Changes and control processes of water and related ecology in the lower reaches of the Tarim River

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Abstract The Tarim River, which is located in the arid region, is the longest continental river in China. The inflow to the mainstream of the Tarim River has been shrinking due to natural and human factors, causing the streamflow to dry up over 300 km in the lower reaches. During the high water period from 2000 to 2003, and the high water level of Bosten Lake, urgent water diversions from Bosten Lake to the lower reaches of the Tarim River were established five times to save the ecology. Thus, the 30-year period of streamflow drying-up to an extent of over 300 km in the lower reaches of the Tarim River, has ended. This is the first water diversion created solely for the purpose of saving the ecology in China. In this paper, the changes of the streamflow drying-up are briefly explained, followed by analyses of control processes and their effects on the water diversion.

Key words changes in the ecology; control processes of the ecology; Tarim River

INTRODUCTION

Water is the source of life, the precious and indispensable resource on which mankind and all living things rely for existence. In arid regions, water is critical for human existence, socio-economic development and environment protection (Maingi *et al.*, 2002; Xia *et al.*, 2003). However, such regions are today facing more difficult problems than ever before. Flow drying-up in middle and lower river reaches and freshwater shortage in many user sectors are leading to various socio-economic and environmental consequences. These are attributed to the shrinkage of upstream inflows resulting from a number of mostly human factors.

The Tarim River basin is the largest inland river in China, and its catchment area is 4.355×10^5 km^2. However, the Tarim River has been drying up by an extent of over 300 km since the 1970s. This situation has led to various ecological consequences. By grasping the chance of the high-water period from 2000 to 2003, and the high water level of Bosten Lake, water diversions from Bosten Lake to the lower reaches of the Tarim River were established five times to save the ecology. Thus, the 30-year period of streamflow drying-up to an extent of over 300 km in the lower reaches has finished.

There have been a number of studies about water and ecology in the Tarim River. For example, Huang *et al.* (2004) applied remote sensing technology to analyse the environmental effect of a water diversion in the Tarim River; Qi *et al.* (2005) discussed environmental effects of water resource development and water use in the Tarim River basin; Cong *et al.* (2005) analysed the hydrological and ecological effects of restoring the ecology in the lower Tarim River; Deng (2005) considered ecological and environmental responses of the lower reaches of the Tarim River to the emerging water diversion. However, few studies have reported on the changes of water and related ecology since the 1950s and the processes that controlled water and related ecology during the diversions that took place from 2000 to 2003 in the lower reaches of the Tarim River.

The objectives of this research are: (a) to introduce the changes of water and related ecology in the lower reaches of the Tarim River; and (b) to analyse the control processes and effects of water diversion from Bosten Lake to Tarim River for saving the ecology.

ABOUT THE STUDY AREA

The part of the Tarim River discussed in this paper is located between the Tianshan Mountains and the Kunlun Mountains, the southern part of the Xinjiang Uygur Autonomous Region, in the arid region of western China. It is the largest continental river basin in China, and its catchment area (34°55′~43º08′N, 73º10′~94º05′E) is 4.355×10^5 km^2. The Tarim River flows along the northern marginal zone of the Taklamakan Desert and through the Tarim basin from west to east. Around the Tarim basin in history, there were nine main converging stream systems, comprising the stream systems of the Kaidu-Kongque River, the Dila River, the Ogan-Kuqa River, the Aksu River, the Kaxgar River, the Yarkant River, the Hotan River, the Small Keriya River, and the Small Qarqan River. Because of human activities, climate change and other factors, six rivers lost their surface water connections with the mainstream of the Tarim River and only three rivers, the Hotan River, the Yarkant River and the Aksu River, still have surface water connections with the mainstream of the Tarim River today (Fig. 1).

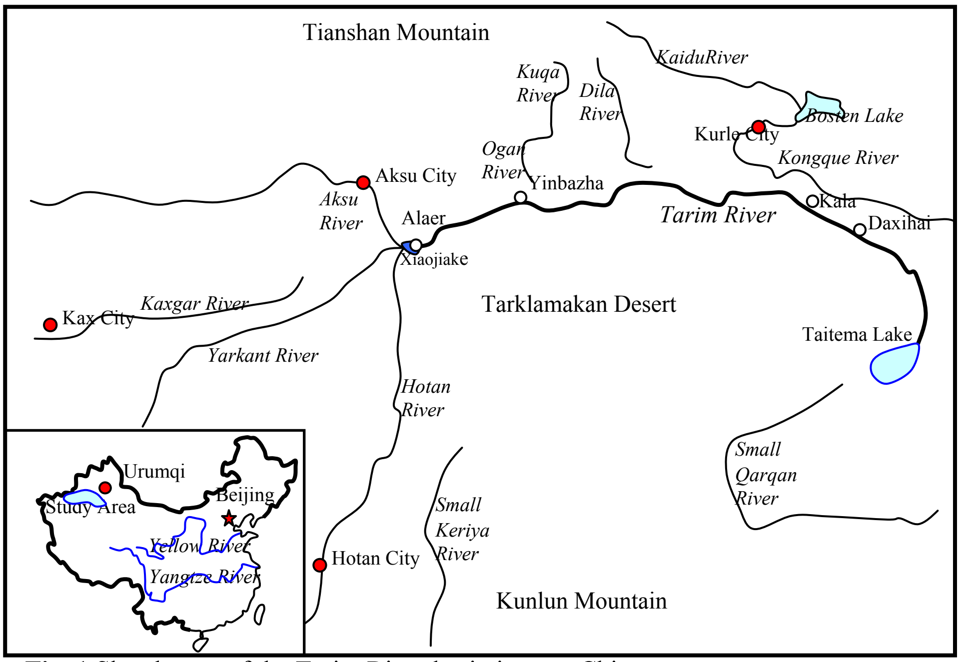

Fig. 1 Sketch map of the Tarim River basin in west China.

CHANGES OF WATER AND RELATED ECOLOGY

The mainstream of the Tarim River is a typical continental river in an arid climate. It is 1321 km in length from Xiaojiake to the Taitema Lake, and its annual runoff is about 4.511×10^9 m^3 (on average 143 m^3 s^{-1}). There is no formation of surface runoff in the mainstream area of the Tarim River, and the mainstream is mainly recharged by its three source streams. The Alaer Hydrology Station is regarded as the entrance of the mainstream of the Tarim River. The river sections from Alaer to Yinbazha and from Yinbazha to Kala are regarded as the upper and middle reaches, respectively, and downstream from Kala is regarded as the lower reach of the mainstream (Fig. 1).

Changes of streamflow

According to the historical record, the Tarim River was long and wide, and its streamflow was abundant in the 1820s. Up to the end of the 19th century, the streamflow was still abundant, and the streamflow could run to the Taitema Lake. Since the beginning of the 20th century, the streamflow of the Tarim River has gradually been reduced (Song *et al.*, 2000; Xia *et al.*, 2003).

The inflow observed at Alaer Hydrological Station at the start of the mainstream has been sharply reduced, although there is no obvious increasing or decreasing trend of the multi-annual average runoff of the three source streams of the Tarim River. The main reason is that the agricultural water use increased from 55×10^8 m^3 to 155×10^8 m^3 in response to population explosion and irrigation area extension in the period from the 1960s to the 2000s. There are as many as 138 voluntary intakes along both riversides of the upper and middle sections of the mainstream. As a result, the streamflow at the start of the lower reaches (the Kala Hydrological Station) is reduced by about 80%, causing the streamflow in the lower reaches to dry up to an extent of over 300 km from the 1970s. The annual runoff at the main hydrological stations along the mainstream of the river is shown in Table 1 and Fig. 2.

Changes of ecosystem in the lower reaches of the Tarim River

The main factors resulting in the streamflow drying-up in the lower reaches of the Tarim River are the increase of the diverted water volume in the upper reaches and the sharp shrinkage of the inflow in the lower reaches. Since the People's Republic of China was founded in 1949, the large-scale wasteland reclamation has been violently developed in the areas of the source streams and the mainstream of the Tarim River. Many reservoirs have been built, many state-owned farms have been established, the water resources in the Tarim River basin have been excessively exploited, and the inflow of the mainstream of the Tarim River from its tributaries has been greatly changed. Consequently, the streamflow drying-up led to a sharp drawdown of the groundwater table and a serious deterioration of the ecosystem in the lower reaches of the Tarim River.

The ecosystems in the lower reaches of an arid river are extremely vulnerable. The ecology and the natural desert vegetation rely on the groundwater. After a long-term

Table 1 The annual runoff at the main hydrological stations along the mainstream of the Tarim River (Unit: 10^8 m^3).

Year	Alaer	Yinbaza	Kala	Daxihai	Year	Alaer	Yinbaza	Kala	Daxihai
1957	48.35	33.50	14.61		1981	59.90	36.20	3.24	0
1958	48.31	35.40	10.77		1982	43.20	29.40	3.49	0
1959	51.40	38.80	10.82		1983	47.00	29.00	4.31	0
1960	49.70	35.00	10.52		1984	49.00	31.80	4.82	0.853
1961	66.55	47.80	7.88		1985	30.00	20.50	2.76	0.628
1962	48.84	33.20	7.80		1986	47.50	24.90	3.40	0
1963	42.12	28.50	7.50		1987	45.70	23.10	5.46	0
1964	53.41	35.60	7.80	0.277	1988	53.80	29.70	4.70	0
1965	34.75	23.80	7.87	0.191	1989	32.71	20.00	3.38	1.043
1966	63.77	44.20	11.90	0.358	1990	42.70	24.90	4.03	0
1967	55.69	39.50	13.00	0.498	1991	35.80	21.60	3.74	0
1968	49.90	39.90	12.00	0.457	1992	31.60	15.10	2.81	0
1969	51.87	41.00	11.84	0.403	1993	25.58	8.19	1.83	0
1970	39.46	31.30	8.90	0	1994	60.84	31.78	2.71	0
1971	56.36	38.40	7.87	0.072	1995	38.74	27.77	3.36	0.280
1972	37.26	22.00	7.34	0.493	1996	49.61	23.02	1.93	0
1973	52.09	33.90	7.56	0.612	1997	38.05	19.61	2.50	0
1974	38.70	26.70	5.34	1.011	1998	54.83	27.30	2.28	0
1975	32.18	20.70	4.25	0	1999	47.1	32.92	7.39	0
1976	32.37	19.80	5.05	0	2000	35.14	21.36	4.02	0
1977	49.44	30.50	5.16	0	2001	45.72	20.99	3.91	0
1978	69.59	45.20	11.00	1.574	2002	55.01	29.59	6.42	0
1979	36.95	19.80	4.56	1.025	2003	44.98	24.44	4.92	0
1980	38.80	21.30	3.64	0	2004	29.48	17.03	2.76	0

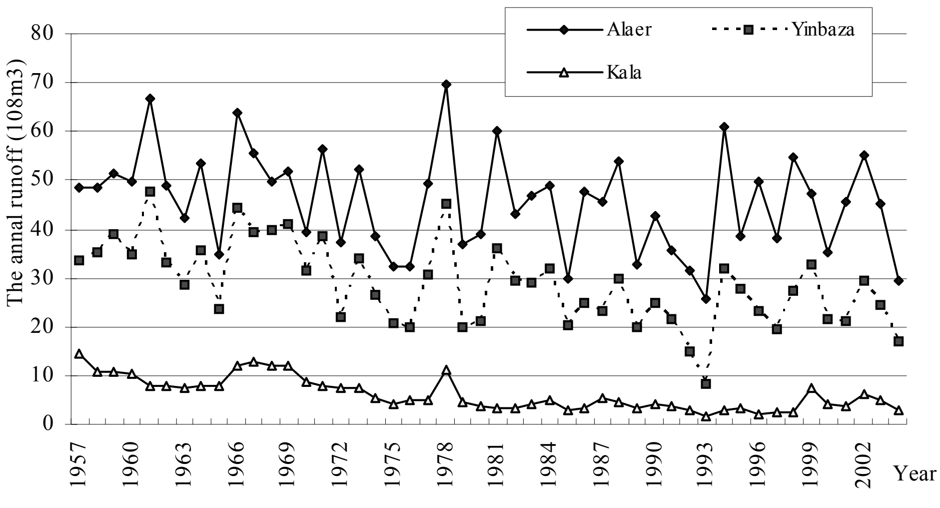

Fig. 2 Change curves of the annual runoff at the main hydrological stations.

evolution, the ecosystem in the lower reaches is formed under the conditions of arid climate, exiguous precipitation and high evaporation. The desertification area in the lower reaches of the Tarim River has increased about 10% from 1957 to 2000 (Fig. 3).

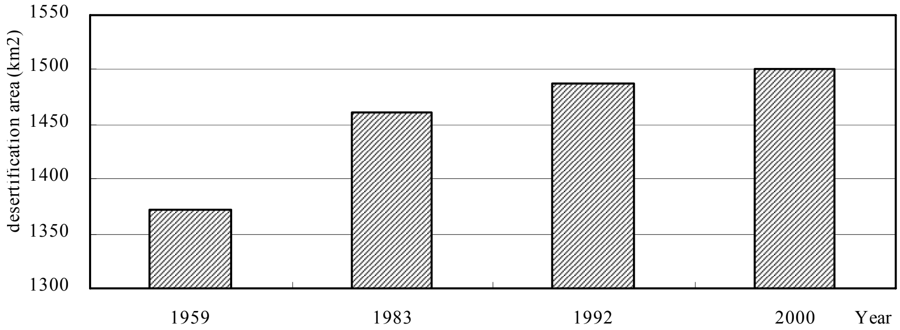

Fig. 3 Change trend of the desertification area in the lower reaches of the Tarim River.

Table 2 The processes of water diversion from the Bosten Lake to the lower reaches of the Tarim River.

Time	The period	Total days	Diverted water volume (10^8 m^3)	The site diverted water arrived	The total distance of water diversion (km)
1	14 May–12 July 2000	59	1.49	Kardayi	602
2	3 Nov. 2000–5 Feb. 2001	95	4.75	Aragan	786
3	1 Apr.–6 Jul. 2001 12 Sep.–8 Nov. 2001	165	6.69	Taitema Lake	963
4	20 Jul.–20 Oct. 2002	92	5.2	Taitema Lake	963
5	2 May to 15 June 2003	45	5.1	Taitema Lake	963

WATER DIVERSION AND ITS EFFECTS

In order to solve the problem of drying-up in the Tarim River, two approaches can be applied: one is to reduce the water consumption by taking regulatory measures (such as to economise water consumption and reduce the water utilization scale) for increasing the inflow of the lower reaches; another is to divert water from other regions to increase the inflow of the lower reaches. During 2000–2003, the water diversion from Bosten Lake to the lower reaches of the Tarim River to save the ecology was implemented to increase the inflow of the lower reaches by taking advantage of the high water level of Bosten Lake (Table 2).

The first water diversion took place during 14 May–12 July 2000. During the 2-months a stream water volume of 1.49×10^8 m^3 was diverted from Bosten Lake to the lower reaches of the Tarim River, of which 9.8×10^7 m^3 of water was discharged from the Daxihai reservoir downstream to the lower reaches of the Tarim River. Kardayi was 102 km downstream from the Daxihai reservoir, and the total distance of the water diversion from Bosten Lake to Kardayi was 602 km. The groundwater table in the areas near the river channel was increased to some extent. The affected width of the groundwater varied in a range from 400 to 500 m along each side of the river channel, and the affected area was as large as 80–100 km^2. The water diversion alleviated the degeneration of the vegetation in the lower reaches of the Tarim River.

The second water diversion was implemented during the period from 3 November 2000 to 5 February 2001. In the 100-day duration, a volume of 4.75×10^8 m^3 was diverted from Bosten Lake to the lower reaches of the Tarim River, of which 3.25×10^8 m^3 of water was discharged from the Daxihai reservoir downstream to the lower reaches of the Tarim River. Aragan was 215.6 km downstream from the Daxihai reservoir, and the total distance of the water diversion from Bosten Lake to Aragan was 786 km. The groundwater table in the areas near the river channel was increased by up to 4.5 m. The affected width of the groundwater was over 500 m along each side of the river channel, and the affected area was over 200 km^2. Ecological benefits were achieved.

The third water diversion was implemented during the periods from 1 April to 6 July and from 12 September to 8 November 2001. In the total duration of 165 days, an accumulated volume of 6.69×10^8 m^3 was diverted from Bosten Lake to the lower reaches of the Tarim River, of which 4.82×10^8 m^3 of water was discharged from the Daxihai reservoir downstream to the lower reaches of the Tarim River. The river tail of the Tarim River, Taitema Lake, is 363 km downstream of the Daxihai reservoir, and the total distance of the water diversion from Bosten Lake to Taitema Lake was 963 km. The groundwater table in the areas was universally increased by 3 m on average (5 m maximum), within an extent of 500–800 m in width on each side of the river channel. The forests of *Populus euphratica* within an extent of 500–800 m in width along both sides of the river channel benefited by the diversion, and the growing conditions of vegetation near the river channel were improved to a large extent.

The fourth water diversion was implemented during the period from 20 July to 20 October 2002. During the 90 days a volume of 5.2×10^8 m^3 was diverted from Bosten Lake to the lower reaches of the Tarim River, of which 4.31×10^8 m^3 of water was discharged from the Daxihai reservoir downstream to the lower reaches of the Tarim River. The water diversion distance from the Daxihai reservoir downstream to the Taitema Lake was 963 km. The affected area of this water diversion was over 200 km^2, and the groundwater was recharged again.

The fifth water diversion was implemented during the period from 2 May to 15 June 2003. In the 45-day duration, a volume of $5.1 \cdot\times 10^8$ m^3 was diverted from Bosten Lake to the lower reaches of the Tarim River, of which there was $3.9 \cdot\times 10^8$ m^3 of water discharged from the Daxihai reservoir downstream to the lower reaches of the Tarim River. The groundwater was further recharged by this water diversion, and the ecological quality was further improved.

The monitoring for the five periods of water diversion to the lower reaches of the Tarim River was carried out in the areas along the mid-lower section of the lower reaches of the Tarim River, i.e. the river section from the Daxihai reservoir downstream to Taitema Lake. In total, four hydrological monitoring sections, nine groundwater monitoring sections, and 33 groundwater observation wells were arranged to monitor the ecological effects of the diverted surface water and of the recharged groundwater during the water diversion, and to understand the changes of the groundwater level and the affected extent along both sides of the river channel after water diversion (Xia *et al.*, 2003; Deng, 2005).

Changes of the groundwater level

According to the measured data, the groundwater level along both sides of the river channel in the lower reaches of the Tarim River had increased remarkably due to the

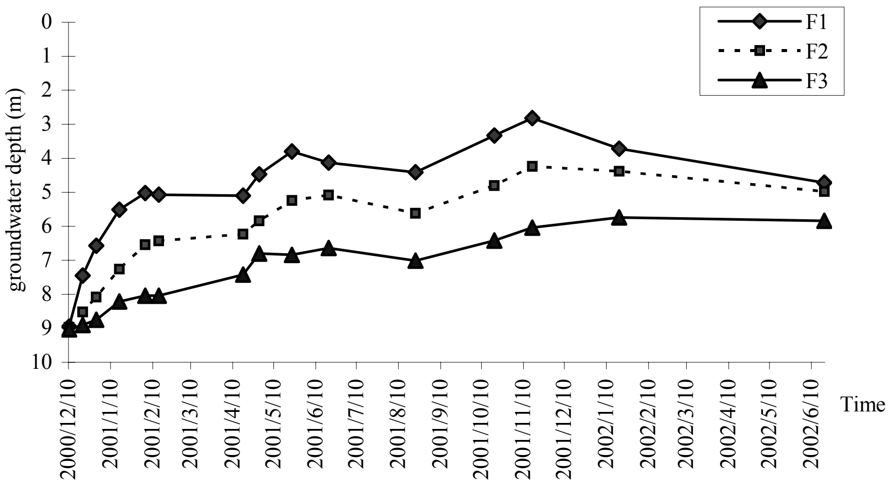

Fig. 4 Changes of the groundwater depth along the Tugmailan Section downstream from the Daxihai reservoir after water diversion.

Table 3 Changes of groundwater mineralization degree along the Kardayi Section in the lower reaches of the Tarim River before and after the water diversions (Unit: mg L^{-1}).

Observation time		November 2000	April 2001	August 2001	January 2002
Observation well	E2	6210	1117	936	888
	E3	2685	1968	1154	931

water diversions. Figure 4 shows the changes of the groundwater level along the typical Tugmailan Section downstream from the Daxihai reservoir after water diversions. In the figure, the observation wells F_1, F_2 and F_3 are distributed outwards from the river channel along the section on the same side.

Changes of the groundwater quality

The measured data of all the monitoring sections revealed that the groundwater quality along both sides of the river channel in the lower reaches of the Tarim River has been greatly improved since the water diversions. The groundwater mineralization degree measured along the Kardayi Section is shown in Table 2. The observation wells E_2 and E_3 are distributed outwards from the river channel along the section on the same side. Table 3 indicates that the groundwater mineralization degree along the Kardayi section was as high as 6210 mg L^{-1} before the water diversions in November 2000, it decreased to 1968 mg L^{-1} or lower after the first water diversion in April 2001. Along with the following water diversions, the groundwater quality was gradually improved, and the mineralization degree obviously reduced.

Changes in vegetation

According to the field investigation, almost no vegetation was present along both sides of the river channel before the water diversions. The sporadic trees of *Populus* *euphratica* grew indomitably only on the riverbed, while all the shrubs and grasses close to the lower reaches died. After diverting water to the lower reaches, the vegetation along both sides of the river channel began to grow. The new branches and leaves grew again on the trunks and branches of *Populus euphratica* trees, which had been withered for many years, and the regenerating and growing speed of the shrubs was higher than that of the arbors (such as *Populus euphratica*, Osier).

ANALYSIS ON THE SUSTAINABILITY OF WATER DIVERSION

It is urgently required that stream water from Bosten Lake be transfused to the lower reaches of Tarim River, and experience has shown that the effects are very good. The current problems are whether the stream water transfusion can be continued, and how high the risk is of not being able to maintain a certain transfused stream water volume.

The basic ideas or steps of the risk estimation are as follows: (1) at first, the monthly inflow series of the lake is obtained from the hydrological department, and the characteristic water level and the characteristic storage capacity of the lake are determined from the controller of the lake; then (2) the local monthly gross water consumption (including the water losses but excluding the transfused water volume) is collected and determined; and finally (3), the sustainability of various transfused water volumes are assessed based on the relationship between the inflow, characteristic water level and storage capacity of the reservoir, as well as the local monthly gross water consumption.

According to an estimation of the actual inflow of Bosten Lake and the actual conditions of water consumption, the risk rate is 91.72% for an annual stream water volume transfusion of 4.5×10^8 m^3 from Bosten Lake to the lower reaches of Tarim River, which is the transfused stream water volume stipulated in the "Document of Bayingolin Mongol Autonomous Prefecture, Xinjiang" (BGD (2002) no. 12). It is obvious that the sustainability of transfusing stream water from Bosten Lake to the lower reaches of Tarim River is very low under the current conditions, and the stream water transfusion to the lower reaches of Tarim River can possibly only be implemented in very few wet years. The risk rate decreases with the reduction of the transfused water volume (Fig. 5).

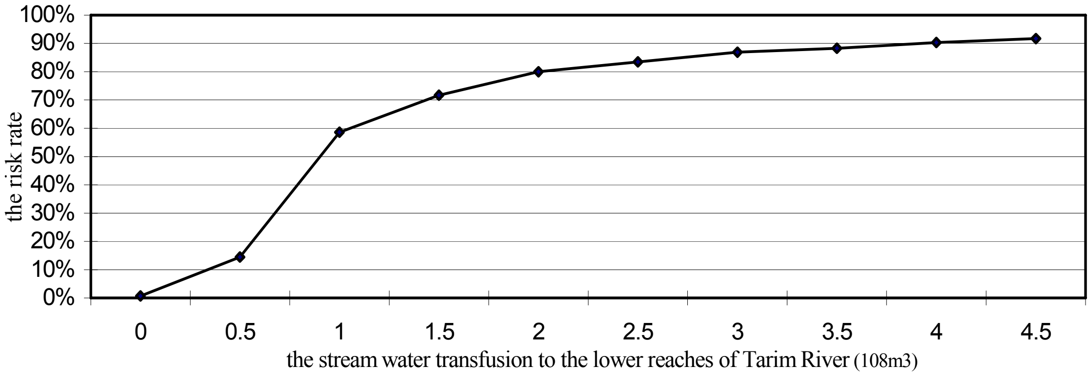

Fig. 5 Relationship between the risk of the water diversion and the transfused stream water volume.

The risk of not being able to transfuse the estimated volume of water from Bosten Lake to the lower reaches of the Tarim River would rapidly decrease, if some measures for increasing the inflow of the lake could be taken. When the inflow to the lake is increased to about 2.5×10^8 m^3, the risk rate will be down to 0.70%, which is estimated under the assumption that the actual water consumption is not changed. Obviously, it is a very effective measure to increase the inflow of Bosten Lake to ensure the stream water transfusion to the lower reaches of the Tarim River. Redistribution of the water resources should be optimized, including a reduction of water consumption in the upper reaches, in order to achieve a sustainable development in both upper and lower reaches and to ensure an annual transfusion of stream water volume to the lower reaches of the Tarim River.

CONCLUSIONS

The Tarim River, which is located in the arid region of western China, is the longest continental river in China. However, the Tarim River has been drying up to an extent of over 300 km since the 1970s. This situation has led to various ecological consequences. By grasping the chance of the high-water period from 2000 to 2003 and the high water level of Bosten Lake, water diversions from Bosten Lake to the lower reaches of the Tarim River were established five times to save the ecology. The reasons for streamflow drying-up have been briefly explained, and the control processes and the effects of recent water diversions from Bosten Lake to Tarim River have been analysed.

The study results reveal that: (1) ecosystems in the lower reaches of a river in arid regions rely on upstream inflows, and the ecology in the lower reaches of the Tarim River has suffered serious deterioration since the 1950s; (2) the water diversion from Bosten Lake to Tarim River is a successful project, which has significantly improved the ecology; and (3) the rational redistribution of water resources is a very effective measure to ensure sustainable water diversion and ecological water use in the lower reaches of the Tarim River.

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