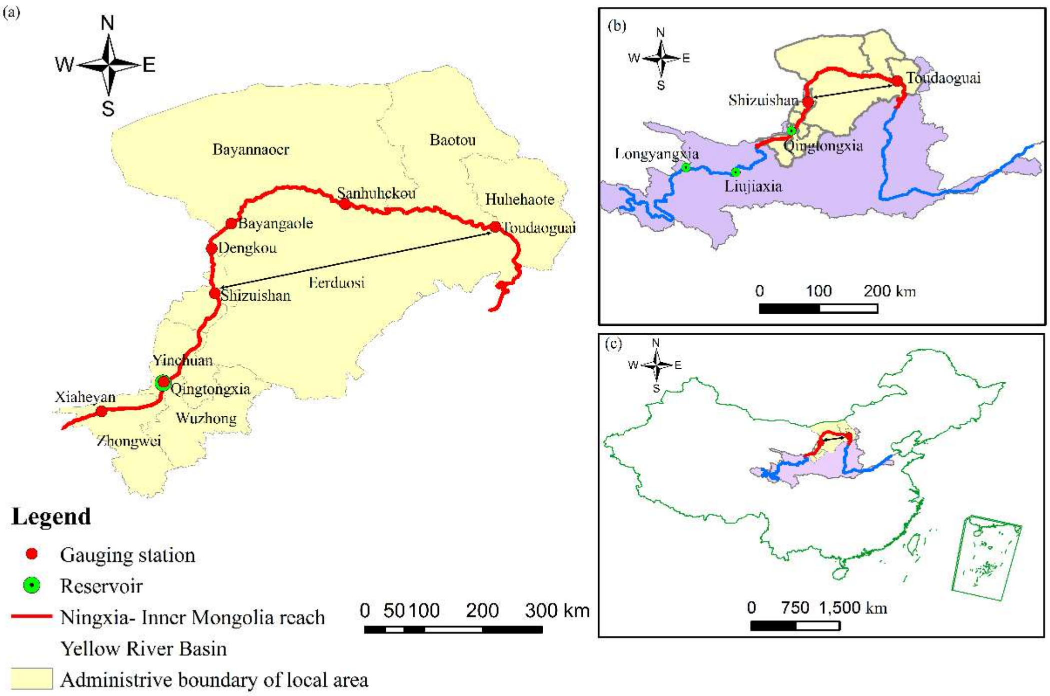

Figure 1. Location of study area: (**a**) the drainage area of the Ningxia-Inner Mongolia Reach; (**b**) the entire drainage basin of the Yellow River; (**c**) location of the Yellow River drainage basin in China.

The channel morphology of the Ningxia-Inner Mongolia reach varies considerably from one place to another, and yet it broadly consists of three sections: a reservoir, the Yinchuan plain, and the Inner Mongolia plain. Under the influence of the regulation and thermal effect of the Qingtongxia Reservoir constructed in 1960, the reservoir section from Zhongwei to the Qingtongxia Dam, and the Yinchuan plain from the Qingtongxia Dam to Shizuishan, are seldom frozen. Dissimilarly, the Inner Mongolia plain from Shizuishan to Toudaoguai is wide and shallow, and it freezes up much more easily, thus it is the main focus of this study.

The Qingtongxia, Liujiaxia, and Longyangxia Reservoirs are the main water control projects influencing the study area (Figure 1b). The main operational characteristics of these reservoirs are listed in Table 1. The Qingtongxia Reservoir, with a storage capacity of 6.06×10^8 m^3, commenced operations in 1968. Although the Qingtongxia Reservoir has a much smaller storage capacity, it is located far downstream of the Liujiaxia and Longyangxia Reservoirs, and in the upper part of the Ningxia-Inner Mongolia reach. Therefore, its discharging process of river flow reflects the integrated effects of the operation of the three reservoirs. The Liujiaxia and Longyangxia Reservoirs, which commenced operations in 1969 and 1986, respectively, are the two biggest water control projects located in the upper Yellow River with respect to their storage capacities. In particular, the Longyangxia Reservoir has a multi-year regulating capacity with a storage capacity of 247×10^8 m^3, and it controls 65% of the runoff in the upper Yellow River. With the joint operation of the three large reservoirs, the risks of ice jam floods have been significantly mitigated [8]. However, the flow process and channel morphology of the Ningxia-Inner Mongolia reach have been considerably altered [36].

Table 1. Main characteristics of the large reservoir constructed in the Upper Yellow River.

Reservoir	Total Storage (10^8 m^3)	Power-Plant Capacity (MW)	Operation Time	Area of the Upper Drainage Basin (km^2)
Qingtongxia	6.06	30.2	1968	275,004
Liujiaxia	57	1160	1969	181,766
Longyangxia	247	1280	1986	131,420

Along the frequently freezing-up reach of the Yellow River over the Inner Mongolia plain, five hydrological gauging stations have been set up to record the river flow process, at Shizuishan, Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai, respectively (Figure 1a). Since the river channel at the five stations exhibits wandering, straight, braided, braided to meandering transitional, and meandering to straight transitional planforms [39], respectively, the variations in the channel cross-sectional forms at the five stations illustrate the channel-form adjustments of the different channel patterns. The channel cross-sections at the five stations are usually measured at least twice each year, with the latter measurement occurring during September to November of each year. To reflect the channel-forms before the ice jam flooding seasons, the cross-sectional measurements obtained during September to November each year were used in this study (Figure 2). All of these data were made available by the Yellow River Conservancy Commission (YRCC) of China.

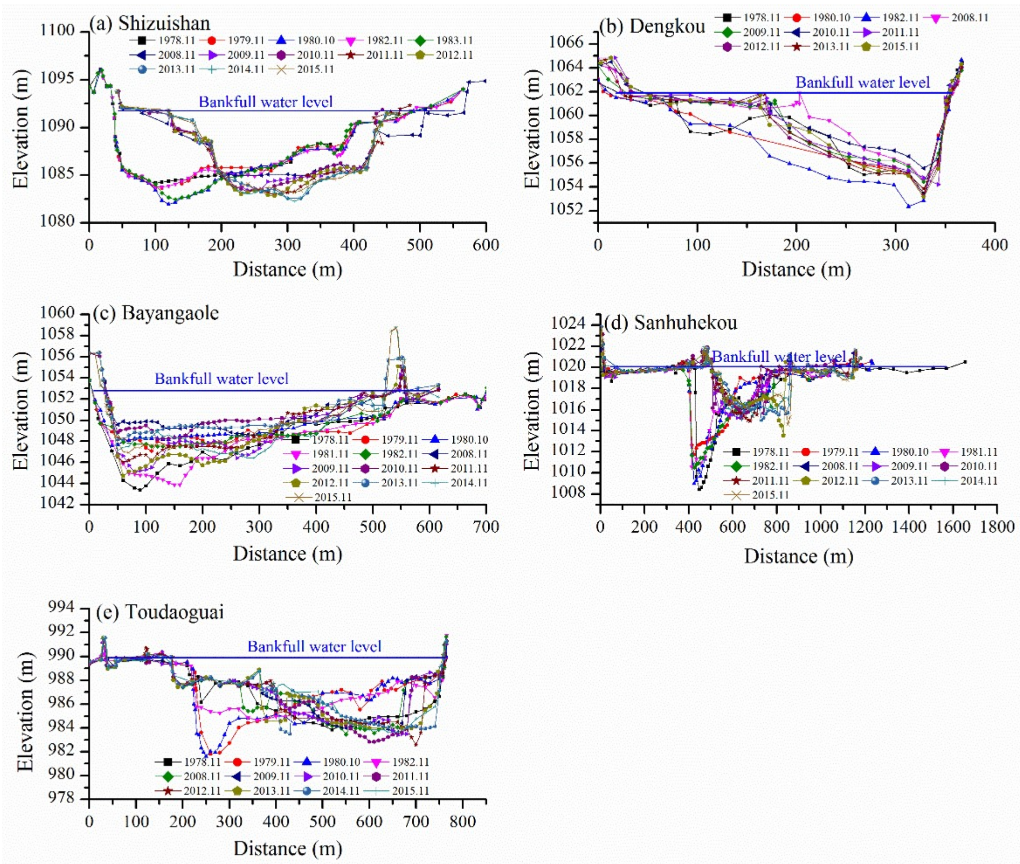

Figure 2. Typical cross-sections and the bankfull water levels at the five gauging stations: (**a**) Shizuishan station; (**b**) Dengkou station; (**c**) Bayangaole station; (**d**) Sanhuhekou station; and (**e**) Toudaoguai station.

The variation in flow discharge can lead to adjustments in the cross-sectional geometric parameters [42,43]. To evaluate these adjustments, it is necessary to determine the bankfull level, since it is geomorphologically suitable for computing the potential discharging capacity of the channel to pass flood flows, and to transport sediment [44]. In terms of the measured channel cross-sectional data, we performed a detailed analysis of the geometrical parameters of the channel cross-sections at the bankfull levels, including the bankfull cross-sectional area, bankfull channel width, and the average channel depth.

Equipped with the determination of the river channel-form adjustments at all five stations in the study reach, we then presented a detailed evaluation of the effects of the channel-form adjustments on the discharging capacity of the channel at each station, using the following widely applied flow relationship:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \quad (1)$$

where Q is the discharging capacity; n is the Manning's roughness coefficient; A is the channel cross-sectional area; S is the channel gradient; and R is the hydraulic radius of the channel cross-section. Equation (1) was used to assess the discharging capacity of the channel on the assumptions that the flow was uniform and the channel was straight.

The data on sediment load used in this article was made available by YRCC in their year-books. The concentration of suspended sediment load was determined in terms of the national hydrological surveying standard, which was set by the state council of China. The surveying standard includes the procedure for collecting water samples, measuring the volume of the water sample, sedimentation of the water sample, weighting the quality of the dry sand, and calculating the concentration of suspended sediment according to the sand quality and water volume. Then, the suspended sediment load (SSL or *Qs*) for each river cross-section was obtained by multiplying the sediment concentration by the corresponding flow discharge.

3. Results and Analysis

3.1. Altered Hydrological Process during the Ice Flooding Seasons

The Qingtongxia Reservoir was the largest water controlling project nearest to our study area, and Figure 3 shows the variation of the annual runoff released from the Qingtongxia Reservoir during the ice jam flooding seasons (15 November to 31 March in the following year) from 1952–2015. We observed that during the period 1952–1968, or before the operation of the Qingtongxia and Liujiaxia Reservoirs, the annual runoff in the ice jam flooding seasons was very small in quantity, approximately 3.93 billion m^3 on average. During the period 1969–1986, or from the operation of the Qingtongxia and Liujiaxia Reservoirs up to the operation of the Longyangxia Reservoir, the average annual runoff during the ice jam flooding seasons reached 5.34 billion m^3, which was 35.84% larger than in the previous period. From 1987 to 2015, the average annual runoff during the ice jam flooding seasons was 5.60 billion m^3, which was slightly larger than in the previous period. Clearly, the annual runoff released from the Qingtongxia Reservoir into the study reach area during the ice jam flooding seasons had significantly increased following the joint operation in 1986 of the three large reservoirs.

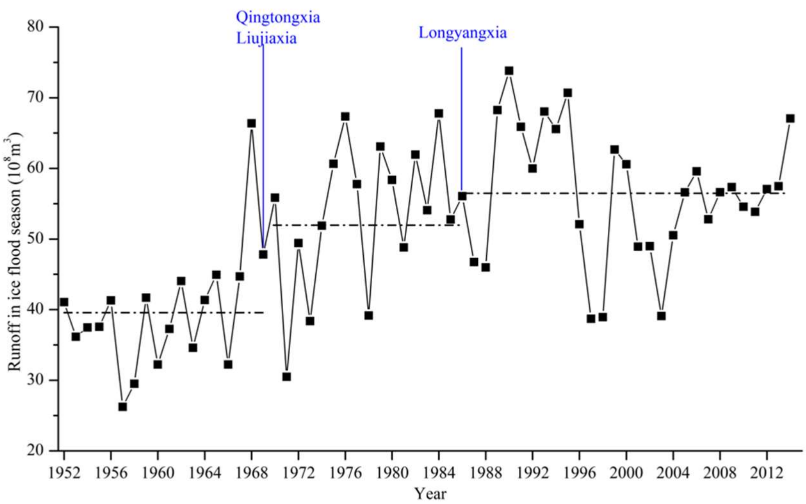

Figure 3. Variation of the annual runoff recorded at Qingtongxia station during the ice jam flooding seasons.

Figure 4 shows the daily discharging processes of the Qingtongxia Reservoir during the freezing-up seasons from 2008 to 2015, and we observe that a very similar pattern is exhibited amongst all the processes, where Table 2 shows the linear regression results. We observe from both Figure 4 and Table 2 that the flow discharge significantly increases from middle November to late November (stage 1) each year. From late November to middle February the next year (stage 2), the flow discharge varies in a small increasing or decreasing range, although it assumed a slightly decreasing trend. From middle February to middle March, the flow discharge gradually decreases (stage 3), whilst from middle to late March, the discharge increases very rapidly (stage 4).

The four-stage variations in the daily flow discharge are the direct result of the joint operation of the three large reservoirs, that is, the Longyangxia, Liujiaxia, and Qingtongxia Reservoirs, and these have effectively mitigated the risks of ice jam flooding in our study reach area [14]. The main reason is that from middle November to late November each year, the river flow on the lower part of the study reach gradually freezes up, because it is located in a higher latitude zone whilst the upper part of the study reach is in a lower latitude zone and remains non-freezing. To avoid disasters that result from the over-topping of river flow upon the ice cover, a small flow discharge needs to be released from the Qingtongxia Reservoir. When the entire Inner Mongolia reach freezes up from late November to middle February, a larger flow discharge warms up the lower part of the ice cover to a certain degree, which is beneficial for the fish and ecosystems. During middle February to middle March each year, the ice cover starts to melt from the lower part of the study reach and to mitigate against ice jam flooding, a small flow discharge needs to be released from the Qingtongxia Reservoir. However, from middle March each year, the water demand for agricultural irrigation is substantial in the region; therefore, a very large flow discharge must be released from the Qingtongxia Reservoir.

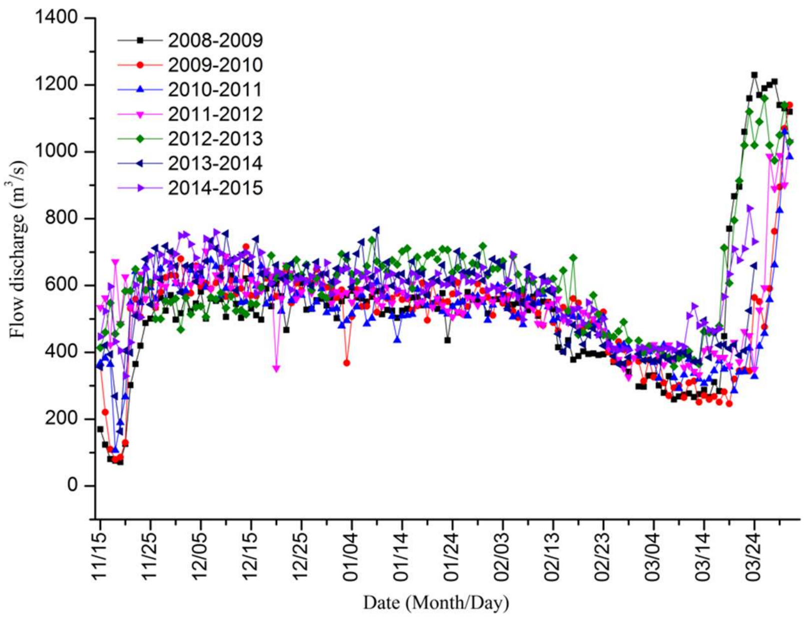

Figure 4. Variation of the daily discharge of the Qingtongxia Reservoir during the ice jam flooding seasons.

Table 2. Linear regression results of the discharging processes during the ice jam flooding seasons.

Year	Stage 1		Stage 2		Stage 3		Stage 4	
	Regression Equation	Q (ave) m^3/s	Regression Equation	Q (ave) m^3/s	Regression Equation	Q (ave) m^3/s	Regression Equation	Q (ave) m^3/s
2008–2009	$y = 86.49 \times x - 7.27$ $R^2 = 0.96$	222	$y = 0.013 \times x + 545.17$ $R^2=0.90$	545	$y = -5.69 \times x + 955.08$ $R^2 = 0.81$	342	$y = 39.74 \times x - 4183.40$ $R^2 = 0.56$	1042
2009–2010	$y = 104.51 \times x + 34.27$ $R^2 = 0.73$	317	$y = -1.04 \times x + 629.00$ $R^2=0.25$	576	$y = -9.35 \times x +1390.90$ $R^2 = 0.87$	385	$y = 65.74 \times x - 8077.80$ $R^2 = 0.87$	566
2010–2011	$y = 93.57 \times x + 148.00$ $R^2 = 0.78$	407	$y = -1.19 \times x + 621.97$ $R^2 = 0.32$	561	$y = -6.38 \times x + 1099.00$ $R^2 = 0.82$	413	$y = 53.62 \times x - 6523.80$ $R^2 = 0.76$	527
2011–2012	$y = 5.64 \times x + 523.87$ $R^2 = 0.53$	554	$y = -1.25 \times x + 642.53$ $R^2 = 0.32$	579	$y = -5.07 \times x + 969.94$ $R^2 = 0.61$	424	$y = 57.65 \times x - 6958.00$ $R^2 = 0.80$	623
2012–2013	$y = 22.13 \times x + 416.47$ $R^2 = 0.71$	538	$y = 1.65 \times x + 534.21$ $R^2 = 0.38$	617	$y = -5.57 \times x + 1061.60$ $R^2 = 0.49$	462	$y = 28.34 \times x - 2751.90$ $R^2 = 0.52$	975
2013–2014	$y = 89.40 \times x +138.27$ $R^2 = 0.91$	414	$y = -0.68 \times x + 675.77$ $R^2 = 0.11$	641	$y = -2.04 \times x + 634.17$ $R^2 = 0.19$	414	$y = 32.79 \times x - 3734.10$ $R^2 = 0.53$	462
2014–2015	$y = 54.86 \times x +294.67$ $R^2 = 0.70$	491	$y = -1.36 \times x + 704.69$ $R^2 = 0.43$	635	$y = -2.15 \times x + 694.81$ $R^2 = 0.16$	463	$y = 31.79 \times x - 3374.70$ $R^2 = 0.69$	693
2008–2015	$y = 28.19 \times x +265.89$ $R^2 = 0.21$	222	$y = -0.55 \times x + 621.94$ $R^2 = 0.45$	545	$y = -5.18 \times x + 972.27$ $R^2 = 0.41$	342	$y = 48.23 \times x - 5595.40$ $R^2 = 0.40$	1042

3.2. Variation in the Water Temperature during the Ice Flooding Seasons

Figure 5 shows the variation of the mean temperature of the river flow released from the Qingtongxia Reservoir during the ice jam flooding seasons, following the fully operational status of the Liujiaxia Reservoir in 1971. Since there is no data available for the period 1985–2007, it is noticeable from Figure 4 that the mean temperature varied within a very limited range during the period 1971–1984. Meanwhile, from 2008–2015, the mean temperature increased up to 3.80 °C on average, which was 34.85% higher than during the period 1971–1984. This increase in the water temperature is beneficial in shortening the freezing-up duration of river flow and reducing the thickness of ice cover, which resulted from the joint operation in 1986 of the Qingtongxia, Liujiaxia, and Longyangxia Reservoirs [9].

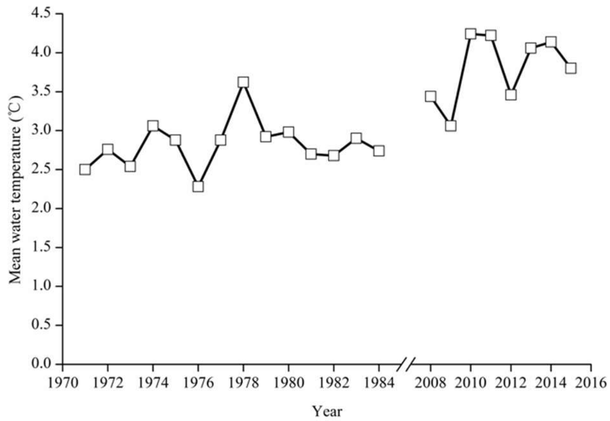

Figure 5. Variation of the mean temperature of the flow released from the Qingtongxia station during the ice jam flooding seasons.

3.3. River Channel-Form Adjustments before the Ice Jam Flooding Seasons

The geometrical parameters of the channel cross-sections at the bankfull level, being the bankfull cross-sectional area, bankfull channel width, and average channel depth, were determined from the collected cross-sectional measurements that were conducted before each ice flooding season (Table 3). The changing trends of the computed cross-sectional areas at the five stations are shown in Figure 6, and we notice that the changing patterns of the cross-sectional areas vary considerably from one station to another during the two periods, with no available data for the period between the two. The cross-sectional areas at Shizuishan station (Figure 6a) fluctuated within a wide range during the first period (1978–1982), with an average value of 1982.48 m^2, whilst in the second period (2008–2015), the areas decreased significantly with an average value of 1752.91 m^2, which was 11.63% smaller than in the first period. At Dengkou station (Figure 6b), the cross-sectional areas fluctuated, with an average value of 1343.46 m^2 in the first period, although they varied within a small range during the second period with an average value of only 814.03 m^2, which was 39.41% smaller than in the first period. The cross-sectional areas at Bayangaole station (Figure 6c) fluctuated within a wide range during both periods, whilst the average value in the second period was 30.00% smaller than the first period. At Sanhuhekou station (Figure 6d), the cross-sectional areas had an average value of 2083.44 m^2 during the first period, where it decreased significantly with an average value of 1240.43 m^2, which was 40.46% smaller than in the first period. The cross-sectional areas at Toudaoguai station fluctuated considerably in both periods. Although the cross-sectional areas at the Dengkou and Sanhuhekou stations during the second period were still smaller than in the first period, to a certain extent, they assumed an increasing trend, whilst the cross-sectional areas at the other three stations changed with no significant decrease during the second period.

These results demonstrate that although a significant contraction occurred during the break between the two periods on account of the dam operation, during the second period or from 2008 to 2015, the channel in the study reach had generally remained stable, with significant increases at some stations. Shi et al. revealed that during the period 1988–2003, the channel of the Inner Mongolia reach suffered a silting-up and shrinkage process [37]. The author pointed out that the weakness in soil conservation efficiency induced by reservoir sedimentation and the enhancement of water regulation ability affected by the operation of the Longyangxia reservoir in 1986 had led to channel shrinkage during the period 1988–2003. The next part of this study analyzed the reasons why the channel in the study reach had not contracted under the new flow and sediment regime, or during the period from 2008 to 2015.

Table 3. Geometrical parameters of the cross-sections at the bankfull levels at the five stations before the ice jam flooding seasons.

Station	Shizuishan			Dengkou			Bayangaole			Sanhuhekou			Toudaoguai		
Bankfull Water Level	1091.15 m			1061.47 m			1052.92 m			1020.09 m			989.94 m		
Date	A (m^2)	W (m)	W/D	A (m^2)	D (m)	W/D	A (m^2)	D (m)	W/D	A (m^2)	D (m)	W/D	A (m^2)	D (m)	W/D
November 1976				1493	332	74									
November 1977				1039	324	101									
November 1978	1919	434	98	1580	320	65	2935	696	165	2146	1062	526	2388	729	222
November 1979	1841	436	103				2437	697	199	1852	981	519	2209	704	224
November 1980	2128	438	90	1172	330	93	2184	697	223	2094	1009	485	2257	689	210
November 1982	1970	439	98	1433	332	77	2985	698	163	2001	1038	538	2811	721	185
November 1983	2055	426	88				2349	696	207	2325	1038	463	2146	659	202
November 2008	1682	412	101	328	306	146	1467	575	225	1034	976	921	2205	723	237
November 2009	1793	382	81	487	305	112	1986	577	168	1158	973	818	2107	725	249
November 2010	1713	309	56	346	272	107	1421	508	181	1039	798	614	2167	725	242
November 2011	1793	310	54	505	246	73	1859	512	141	1040	970	907	2158	679	214
November 2012	1749	323	60	580	264	75	2075	549	145	1286	960	716	2261	640	181
November 2013	1752	321	59	582	283	87	1521	503	167	1400	984	693	2325	643	178
November 2014	1803	315	55	454	270	94	2162	498	115	1526	1039	707	2262	667	197
November 2015	1731	322	60	548	289	93	1955	498	127	1442	1021	724	2104	701	234

Note: A is the bankfull cross-sectional area; W is the bankfull channel width; W/D is the ratio of bankfull channel width to mean channel depth.

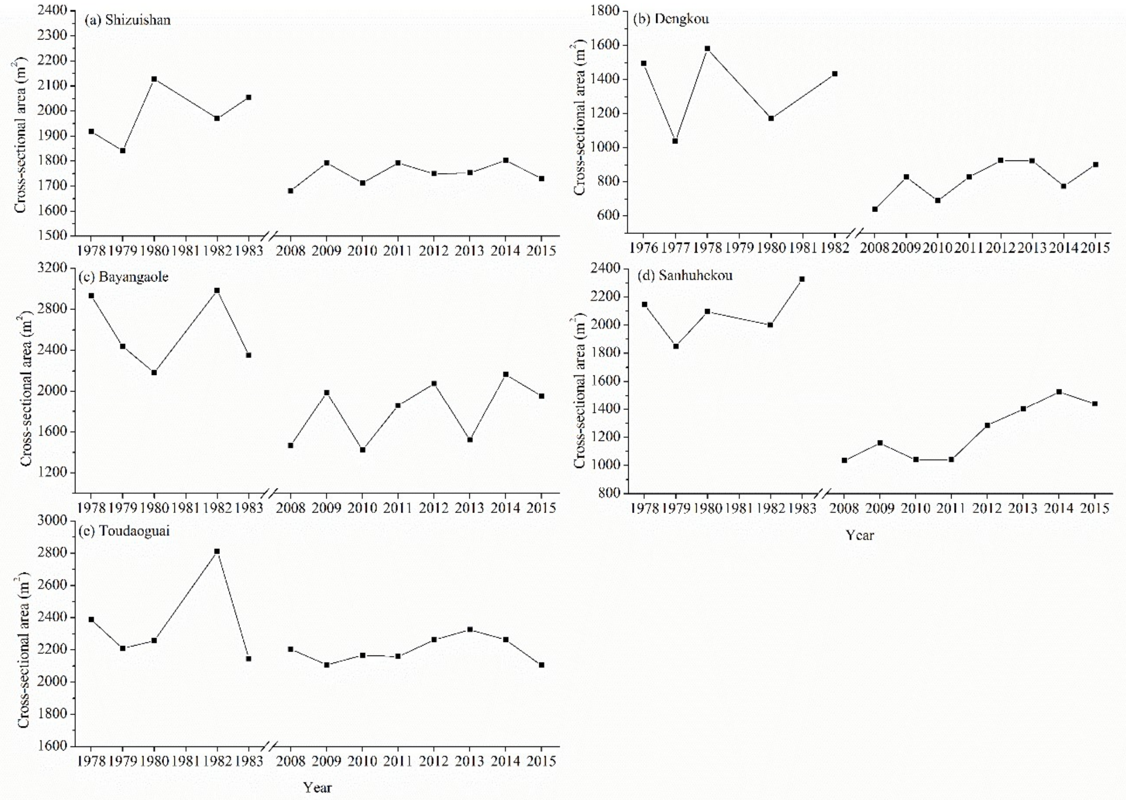

Figure 6. Variations in the bankfull cross-sectional area at the five stations before the ice jam flooding seasons: (**a**) Shizuishan station; (**b**) Dengkou station; (**c**) Bayangaole station; (**d**) Sanhuhekou station; and (**e**) Toudaoguai station.

With the collected measured channel cross-sections in the study reach, we determined the changes in the thalweg's elevation of the cross-sections measured just before the river flow froze up each year at the five stations, and these are shown in Figure 7. From 2008 to 2015, the thalweg's elevation at Shizuishan station decreased yearly in a consistent manner, except in 2015, with a total reduction of 1.68 m (Figure 7a), whilst it fluctuated in a wide range within a total reduction of 1.43 m at Dengkou station (Figure 7b), and there was a total reduction of 1.60 m at Bayangaole station (Figure 7c). At Sanhuhekou station (Figure 7d), the thalweg's elevation decreased yearly from 2008 to 2012, although it increased in 2013 up to the elevation in 2011. At Toudaoguai station (Figure 7e), the thalweg's elevation decreased significantly from 2010 to 2012, and then it increased in 2013 up to the value highest during the entire period from 2008 to 2013.

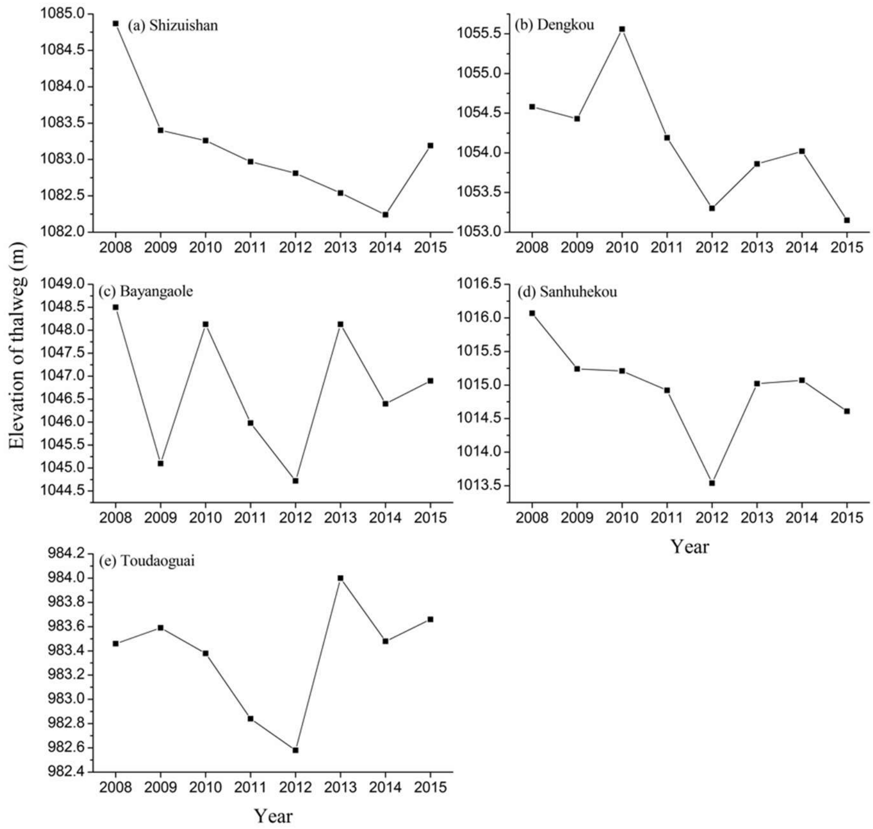

Figure 7. Variation of the thalweg's elevation at different gauging stations before each ice jam flooding season: (**a**) Shizuishan station; (**b**) Dengkou station; (**c**) Bayangaole station; (**d**) Sanhuhekou station; and (**e**) Toudaoguai station.

4. Discussion

4.1. Physical Cause for Adjustments in the Channel-Forms and Discharging Capacities

Although Figure 6 shows that the cross-sectional areas at the Shizuishan, Dengkou, Sanhuhekou, Bayangaole, and Toudaoguai stations decreased significantly after the joint operation of the three large reservoirs upstream. From 2008 to 2015, they varied in a generally increasing trend, at least not decreasing, at the five stations under the new flow and sediment regime. Physically, these adjustments in the channel-forms resulted from aggradation or deposition in the study reach [45,46]. Therefore, we examined the difference in the annual sediment load recorded at the Qingtongxia and Toudaoguai stations, which were located separately at the start and end of the study reach (Figure 8). The annual sediment load recorded at the Qingtongxia and Toudaoguai stations showed a decreasing trend since 1960, with sharp decreases occurring around 1968 and 1986 when the Liujiaxia and Longyangxia Reservoirs began to operate (Figure 8a). According to the annual sediment load recorded at the Qingtongxia and Toudaoguai stations and the input from the main tributaries in the study reach, the difference between the sediment input and output in the entire study reach was calculated from the following relationship:

$$Q_s = Q_{send} - Q_{sstart} - Q_{\mathrm{stri}} \quad (2)$$

where Q_s is the difference between the annual sediment input and output in the study reach; Q_{send} is the annual sediment output from the end point of our study reach (Toudaoguai station); Q_{sstart} is the annual sediment input at the start point of the study reach (Qingtongxia station); Q_{stri} is the annual sediment input from the main tributaries into the main channel of the Yellow River.

We observe in Figure 8b that Q_s mainly takes positive values from 1960 to 1987. This meant that the sediment in quantity input from the upstream and main tributaries into our study reach was smaller than the output. As a result, degradation occurred in the study reach. From 1987 to 2006, Q_s assumed mainly negative values, meaning that the sediment in quantity input from the upstream and main tributaries into our study reach was larger than the output. Hence, aggradation occurred in the study reach. In correspondence to the degradation and aggradation, the cross-sectional areas of the channel varied across a significantly decreasing trend during the period 1960–1987, and during the period 1987–2006. From 2007, Q_s assumed positive values, meaning the occurrence of degradation in the study reach, and yielding a gradually increasing trend in the cross-sectional areas from 2008 to 2015.

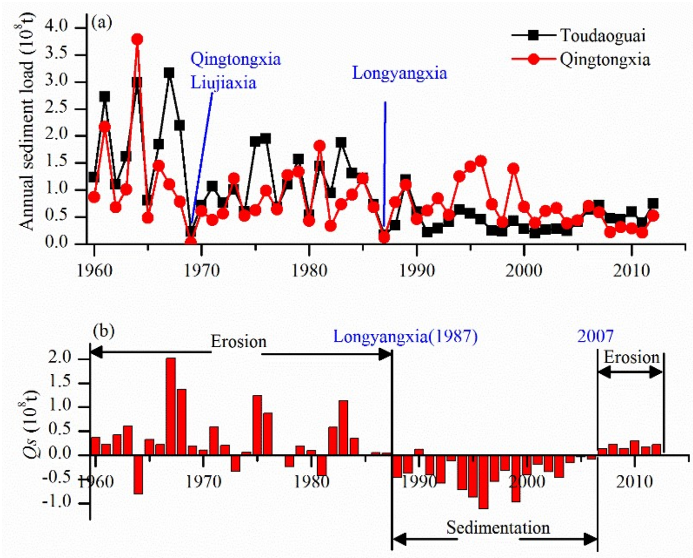

Figure 8. Variations of sediment load recorded at the Qingtongxia and Toudaoguai stations: (**a**) variations of annual sediment load; and (**b**) difference in sediment load between the Qingtongxia and Toudaoguai stations (the positive value means the annual sediment output is larger than the sediment input, whilst the negative value means the annual sediment input is larger).

While it is clear that the imbalance between the input and output of sediment in the study reach prompted the channel-forms to adjust; it is important to understand the degree to which channel-form adjustments affect the discharging capacity of the channel. In terms of Equation (1), the discharging capacities of the cross-sections in the study reach could be calculated in terms of the cross-sectional parameters computed from the field measurements and presented in Table 2. Figure 9 shows the plotted calculated results, and we observe that the discharging capacities of the cross-sections at Shizuishan station increased significantly from 2008 to 2015, a change of 22.49%, before the ice jam flooding seasons. Whilst the discharging capacities of the cross-sections at Dengkou station showed a generally increasing trend, they were significantly larger during the period 2011–2015 compared to earlier periods. However, the discharging capacities of the cross-sections at Bayangaole station fluctuated within a wide range and without a significant increase or decrease. The discharging capacities of the cross-sections at Sanhuhekou station were significantly larger during the period 2011–2015 compared to earlier periods, increasing by 68.78% from 2008 to 2015. The discharging capacities of the cross-sections at Toudaoguai station were minimal from 2008 to 2010, although they took on much larger values during the period 2011–2013 following by declining a trend from 2014. Although the discharging capacities of the cross-sections before the ice jam flooding seasons at different stations varied significantly during the period 2008–2015, they were generally increasing or remained fluctuating within a certain range, indicating that the discharging capacities of the channel in the study reach were enhanced or did not decrease during the period 2008–2015.

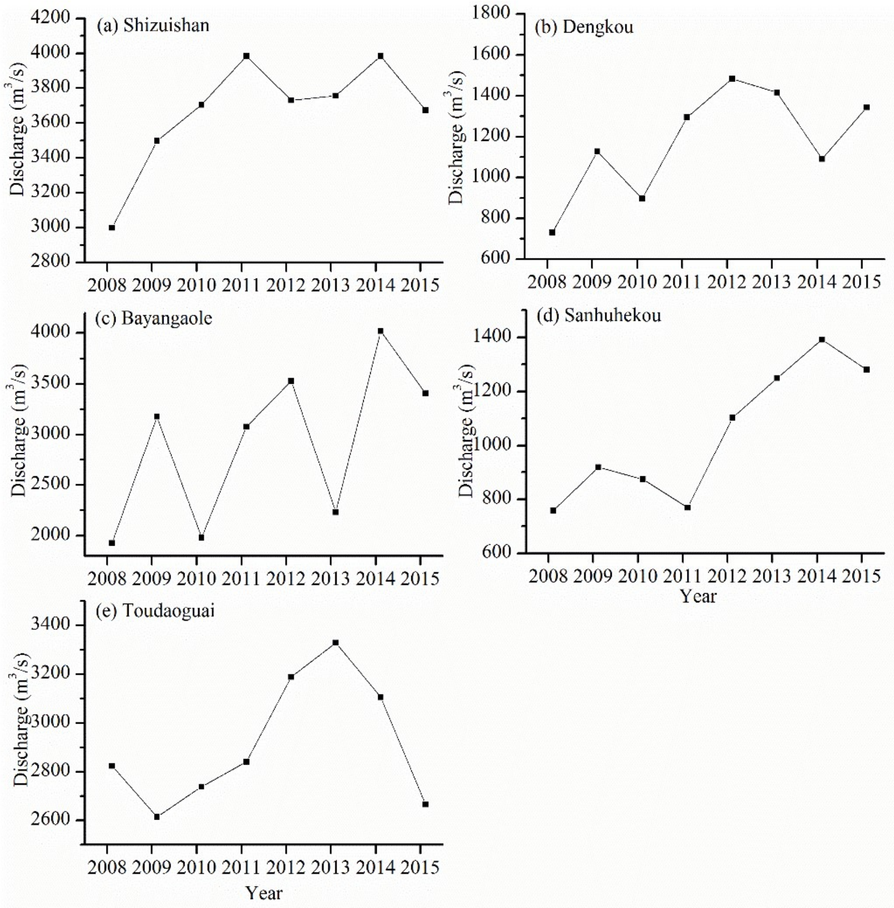

Figure 9. Variations of the discharging capacity of the cross-sections at the five gauging stations before each ice jam flooding season: (**a**) Shizuishan station; (**b**) Dengkou station; (**c**) Bayangaole station; (**d**) Sanhuhekou station; and (**e**) Toudaoguai station.

In addition, the channel-forms and discharging capacities of the cross-sections at Bayangaole stations showed a significantly fluctuating pattern. This reason was that the river channel at the station had a braided or from braided to meandering transitional planform, in contrast to the straight or meandering planforms exhibited at the other stations [39]. The braided channel cross-sections were characterized by a very large number of central sandbars, which were unstable to a degree and made flow switches amongst the bars within the channel.

4.2. Impact of Large Summer Floods on the Channel-Forms

Figure 7 presents the variations in the thalweg's elevations of all the five channel cross-sections on the Ningxia-Inner Mongolia reach of the Yellow River measured during the period 2008–2015. We observed that the thalweg's elevations at all the five cross-sections showed a similar gradually declining trend. However, we also noticed in Figure 7, that the thalwegs of the cross-sections declined dramatically in 2012, specifically at the Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai stations. This was due to the occurrence of a very large flood in August 2012, which caused significant incisions in the channel-bed along the study reach [47]. Nevertheless, the thalwegs of the cross-sections rose considerably in 2013 at the places where the significant incision occurred in 2012. This meant that a very large flood could exert a significant influence on the geometry of a river channel cross-section, which may determine the discharging capacity before the ice jam flooding seasons.

Table 4 shows the changes in the channel geometrical parameters over the study reach induced by flows in the flooding seasons during the period 2008–2015. The cross-sectional areas at the five stations became larger and the channel became narrower and deeper after each summer flooding season. All of these changes in the channel cross-sectional forms, and the gradual lowering of the channel thalweg's elevation before the ice flooding seasons, are deemed beneficial for discharging floods and mitigating the potential risks.

Table 4. Changes in the channel geometrical parameters at the five stations after each summer flooding season.

Year\Station	Shizuishan		Dengkou		Bayangaole		Sanhuhekou		Toudaoguai	
	A	W/D	A	W/D	A	W/D	A	W/D	A	W/D
2008	−2.78%	55.13%	25.75%	−4.33%	45.38%	−8.78%	−12.53%	17.15%	−5.98%	−15.67%
2009	31.34%	−26.56%	47.53%	−27.18%	196.39%	−14.37%	−24.69%	26.58%	12.87%	−16.85%
2010	12.78%	−4.89%	−2.36%	−8.15%	18.25%	8.23%	−19.12%	16.31%	12.18%	−1.56%
2011	42.14%	−28.81%	49.14%	−22.41%	111.23%	−56.26%	−13.87%	20.60%	40.74%	−31.25%
2012	53.49%	−11.33%	43.75%	−19.32%	89.72%	−14.65%	42.18%	80.15%	42.58%	−25.54%
2013	60.34%	−40.98%	45.62%	−3.56%	5.19%	52.04%	29.65%	−2.17%	11.98%	−4.15%
2014	80.07%	−46.36%	15.83%	23.35%	143.45%	−21.90%	27.15%	23.56%	−7.05%	−4.32%
2015	14.28%	−27.34%	14.67%	−13.43%	−12.12%	85.65%	15.32%	−8.16%	2.91%	25.32%

Note: A is the bankfull cross-sectional area; W/D is the ratio of bankfull channel width to mean channel depth.

Figure 10a shows a plot of variations in the annual runoff and the suspended sediment load (SSL) during the summer flooding seasons recorded at the Qingtongxia station from 1951–2015. We observed that both the runoff and SSL had a similar decreasing trend from 1951 to 2000, and they were subject to considerable influences from the operation of the Liujiaxia and Longyangxia Reservoirs. However, from 2000 to 2015, the variation in runoff during the summer flooding seasons changed into a slightly increasing trend, whilst the SSL decreased in a much more dramatic form. As a result, the sediment concentration of flow during the summer flooding seasons from 2008–2015 assumed significantly lower values (Figure 10b). Since alluvial rivers are very complex self-adjusting systems, difficulties still remain in directly quantifying the effect of changes in the runoff and sediment input on the river channel geometry [48–50]. Nevertheless, it can be inferred from several widely recognized previous qualitative studies, as summarized by Schumm [51] and Chang [49], that the changes in runoff, SSL, and sediment concentration can enhance the sediment carrying capacity of the channel by a considerable degree. The main physical cause for the enhancement was that the changes in the runoff and sediment input of the Ningxia-Inner Mongolia reach during the period 2008-2015 were able to induce a significant increase in the channel cross-sectional area, as well as severely scouring the channel-bed, such that the cross-sectional geometry adjusted from a wide-shallow form to a narrow-deep form.

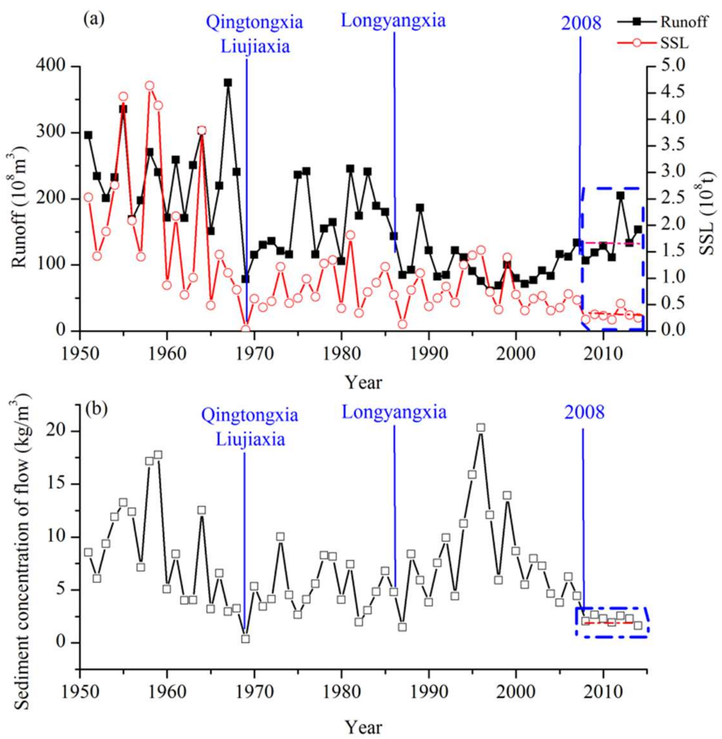

Figure 10. Variations in (**a**) the runoff and suspended sediment load (SSL), and (**b**) the sediment concentration, during the summer flooding seasons at the Qingtongxia station.

5. Conclusions

Dam operation can effectively mitigate the risks of ice jam flooding, although this may result in a considerable shrinkage in the downstream river channel. Since 1968, dam operation in the Ningxia-Inner Mongolia reach of the Upper Yellow River has significantly shortened the freezing-up duration and considerably reduced the thickness of the ice cover, resulting in a significant channel shrinkage in the reach prior to 2008. This casts doubt on whether the shrinkage will be exacerbated and whether the channel's capacity to discharge ice floods will decline significantly, under the post-2008 new flow-sediment regime. Using available measurements of river flow and sediment conditions, as well as channel cross-sections in the Ningxia-Inner Mongolia reach since 1951, this study presented a detailed investigation of the effectiveness of dam operation in the mitigation of risks arising from ice jam flooding. The study also addressed the causes of channel-form adjustments, and the factors influencing the discharging capacities of different channel cross-sections, using the widely applied flow relationship. The main results of this study are:

1. From 1968, the joint operation of the Qingtongxia, Liujiaxia, and Longyangxia Reservoirs has led to significant increases in both the annual mean runoff and the mean water temperature during the ice jam flooding seasons in the Ningxia-Inner Mongolia reach. This aids in the shortening of the freezing-up duration and the decrease of the ice cover thickness.
2. The significant channel shrinkage that prevailed in the study reach during 1987 to 2006 was mainly due to the input of a relatively larger amount of sediment from the upstream.
3. In the new flow regime from 2008, there was a slight increase in the discharging capacity and no significant channel shrinkage occurred due to a significantly smaller amount of sediment load carried by a slightly increased annual runoff.

Although dam operation is still an effective means for mitigating the risk of the ice jam flooding in the Ningxia-Inn Mongolia reach under the new flow regime, care needs to be taken when the favorable flow-sediment condition changes. In addition, different channel planforms can exert very significant influences on the effectiveness of the dam operation, where detailed studies are currently lacking and need to be urgently addressed.

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