Nat Hazards (2016) 80:1015–1030
DOI 10.1007/s11069-015-2010-5

Ice regime variation impacted by reservoir operation in the Ning-Meng reach of the Yellow River

Jianxia Chang[1] · **Xuebin Wang**[1] · **Yunyun Li**[1] ·
Yimin Wang[1]

Received: 11 June 2015 / Accepted: 9 October 2015 / Published online: 15 October 2015

Abstract The Ning-Meng reach of the Yellow River in China is located in a high-latitude area, and river freezes up and breaks up every year, leading to ice flood and disaster. Since the 1990s, due to the rising winter temperatures, river channel shrinkage and impacts of reservoir operation, the river ice regime of the Ning-Meng reach has changed. This paper investigated reservoir operation effect on river ice regime by eliminating the impact of climatic conditions, and the test method could be applied to other rivers, where similar anthropogenic impacts can be suspected to affect the river ice regime. The results show that compared to the statistics when there were no reservoirs, the duration of ice freezing days reduced 8–33 days, and the ice cover thickness was 16–25 cm thinner than that without reservoirs. The average number of ice flood incidents per year decreased from 11.61 to 3.25, and the number of disasters reduced from 1.69 to 1.41. Moreover, the changes induced by reservoirs joint operation may vastly exceed that by single reservoir operation. The smaller is the distance to the upstream reservoir, the more obvious is the impact from the reservoir.

Keywords Ice regime · Reservoir operation · The Yellow River · Climatic conditions

1 Introduction

Appearance date of the ice run, freeze-up and ice cover break-up, the length of ice-affected period and the ice freezing seasons describe the ice regime of a river. The ice regime has important impacts on hydraulic engineering, such as the operation and maintenance of hydraulic plants, waterpower, shipping and water transfer, and has great influence on the river's environment and ecology (Wang et al. 2008; Morin et al. 2015). River ice is

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✉ Jianxia Chang
chxiang@xaut.edu.cn

[1] State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an 710048, China

sensitive to climate warming. An increasing number of studies have showed significant trends for later freeze-up and earlier break-up occurrence, and annual number of ice freezing days decrease (Loader et al. 2011; Hodgkins et al. 2005; Prowse and Beltaos 2002). Some records show that, for the twentieth century, freeze-up dates occur on average 2–25 days later, break-up dates 2–24 days earlier, and the ice freezing period also has decreased by an average of 2–38 days over the past 100 years in the Northern Hemisphere (Agafonova and Frolova 2007; Jiang et al. 2008; Klavins et al. 2009). Also, many non-climatic factors could also influence the occurrence of different river ice phenomena, including bed morphology or human activity (Starosolszky 1990; Radoane et al. 2010; Agafonova and Frolova 2007), which could exaggerate or hide natural trends in the river ice regime if they operate in either the same or opposite direction as the natural forces. Therefore, understanding the new ice regime characteristics impacted by environmental change is very important for avoiding ice flood disaster.

The Yellow River is the second-longest river in China. The total length of the main river course is 5464 km; the river basin area is 795,000 km^2; and the altitude difference between the river source and the estuary is 4830 m. Compared with other large rivers, Yellow River has the characteristics of high silt content, many twists and turns for its flow, and significant terrain differences. The Ning-Meng reach of the upstream Yellow River (104°E–112°E, 38°N–41°N) is located at the northern part of the Yellow River basin in China, which is more than 1237 km long, and the total water catchment area is 144,000 km^2. In this region, the time of air temperature below zero usually lasts from November to March of next year. Also, because the water flows from a low latitude to a high latitude, the freeze-up occurs from downstream to upstream in winter and break-up occurs from upstream to downstream in spring, which may lead to ice jams or ice dams due to the quick increase in the ice-melt flood (Ashton 1986; Beltaos and Burrell 2003; Yang 1996; Wu et al. 2015). The Ning-Meng reach of the Yellow River has experienced frequent ice flooding disasters, which have occurred 88 times in 60 years from 1951 to 2010. Since the 1990s, under the influence of natural factors and human activities, such as higher temperature and reservoir regulation, the ice conditions of the Ning-Meng reach have experienced significant changes. Many existing studies have examined the weather change and water resource evolution for the Yellow River (Huang and Zhang 2004; Saito et al. 2001; Fu et al. 2007; Liu et al. 2012; Zhang et al. 2011); this paper mainly investigates the ice condition changes during the ice flood season. In this paper, simple test is introduced to detect the effect of reservoir operation impacts on river ice regime by using the meteorological, hydrological and ice condition observation data of the Ning-Meng reach.

2 Study area and materials

2.1 Study area

The Ning-Meng reach of the upstream Yellow River belongs to the temperate, arid and semi-arid desert and desert steppe zone. The annual average precipitation is 155–366 mm, with more in the eastern part and less in the western part. In addition, the rainfall is very unevenly distributed during the year, with 75 % of the rainfall concentrated between July and September. Influenced by the continental monsoon climate, the Ning-Meng reach has a cold and dry winter. The days with an average daily temperature below 0 °C can last 4–5 months, and the lowest temperatures in winter can reach −35°. For the whole region, January has the lowest temperature, followed by December, February, November and March. The total freezing periods from November to March of next year can last approximately 120 days, and the total freezing length can reach 1000 km.

The study reaches have six hydrological stations: Xiaheyan, Qingtongxia, Shizuishan, Bayangaole, Sanhuhekou and Toudaoguai, as illustrated in Fig. 1 and Table 1. These stations divide the study reaches into five sections.

The Ning-Meng reach belongs to the second terrace of the Yellow River. Most areas in this zone are desert and desert steppe, with a gentle river bed and slow water flow, and there are large alluvial plains on both banks. Table 2 lists the mainstream watercourse characteristics for the upstream of the Yellow River. As we can see, the watercourse cross-sections from upstream to downstream display a pattern from relatively narrow and deep to relatively wide and shallow. Once the Yellow River flows into Inner Mongolia, its slope becomes smaller. The watercourse morphology for the Ning-Meng reach and its changes have a significant correlation with the ice flooding disasters. This reach of the river flows from Southwest to Northeast; the temperature is warm in the upstream and cold in the downstream; the watercourse is wide in the upstream and narrow in the downstream; and the slope is steep in the upstream and gradual in the downstream (Fig. 1). These features are all adverse with regard to ice discharge. Among them, the river reaches located downstream of the Shizuishan station are the reaches associated with the highest latitude in the Yellow River basin, where the watercourse is wide and shallow, and the mainstream swings and meanders. Therefore, they are the main reaches of the Yellow River to produce ice floods.

2.2 Data

On the Yellow River, ice monitoring was started at the end of the nineteenth century in several hydrological stations. Both the freeze-up and break-up dates, drift-ice and ice cover

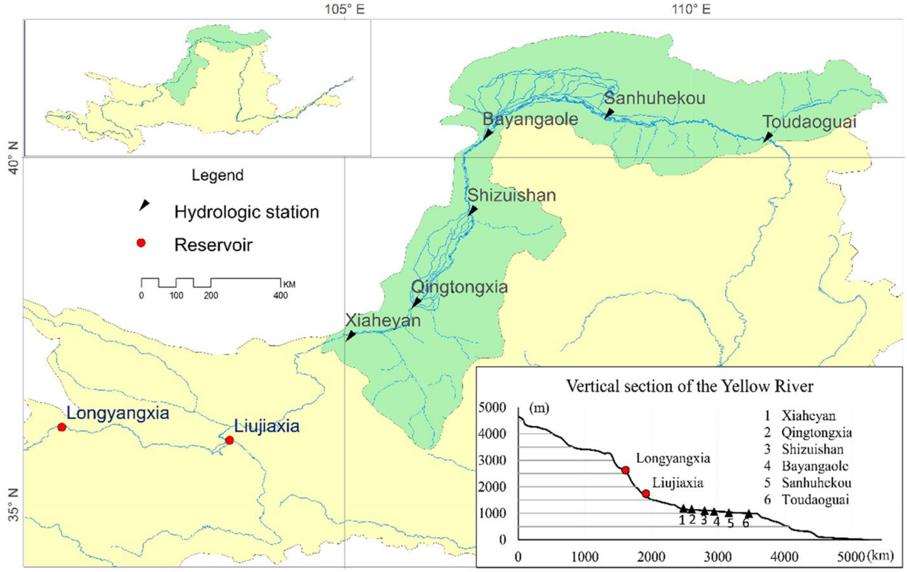

Fig. 1 Map of Ning-Meng reach of the Yellow River

Table 1 Hydrological station data for the Ning-Meng reach

Hydrological station	East longitude	North latitude	Catchment area (km^2)	Average annual runoff volume (10^8 m^3)	Average annual sediment load (10^8 t)	Distance to estuary (km)
Xiaheyan	105°03′	37°27′	254,142	294.0	1.17	2983
Qingtongxia	106°00′	37°54′	275,010	260.1	1.44	2859
Shizuishan	106°47′	39°15′	309,146	285.1	1.21	2665
Bayangaole	107°02′	40°19′	314,000	231.4	1.16	2523
Sanhuhekou	108°46′	40°37′	347,909	223.5	1.08	2302
Toudaoguai	110°04	40°16′	367,898	217.5	1.08	2002

Table 2 Mainstream watercourse characteristics for the Yellow River upstream

River reaches	River length (km)	Average river width (m)	Riverbed composition	Average gradient (‰)	Type of river
Tangnaihai–Guide	189.6	240	Pebble	2.44	Gorge
Guide–Xunhua	165.6	350	Sand, Pebble	2.12	Transition Gorge
Xunhua–Yanguoxia	146.6	320	Sand, Pebble	1.9	Gorge
Yanguoxia–Lanzhou	64.8	290	Sand, Pebble	0.94	Deep Gorge
Lanzhou–Xiaheyan	362.1	300	Sand, Pebble	0.79	Transition
Xiaheyan–Qingtongxia	124	200–3300	Sand, Pebble	0.78	Transition
Qingtongxia–Shizuishan	196	200–5000	Coarse Sand	0.20	Bending
Shizuishan–Bayangaole	142	200–5000	Sandy	0.21	Bending plain
Bayangaole–Sanhuhekou	221	600–8000	Sandy	0.14	Bending plain
Sanhuhekou–Toudaoguai	400	900–7000	Sandy	0.10	Bending plain

were observed. In parallel with ice monitoring, regular water level observation also started in the nineteenth century. In this paper, long-term records of river ice observation (water level, ice cover thickness and a variety of other factors) from 1951 to 2010 for the hydrological stations from the Hydrology Bureau of the Yellow River Conservancy Commission are used. Ice phenomena are recorded daily (i.e., day–month–year), and the definition criteria of the different year river ice phenomena are common and consistent through the entire record. Daily temperature data for the upstream Yellow River are available from the standard methodology of the China Meteorological Administration.

2.3 Overview of ice condition in the Ning-Meng reach

An ice condition is the phenomenon of a rising river water level caused by resistance to the water flow by the ice. It is the consequence of the combined effects of heat, power and watercourse morphology (Smith 2000; Choinski et al. 2010). The concrete manifestations are ice jams, ice dams and drifting ice (Fig. 2). Ice jam is the phenomenon that a large number of small ice deposits formed under the ice cover, leading to the rising of upstream water level. The ice jams formation is a part of surface ice cover progression process. The

Fig. 2 Ice jam and ice dam in the Ning-Meng reach of the Yellow River

transport and deposition of the entrained ice floes on the underside of the cover can form thick accumulations commonly known as ice dams. Ice dams usually appear in the ice break-up period across all or most of the section, and then the flow capacity in the river channel is greatly reduced. During the ice-affected season, frazil ice phenomenon could cause a serious ice flood disasters such as overflow, bursting and river building damage. The ice flooding disasters can be categorized into three types: ice jam disasters, ice dam disasters and drifting ice impact disasters. The ice dam disasters can be more abrupt and violent with a higher potential of ice dam formation.

For the Ning-Meng reach, ice condition occurs every year. From 1951 and 2010, ice condition occurred 346 times, and the average number per year is 5.77 (Table 3). These instances included 88 disasters, accounting for 25.4 %. No disasters were generated for the other 258 incidents, accounting for 74.6 %. From the type of the ice condition, there were 23 ice jams, accounting for 6.7 %; 322 ice dams, accounting for 93 %; and 1 drifting ice, accounting for 0.3 %. Also, ice dam disasters are the main form of ice flood disasters in the Ning-Meng reach. The reaches associated with the most serious ice jam disasters and ice dam disasters are the reaches between Xiaheyan–Shizuishan and Sanhuhekou–Toudaoguai, respectively.

3 Factors of influencing river ice regime

3.1 Temperature

River ice occurrence and the amount of drift-ice are directly controlled by air temperatures. The relationship between river ice phenomena and monthly mean temperatures for the Ning-Meng reach was analyzed by correlation tests (Table 4). The strongest relationship was found between mean winter air temperature and the ice cover thickness of ice-affected days.

Since the 1990s, influenced by global warming, warm winter phenomena have occurred along the Ning-Meng reach. The average temperatures for the Shizuishan, Bayangaole and Sanhuhekou stations during the ice freezing season have been on the rise for the past 20 years (Fig. 3). Table 5 lists the decade averages of the temperature characteristics for the past 50 years during the ice freezing season of the Shizuishan station. In the 1990s, the average monthly temperatures are higher than in the 1980s. After 2000, the temperatures increased further. In particular, the temperature rise (up to 3.6 °C) has been very significant

Table 3 Ice dam and ice jam in the Ning-Meng reach of the Yellow River in 1951–2010

River reaches	Ice jam				Ice dam			
	Times	Percentage (%)	Number of disasters	Percentage (%)	Times	Percentage (%)	Number of disasters	Percentage (%)
Xiaheyan–Shizuishan	11	49	9	45	29	9	9	14
Shizuishan–Bayangaole	4	17	3	15	34	11	11	16
Bayangaole–Sanhuhekou	3	13	3	15	53	16	16	24
Sanhuhekou–Toudaoguai	1	4	1	5	206	64	31	46
Downstream of Toudaoguai	4	17	4	20				
Whole river reach	23	100	20	100	322	100	67	100

Table 4 Relations between river ice phenomena and mean monthly temperatures (Unit: °C)

Data	Beginning date of ice run	Beginning date of freeze-up	Beginning date of break-up	Date of ice disappearance	Duration of ice freezing days	Ice cover thickness
Month	Nov.	Nov.–Dec.	Feb.–Mar.	Jan.–Mar.	Mean winter	Mean winter
Correlation coefficient	0.66	0.54	–0.79	–0.7	–0.76	0.82

during December–February. The higher temperature during the ice freezing season is the main reason for the ice break-up date advance and the freeze-up date delay.

3.2 River channel shrinkage

For the past 20 years, water consumption along the Yellow River basin has accelerated because of increasing water demand by a growing population and extensive agricultural development. Over the same period, climatic changes have led to a reduction in precipitation in the river basin (Fu et al. 2007; Liang et al. 2010). Also, the amount of sediment entering Yellow River has sharply increased. As a result, the main channel for the Inner Mongolia reach has shrunk year by year, and the riverbed has been consistently elevated due to siltation.

The Yellow River has experienced a series of dry years since 1986. In the period of 1987–2005, the annual average runoff and sediment load for all the major control stations along the Yellow River upstream decreased compared to the multi-year averages. Among them, the Lanzhou and Toudaoguai stations experienced reductions of 16, 41, 30 and 64 % (see Table 6). The reduction in the sediment transport capacity results in serious silting (Xu 2002; Vanacker et al. 2005). With the Sanhuhekou station as an example, the section morphology in 2005 underwent serious deformation compared with it in 1987. In particular, the main river channel width was reduced by 120 m; the average silt thickness was greater than 1.9 m; and the cross-sectional area was reduced by 794 m^2 (27 %). So, the river channel had experienced serious shrinkage. The silt resulted in reduced flow capacity across the cross section. The water levels of 550 m^3/s flow at the Sanhuhekou station during 2001–2005 were 1018.8, 1018.7, 1019.3, 1019.4 and 1019.4 m, respectively, and

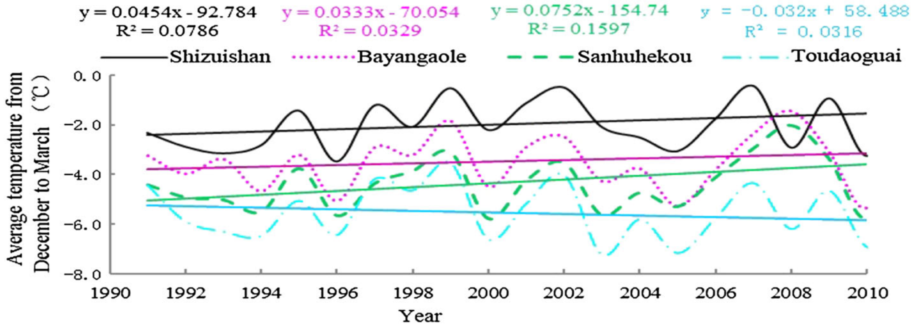

Fig. 3 20-Year temperature data from 1991 to 2010

Table 5 Temperature statistics during ice period of the Ning-Meng reach (Unit: °C)

Decade	November	December–February	March	Average
50 s	2.2	−10.9	0.0	−6.9
60 s	−2.0	−10.9	0.9	−6.7
70 s	−1.9	−9.9	−0.3	−6.3
80 s	−1.3	−9.5	0.0	−6.0
90 s	−0.4	−7.9	1.9	−4.6
2000 s	0.2	−4.3	2.0	−4.0

the bankfull discharge flow volume fell from 4000–5000 m^3/s in the 1970s to the present 1000–2500 m^3/s, indicating a significantly reduced flow capacity in the river channel.

3.3 Reservoir Ice control operation

The past 50 years were a period of dramatic and unprecedented change in human history, during which many aspects of human activities, including world population, water use and damming of rivers, have changed at an increasing rate, resulting in global-scale changes in the earth's system. Dams and reservoirs are globally essential to the river fragmentation and thus having significant impacts on the water regulation and sediment retention. For the Yellow River, the construction of dams and reservoirs is the most important human activities affecting the river ice condition. Since the 1950s, more than 3147 reservoirs had been built in the Yellow River basin, with a total storage capacity of 57.4×10^9 m^3 (Ta et al. 2008; Shao and Wang 2002). There are 24 reservoirs scattering widely in the river basin with storage capacities exceeding 0.1 billion m^3, among which four major reservoirs (Longyangxia, Liujiaxia, Sanmenxia and Xiaolangdi) with a total storage capacity of 30.4 billion m^3 and a regulation capacity of 23.5 billion m^3 make the greatest contribution to water regulation. All others are runoff stations. The reservoirs closely related to the Ning-Meng reach ice flood prevention are mainly Longyangxia and Liujiaxia stations.

The Liujiaxia and Longyangxia reservoirs were constructed in the upper reaches above Lanzhou in 1968 and 1985, respectively. The Liujiaxia reservoir has a storage capacity of 5.7 km^3 and a 147-m-high dam wall. It normally stores about 2.7 km^3 of water and traps 0.06 Gt of sediment annually. The Longyangxia reservoir (27.6 km^3 of storage capacity and 178-m-high dam wall) is a multi-year reservoir. Reservoir regulation changes the river ice regime, because the morphological conditions of the river are altered by dams and other engineering structures. In the Yellow River, after the Liujiaxia reservoir was put into operation in October 1968, the regulation effect on the Ning-Meng reach ice flood

Table 6 Flow and sediment discharge at the main stations

Station name	Runoff flow (m^3/s)		Sediment load (10^8 t)	
	Multi-year average	1987–2005	Multi-year average	1987–2005
Tangnaihai	200.6	179.3	0.126	0.119
Lanzhou	309.4	259.7	0.715	0.419
Toudaoguai	218.3	152.1	1.083	0.393

prevention was apparent. Since the joint operation of Liujiaxia and Longyangxia reservoir after 1986, the regulation functions have been enhanced.

In order to see the potential effect of the reservoir impacts, the ice regime of years with similar conditions before and after the reservoir operation impact was compared. The entire observation term of river ice has been separated into three characteristic periods:

The first period: 1950–1967, no reservoir regulation.
The second period: 1968–1986, intensive period of regulation by Liujiaxia reservoir.
The third period: 1987–2010, joint regulation by Liujiaxia reservoir and Longyangxia reservoir.

Increasing average winter temperature suggests that the occurrence of ice phenomena would be expected to decrease. In order to exclude the effect of rising air temperature and to test the impact of reservoir operation on ice regime, the effect of interannual variability of winter air temperature was eliminated by selecting years from each period with mean temperature between −9.4 and −2.3 °C (Table 7). Then the ice regime of years with similar mean winter air temperature for each period was compared.

4 Reservoir operation impacts on ice regime variation

4.1 Duration of ice freezing season and length of freezing reaches reduce

In the first period, without the Longyangxia and Liujiaxia reservoirs, Ning-Meng reach was essentially all frozen: the Shizuishan, Bayangaole, Sanhuhekou and Toudaoguai stations experienced 73, 100, 107 and 93 freezing days on average, respectively. In the second period, the durations of ice freezing at Shizuishan and Bayangaole stations reduced by 10 and 4 days, respectively, while the other two stations' extended by 8 and 15 days, respectively. In the third period, the durations of ice freezing at Shizuishan, Bayangaole and Sanhuhekou stations reduced by 33, 22 and 8 days, respectively, compared to the duration without the reservoirs. In addition, the beginning date of break-up for the main stations all moved ahead after the joint operation of the reservoirs (Table 8).

4.2 Ice cover becomes thinner

Figure 4 lists the statistics on the ice cover thickness changes. It can be observed that in the first period, the ice cover thickness was relatively even. In the second period, the thickness for the Shizuishan and Toudaoguai station underwent 13 and 17 cm reductions, respectively, while in the third period, the ice cover thickness at the Shizuishan, Bayangaole,

Table 7 Temperature characteristics of the selected winters

Periods	Number of winters	Mean	SD	Min.	Max.
The first period of 1950–1967	13	−5.7	1.7	−9.4	−2.3
The second period of 1968–1986	12	−5.6	1.8	−9.2	−2.3
The third period of 1987–2010	15	−5.4	1.7	−9.1	−2.1

Sanhuhekou and Toudaoguai station was respectively 16, 22, 25 and 24 thinner than that without reservoirs.

4.3 Channel storage water increase significantly increases

Since the joint operation of the Longyangxia and Liujiaxia reservoirs, the runoff along the Ning-Meng reach has increased by approximately 20 %. Using Bayangaole and the Sanhuhekou station as examples, in the first period, the average discharge was 6.09 and 5.96 billion m^3, respectively, during the ice freezing season. In the third period, the average discharge was 7.35 billion and 7.25 billion m^3, respectively. When the runoff increases during the ice freezing season, the channel storage water significantly increases. In the first period, the average annual maximum channel storage water was 0.883 billion m^3. In the second and third period, it was 0.996 and 1.28 billion m^3, respectively, which increased by 12.8 and 45 % compared to the average with no reservoir regulation.

4.4 The number of ice dams reduced, and the ice jam disasters exacerbated

Table 9 compared the times of ice conditions before and after reservoir constructions for the selected years. There were 149 ice dam incidents along the Ning-Meng reach during the period 1951–1968. For the period 1969–2010, there were 75 ice dam incidents, and the average number of ice dam incidents per year was, respectively, 11.46 and 2.78, such that the number of ice dam had reduced significantly. In contrast, the ice jam disasters grew worse. During the period 1951–1968, there were only two ice jams along the Ning-Meng reach, while during the period 1969–2010, 13 ice jams occurred, and the average number of ice jam incidents per year was, respectively, 0.15 and 0.48. Also, the average number of ice flood disasters per year decreased from 1.69 to 1.41, and the number of ice dam disasters reduced from 1.61 to 1.03.

5 Discussion

Various factors determine the ice regime of a river, including air temperature, bed morphology, water level, runoff velocity and other technical objects (Beltaos and Prowse 2009). Although the date of ice appearance and the intensity of ice-drifting are determined mainly by the temperature under natural conditions, morphological factors and anthropogenic effects play an important role in the date of ice cover formation (Agafonova and Frolova 2007). Reservoir usage changes the river ice regime, because the morphological conditions of the river are altered by dams and other engineering structures. Also, reservoir

Table 8 Beginning date of ice break-up along the Ning-Meng reach

Year	Shizuishan station	Bayangaole station	Sanhuhekou station	Toudaoguai station
Multi-year average	Mar. 6	Mar. 14	Mar. 19	Mar. 20
Before 1968	Mar. 7	Mar. 16	Mar. 18	Mar. 22
1968–1986	Mar. 6	Mar. 19	Mar. 23	Mar. 23
1986–2004	Feb. 25	Mar. 9	Mar. 16	Mar. 15

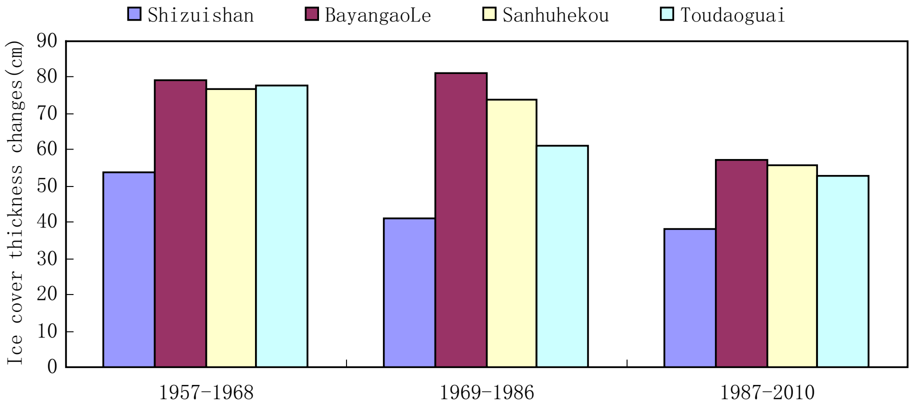

Fig. 4 Ice cover thickness changes at stations along the Ning-Meng reach

Table 9 Comparison of the number of ice flooding incidents and disasters before and after reservoir operation for the selected years

Time	Before reservoir construction (1951–1968)	After reservoir construction (1969–2010)
Total number of years	13	27
Number of ice flood incidents	151	88
Number of ice dam incidents	149	75
Number of ice jam incidents	2	13
Average number of ice flood incidents per year	11.61	3.25
Average number of ice dam incidents per year	11.46	2.78
Average number of ice jam incidents per year	0.15	0.48
Number of disasters	22	38
Number of ice dam disasters	21	28
Number of ice jam disasters	1	10
Average number of disasters per year	1.69	1.41
Average number of ice dam disasters per year	1.61	1.03
Average number of ice jam disasters per year	0.08	0.37

operation and the altered morphological parameters change water temperature conditions (Meilutyte-Barauskiene et al. 2005; Takács et al. 2013). Consequently, downstream of the dam, flow velocity and turbulence grow, so ice occurrence and freeze-up become less frequent (Starosolszky 1990).

For the upstream Yellow River, reservoir operation is a complex decision-making process that yields maximum benefits with respect to multiple objectives such as water demands, ecosystem requirements hydropower generation and ice control. In the ice flood season from November to March of next year, the ice control is the most important objective. From 1968–1986, Liujiaxia reservoir was in operation by itself. The mode of ice control operation of Liujiaxia reservoir is as follows: (1) in order to increase the ice conveyance capacity and avoid the ice jam disaster before freeze-up period, the reservoir discharge should increase appropriately from 600 to 700 m^3/s. (2) During freeze-up period, the Liujiaxia reservoir discharge is controlled as about 600 m^3/s and decreased progressively with the thawing of the river to create good conditions for ice break-up. (3) In break-up period, reservoir discharge should be little than 500 m^3/s to make the downstream water level of Shizuishan and Bayangaole reach decrease steadily. Table 10 is the average monthly inflow and outflow of Liujiaxia reservoir during ice flood season from 1972 to 1986. With the operation of Liujiaxia reservoir, the ice threat of Ningxia–Inner Mongolia reach reduces dramatically by controlling the reservoir discharge every month. After the joint operation of Longyangxia and Liujiaxia reservoir after 1986, the discharge limitation of Liujiaxia reservoir is the same with that before 1986. However because of the good regulation performance of the Longyangxia reservoir, the Liujiaxia reservoir has become a re-regulating reservoir to Longyangxia reservoir, and the regulation ability to comply with the ice control flow limitation is increased. Table 11 is the average monthly inflow and outflow of Liujiaxia reservoir with the joint operation of Longyangxia and Liujiaxia reservoirs.

After the reservoir construction, the seasonal distribution of the runoff changed. The average monthly discharge at Shizuishan, Bayangaole, Sanhuhekou and Toudaoguai stations during the ice freezing season from December to March all displayed increasing trends (Fig. 5). In particular, the discharge increased during the river freeze-up season, leading to postponed dates of ice run and freeze-up at all stations, but the further downstream the station was, the less was the impact.

In the second period, while the Liujiaxia reservoir was operated alone, the beginning date of ice run across the Shizuishan and Bayangaole station was postponed by 5 and 6 days, respectively, and the river freeze-up date was postponed for 11 and 5 days, respectively. In the third period, after the Longyangxia and Liujiaxia reservoirs were put

Table 10 Average monthly inflow and outflow of Liujiaxia reservoir with the single operation (m^3/s)

Year	Inflow					Outflow				
	12	1	2	3	Average	12	1	2	3	Average
1972–1973	276	217	244	265	251	454	437	448	500	460
1973–1974	314	216	245	306	270	502	490	509	482	496
1974–1975	328	230	244	299	275	561	580	505	491	534
1975–1976	439	340	347	415	385	604	585	589	460	560
1976–1977	383	270	280	382	329	637	617	555	459	567
1977–1978	249	161	201	262	218	325	326	277	306	309
1978–1979	378	264	254	283	295	525	532	550	481	522
1979–1980	345	228	240	313	282	490	450	444	454	460
1980–1981	276	197	231	265	242	402	443	352	415	403
1981–1982	407	308	315	358	247	574	549	528	442	523
1982–1983	358	250	260	307	294	557	537	401	416	478
1983–1984	462	294	317	386	265	597	644	563	518	581
1984–1985	348	247	237	294	282	477	546	400	383	452
1985–1986	346	237	254	300	284	559	507	368	463	474
Average annual flow	352	247	262	317	294	520	517	464	448	487

into operation, the monthly average discharge at Lanzhou station increased by 100–150 m^3/s compared to its value before the reservoir operation and the water temperature increased by more than 2°–4°. As a result, the Lanzhou reach becomes a perennial smoothly flowing reach. Tens of kilometers of reaches downstream of Qingtongxia station do not freeze anymore. Under the joint impacts of hydro and thermal effects, the ice run dates for the Shizuishan and Bayangaole stations were postponed by 15 and 12 days, respectively, and the freeze-up dates were postponed by 18 and 17 days, respectively, compared with the dates before the reservoirs operation. The ice run date for the Sanhuhekou station did not change, but under the influence of the delayed ice run from the upstream reaches, its freeze-up date postponed for 7 days (Table 12; Fig. 6).

The evolution of ice condition in the Yellow River is complex and is difficult to predict. Therefore, prevention and control of ice flood is particularly important. Here are two suggestions to reduce the ice flood disasters. (1) Reservoir real-time operation combined with weather forecast is the key to ice flood prevention in the Ning-Meng reach of the Yellow River. Controlled by the Siberia monsoon climate, the weather is dry and cold in winter of the Ning-Meng reach, and sometimes the temperature could drop because of the influence of strong cold air, leading to the river freeze-up after 1 or 2 days of ice run. Also, the Liujiaxia reservoir is 1267 km from the Ning-Meng reach, and the water transmission period is only about 16.5 days during ice flood season. So, reservoir operation scheme should be made based on the weather and hydrological forecast. However, the current weather and hydrological forecast accuracy and period could not fully meet the requirements of ice flood prevention, and hence, reservoir operation scheme should be fixed according to the short-term forecast results. (2) Construction of ice flood diversion project is another effective measure. Some flood detention zones in the Ning-Meng reach have been constructed, such as the Wuliangsuhai detention zone. Optimization of the ice flood diversion process could alleviate the pressure of Liujiaxia reservoir for ice flood control and ensure the safety of the Ning-Meng reach in the ice flood season.

Table 11 Average monthly inflow and outflow of Liujiaxia reservoir with the joint operation (m^3/s)

Year	Inflow					Outflow				
	12	1	2	3	Average	12	1	2	3	Average
1987–1988	424	337	435	506	426	388	356	295	321	340
1988–1989	495	663	469	497	531	655	635	517	462	567
1989–1990	515	659	693	751	665	675	573	550	565	591
1990–1991	634	607	582	652	619	622	553	526	453	539
1991–1992	348	668	412	394	456	530	496	486	369	470
1992–1993	703	569	699	578	637	600	552	541	500	548
1993–1994	607	642	682	732	666	550	519	532	489	523
1994–1995	725	720	680	686	703	616	581	538	498	558
1995–1996	352	469	513	490	456	494	384	345	400	406
1996–1997	468	134	398	312	328	326	292	266	261	286
1997–1998	470	410	352	378	403	311	291	288	300	298
1998–1999	567	579	613	618	594	531	487	449	588	517
1999–2000	634	686	635	598	638	559	513	423	442	484
Average annual flow	535	550	551	553	547	528	479	443	435	471

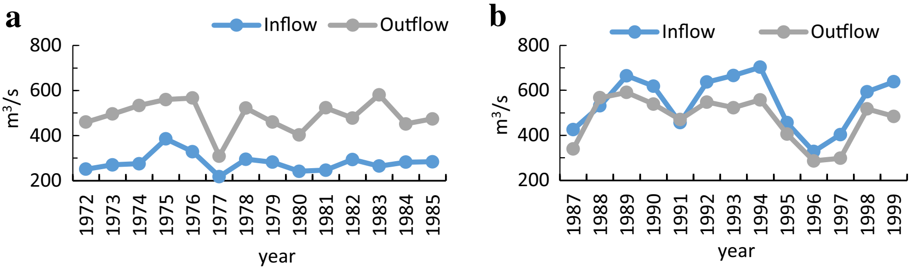

Fig. 5 Average inflow and outflow of Liujiaxia reservoir in the ice-affected season **a** single operation, **b** joint operation

Table 12 Freeze-up date at stations along the Ning-Meng reach

Year	Shizuishan station	Bayangaole station	Sanhuhekou station	Toudaoguai station
Multi-year average	Dec. 31	Dec. 2	Dec. 4	Dec. 15
Before 1968	Dec. 24	Dec. 5	Dec. 1	Dec. 21
1968–1986	Jan. 1	Dec. 10	Dec. 1	Dec. 10
1986–2010	Jan. 12	Dec. 22	Dec. 8	Dec. 14

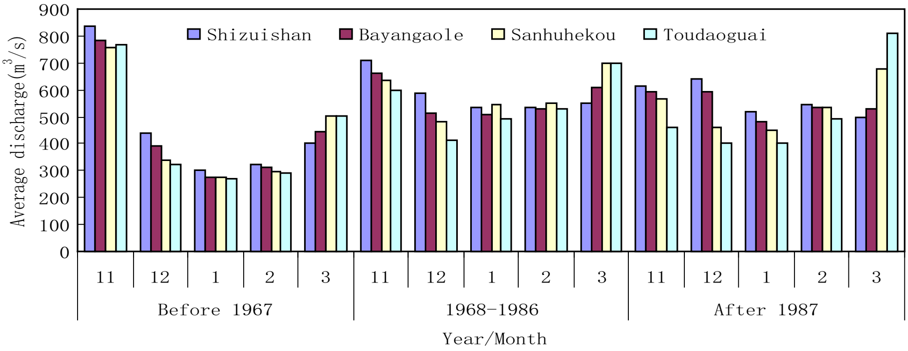

Fig. 6 Average discharge during the ice-affected season

6 Conclusion

For the Ning-Meng reach in the Yellow river, due to its weather conditions, channel morphology and hydrology, ice conditions occur every year. There were 23 ice jam incidents and 322 ice dam incidents during 1951–2010. Among them, 88 became disasters, and the number of ice dams is far greater than the number of ice jams. Since the 1990s, the characteristics of ice regime along the Ning-Meng reach have shown significant changes affected by climate change, river erosion and deposition, reservoir operation and river engineering.

The warmer temperature is the one of the main reasons for the earlier ice break-up date, postponed river freeze-up date and thinner ice cover. Compared to the 1980s, the average temperature during the ice freezing season increased by 1.4° in the 1990s. After 2000, it increased by 2.0°. Another natural factor is the main channel of the Inner Mongolia reach has shrunk year by year, and the riverbed has been consistently elevated due to siltation. For the Sanhuhekou station, the discharge reduced from 4000–5000 m^3/s during the 1970s to 1000–2500 m^3/s at present, leading to poor ice discharge during the ice-affected season, increasing the probability of ice jams.

The use of reservoirs had significant impacts on the ice regime along the Ning-Meng reach under the influences of hydrodynamic and thermal effects. This paper investigated reservoir operation effect on river ice regime by eliminating the impact of climatic conditions, and the test method could be applied to other rivers, where similar anthropogenic impacts can be suspected to affect the river ice regime. Compared to the statistics when there were no reservoirs, the ice dam disasters reduced significantly, but the ice jam disasters exacerbated during the river freezing period. The dates of freeze-up for the Shizuishan, Bayangaole and Sanhuhekou stations delayed by 18, 17 and 7 days, respectively. The duration of ice freezing days reduced 33, 22 and 8 days, respectively. The Shizuishan station's ice break-up date moved ahead 14 days, and the Bayangaole and Toudaoguai station's ice break-up date moved ahead by 7 days. At the same time, after the reservoir began operation, the annual channel maximum storage water reached 1.28 billion m^3, which is 45 % compared to the same statistics without reservoirs. The ice regime on the downstream reach of the Ning-Meng reach along the east–west direction is primarily affected by the regional weather environment. The upstream reach along the south–north direction is affected not only by regional weather environment change but also by reservoir projects. In addition, with decreasing distance from the upstream reservoir, its impact becomes more obvious.

Acknowledgments This research was supported by the Natural Science Foundation of China (51179148, 51179149) and Key Innovation Group of Science and Technology of Shaanxi (2012KCT-10). Sincere gratitude is extended to the editor and the anonymous reviewers for their professional comments and corrections.

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