Hydrological Changes of the Irtysh River and the Possible Causes

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Abstract Hydrological changes of the Irtysh River were analyzed concerning the changes of annual runoff and its distribution features within a year measured by coefficient of variation and concentration degree. Abrupt changes were detected by the heuristic segmentation method. Possible causes of the hydrological changes were investigated considering climate changes and human activities (especially the reservoir operation). The Mann-Kendall method was applied to estimate whether the temperature and precipitation was changed. The increased precipitation in winter may increase the runoff of April. The increased temperature and the decreased precipitation in the flood season may decrease the runoff. At the middle reaches, the impact of the reservoirs at the upper reaches is significant and may be the main factor leading to the abrupt decreases in annual runoff and its intra-annual variability and concentration. The increased water surface area of the reservoirs aggravates the evaporation and leads to annual runoff reduction. The reservoirs regulate runoff by storing water in the flood season and releasing water in the dry season. While at the lower reaches, the annual runoff remained steady and its intra-annual variation and concentration were reduced gradually because the impact of the reservoirs is relative small and the climatic impact may be more relevant.

Keywords Hydrological change · Climate change · Reservoir operation · The Irtysh River

1 Introduction

The Irtysh River Basin is an international basin partially joining the territories of three countries, namely China, Kazakhstan and Russia. The hydrological regime of the Irtysh

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River has been changed dramatically in recent decades, probably influenced by human activities or climate changes (McClelland et al. 2004). As is common sense, water resources is vital for human beings. Hydrological changes (e.g. annual runoff reduction) may provoke conflicts between the countries. Furthermore, hydrological regimes (magnitude, frequency, duration, timing, and rate of change) are crucial for riverine ecosystems (Poff et al. 1997). Hydrological regimes control many physical and ecological aspects of river forms and processes, including sediment transports and nutrient exchanges. So it is necessary to analyze the hydrological changes of the Irtysh River, and investigate the possible causes. The results may provide some references for the integrated water resources management of the Irtysh River and the cooperation between the countries for sustainable development.

Many studies about worldwide hydrological changes have been done considering climate changes and human activities, including dam construction, water diversion and agricultural irrigation (Mix et al. 2012; Ouyang et al. 2011). In Siberia, some studies also have been done about the hydrological changes of three major rivers (the Lena, Yenisei, and Ob River) which together contribute more than 45 % of the total fresh water inflow to the Arctic Ocean (Ye et al. 2004). The reservoir regulation has significantly altered the monthly flow regimes toward less seasonal variation in terms of the decreased summer (high) flow and the increased winter (low) flow (Yang et al. 2004a; Ye et al. 2003). In the Ob River Basin, Yang et al. (2004b) found that the changes in streamflow (1936–1990) pattern were different between the upper and lower parts of the watershed. In the upper Ob regions, streamflow was decreased in summer but increased in winter. The decreases in summer flow are mainly due to water uses along the river valley for agricultural and industrial purposes and reservoir regulation for reducing the summer peak floods. The increases in winter flow are caused by the reservoirs which release water for power generation in winter. In the lower Ob regions, however, streamflow was increased during midsummer and winter months and weekly decreased in autumn. This paper concerns on the Irtysh River which is a tributary of the Ob River. Longer flow data series (1936–1999) were collected to analyze the recent hydrological changes in terms of the changes in annual runoff and its intra-annual distribution features measured by coefficient of variation and concentration degree. Furthermore, corresponding long term observed temperature and precipitation data were also collected to separate climate effect from human influence.

2 Data and Methods

2.1 Study Area and Data

The Irtysh River (Fig. 1), the largest tributary of the Ob River, is 4248 km long and drains an area of 160×10^4 km². It rises in the Altai Mountains in Sinkiang, China, crosses the Chinese border, and flows west through Zaysan Lake and northwest across eastern Kazakhstan. The Irtysh River traverses Russian territory and joins the Ob River at Khanty-Mansiysk. The extent of the basin up to the Russian border is 59.6×10^4 km², of which 5.6×10^4 km² cover the spring area in China (Hrkal et al. 2006). The Irtysh River has two main tributaries, the Ishim River and the Tobol River. The Ishim River rises in the north of the Kazakhstan Uplands and flows first west then north, crossing the Russian-Kazakhstan border near Petropavlovsk. It enters the Irtysh River at Ust-Ishim. The river is 2450 km long and drains an area of 14.4×10^4 km². The Tobol River, another left bank tributary of the Irtysh River, is 1591 km long and drains an area of 42.6×10^4 km². It flows northeast across the West Siberian Plain through the Kustanai oblast of Kazakhstan and Kurgan and Tyumen oblast of
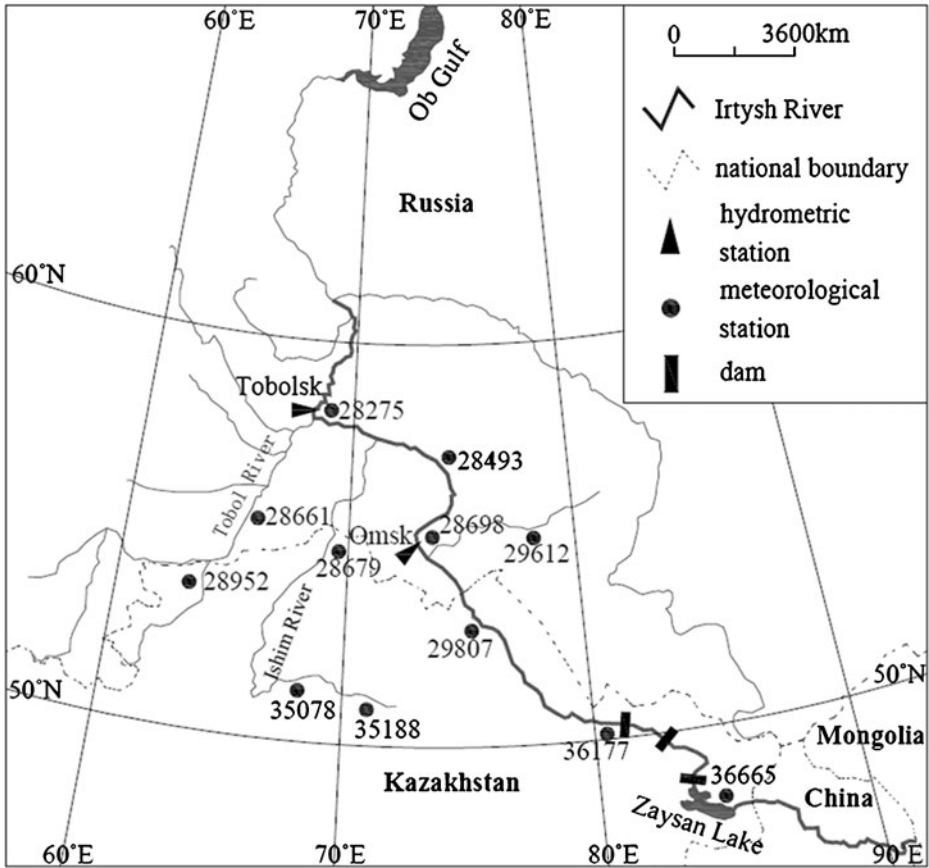
Fig. 1 The Irtysh River Basin

Russia before entering the Irtysh River. Cascades of large reservoirs (Table 1) have been constructed at the upper reaches of the Irtysh River.

Omsk hydrometric station is located at the middle reaches of the Irtysh River and Tobolsk hydrometric station is located at the lower reaches (Table 2). Monthly flow data of the two hydrometric stations from 1936 to 1999 were collected. The flood season is from April to October, and the dry season is from November to March of the next year. Twelve meteorological stations (Table 3) with long term observed precipitation data were selected. Only ten of them have long term observed temperature data. Monthly precipitation and monthly mean temperature data from 1936 to 1999 were collected. For the Irtysh River Basin, spring is from April to May when is the snowmelt period, summer is from June to August, autumn is from September to October, and winter is from November to March of the next year.

2.2 Analysis Methodology

Annual runoff and its distribution within a year of the Irtysh River were analyzed. Coefficient of variation (C_v) was applied to describe the unevenness and concentration degree (C_d)

Table 1 Reservoirs at the upper reaches of the Irtysh River

Reservoir name	Location	Reservoir volume (10^8 m^3)		Water surface area (km^2)	Start operation year
		Total	Effective		
Bukhtarma	[49.7°N, 83.3°E]	497	306	5490	1960
Ust-Kamenogorsk	[49.9°N, 82.7°E]	6.5	1.7	87	1952
Shul'binsk	[50.4°N, 81.0°E]	24	15	507	1989

was applied to describe the concentricity of the runoff distribution within a year. For a time series, such as the annual runoff series, the C_v series and the C_d series, abrupt changes were detected by the heuristic segmentation method (Fukuda et al. 2004).

Two main factors may lead to hydrological changes: climate changes and human activities. Long term observed temperature and precipitation data were analyzed by the Mann-Kendall method (Yue et al. 2002) to estimate whether the climate condition has changed. Hydrological changes may be attributed to human activities if climate effect is excluded.

2.3 Methods

2.3.1 Coefficient of Variation

Coefficient of variation (C_v) is a popular value for describing the uneven distribution of runoff within a year in term of quantitive scale. It is calculated by the following equations:

$$C_v = \delta/\overline{R} \tag{1}$$

$$\overline{R} = \frac{1}{12}\sum_{i=1}^{12} R(i) \tag{2}$$

$$\delta = \sqrt{\frac{1}{12}\sum_{i=1}^{12}\left(R(i) - \overline{R}\right)^2} \tag{3}$$

In Eqs. (2) and (3), $R(i)$ is the mean flow of the ith month. The value of C_v ranges in $[0, +\infty)$. The value 0 indicates the even distribution of runoff without any intra-annual variability and larger value indicates greater intra-annual variability.

Table 2 Hydrometric stations of the Irtysh River

Hydrometric station	Location	Drainage area (10^4 km^2)	Multi-year mean runoff (10^8 m^3)
Omsk	[55.0°N, 73.4°E]	76.9	277
Tobolsk	[58.2°N, 68.2°E]	150	676

Table 3 Meteorological stations of the Irtysh River Basin

Code	Location	Multi-year mean precipitation (mm)	Multi-year mean temperature (°C)
36665	[47.5°N, 84.9°E]	305	4.3
36177	[50.4°N, 80.2°E]	263	
29807	[53.4°N, 75.5°E]	271	1.7
29612	[55.3°N, 78.4°E]	362	0.2
28698	[55.0°N, 73.4°E]	362	1.1
28493	[57.0°N, 74.4°E]	418	0.0
35188	[51.2°N, 71.4°E]	288	2.3
35078	[51.8°N, 68.4°E]	277	
28679	[54.8°N, 69.2°E]	335	1.2
28952	[53.2°N, 63.6°E]	301	2.4
28661	[55.4°N, 65.4°E]	365	1.8
28275	[58.2°N, 68.2°E]	462	0.3

2.3.2 Concentration Degree

Different from C_v, concentration degree (C_d) describes the runoff distribution within a year from another perspective in term of temporal scale. It is calculated by the following equations (Li et al. 2008):

$$R_x = \sum_{i=1}^{12} R(i) \cos \theta_i \tag{4}$$

$$R_y = \sum_{i=1}^{12} R(i) \sin \theta_i \tag{5}$$

$$C_d = \sqrt{R_x^2 + R_y^2} \Big/ \sum_{i=1}^{12} R(i) \tag{6}$$

In Eqs. (4)–(6), $R(i)$ is the mean flow of the ith month. θ_i is the angle of the ith month: 0° corresponds to January, 30°corresponds to February, 60°corresponds to March,…, 330° corresponds to December. The value of C_d ranges in [0, 1]. The value 0 indicates the even distribution of runoff without any concentration while the value 1 indicates that runoff is concentrated in 1 month. Larger value indicates heavier concentration of runoff during a period, e.g. the flood season.

2.3.3 Heuristic Segmentation Algorithm

Heuristic segmentation algorithm is powerful in detecting abrupt changes and has been successfully applied in the meteorological and hydrological researches (Chen and Xie 2008; Feng et al. 2005; Gong et al. 2006). For a non-stationary time series $\{x(t)\}(t=1,2,…,N)$, move a sliding pointer from left to right along the time series. At each position of the pointer,

compute the means of the sub-sets of the time series to the left of the pointer (μ_1) and to the right (μ_2). The statistical significance of the difference between the means of the two sub-sets is given by the statistic t:

$$t = \left| \frac{\mu_1 - \mu_2}{S_D} \right| \tag{7}$$

where

$$S_D = \left(\frac{(N_1 - 1)s_1^2 + (N_2 - 1)s_2^2}{N_1 + N_2 - 2} \right)^{1/2} \left(\frac{1}{N_1} + \frac{1}{N_2} \right)^{1/2} \tag{8}$$

is the pooled variance. s_1 and s_2 are the standard deviations of the data to the left and to the right of the pointer, and N_1 and N_2 are the number of points to the left and to the right of the pointer.

As a function of the position in the time series, the statistic t is used to quantify the difference between the means of the left-side and right-side time series. Larger t means that the values of the mean of both time series are more likely to be significantly different, making point t_{max}, with the largest value of t, a good candidate as a cut point. Then the statistical significance $P(t_{max})$ is calculated. $P(t_{max})$ is numerically approximated as

$$P(t_{max}) \approx \left\{ 1 - I_{\left[\nu / \left(\nu + t_{max}^2 \right) \right]} (\delta \nu, \delta) \right\}^{\eta} \tag{9}$$

where $\eta = 4.19 \ln N - 11.54$ and $\delta = 0.40$ are obtained from Monte Carlo simulations, N is the length of the time series, $\nu = N-2$, and $I_x(a,b)$ is the incomplete beta function.

The significance is checked whether it exceeds a selected threshold which is usually set as 0.05 (significance level). If so, then the time series is separated at this point into two subsequences; otherwise the time series remains undivided. If the time series is divided, the above procedure is iterated recursively on each segment until the obtained significance value is smaller than the threshold.

2.3.4 Mann-Kendall Algorithm

The rank-based Mann-Kendall method is a traditional and commonly used method for the change detection (Dou et al. 2008; Hao et al. 2007; Wu et al. 2007; Xu et al. 2004; Zhang et al. 2008). The Mann-Kendall test is based on the test statistic S defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \tag{10}$$

Where the x_j and x_i are the sequential data values, n is the length of the data set, and

$$\text{sgn}(\theta) = \begin{cases} 1 & if & \theta > 0 \\ 0 & if & \theta = 0 \\ -1 & if & \theta < 0 \end{cases} \tag{11}$$

When $n \geq 8$, the statistic S is approximately normally distributed with the mean and the variance as follows:

$$E(S) = 0 \tag{12}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum\limits_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \tag{13}$$

Where t_i is the number of ties of extent i. The standardized test statistic Z is computed by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{14}$$

Z follows the standard normal distribution with mean of zero and variance of one. A positive or negative value of Z represents an upward or downward change respectively. In a two-tailed test, the null hypothesis (no trend) is rejected at significance level α if $|Z| > Z_{\alpha/2}$, where $Z_{\alpha/2}$ is the value of the standard normal distribution with an exceedance probability of $\alpha/2$. The significance level α is usually set as 0.05.

3 Results and Discussion

3.1 Changes of Annual Runoff

For Omsk hydrometric station, the annual runoff was changed abruptly at 1961 (Fig. 2a). The multi-year mean runoff of 1936–1960 was 306×10^8 m³, but that of 1961–1999 was just 258×10^8 m³, sharply decreased by 48×10^8 m³. However, for Tobolsk hydrometric station, no abrupt change was detected in the annual runoff series and so the annual runoff could be considered to be steady (Fig. 2b).

3.2 Changes of Runoff Distribution within a Year

For Omsk hydrometric station, two significant abrupt changes which occurred at 1960 and 1990 respectively were detected in the C_v series and separated the C_v series to three sub-series (Fig. 3a). The mean C_v values of the three sub-series were 0.78, 0.63, and 0.48 respectively. The change pattern of C_d was similar with that of C_v. The C_d series was also separated to three sub-series by two significant abrupt changes which occurred at 1961 and 1990 respectively (Fig. 3b). The mean C_d values of the three sub-series were 0.45, 0.32, and 0.23 respectively. However, for Tobolsk hydrometric station, no abrupt change was detected in the C_v series or the C_d series. Gradually decreasing trend was observed in these two series (Fig. 4).

3.3 Changes of Monthly Flow

For Omsk hydrometric station, the changes of monthly flow were analyzed by comparing the mean values of sub-series because abrupt changes were detected in the distribution features of annual runoff. The C_v series was abruptly changed at 1960 and 1990, and the C_d series was abruptly changed at 1961 and 1990 respectively. To make things simple, the monthly flow series were divided into three sub-series at 1961 and 1990. Figure 5 shows the changes of the monthly flow. In Fig. 5, D-values 1 is the difference between the mean values of 1961–1989 and 1936–1960, and D-values 2 is the difference between the mean values of 1990–1999 and 1961–1989. D-values 1 show that the flow is decreased in the flood season
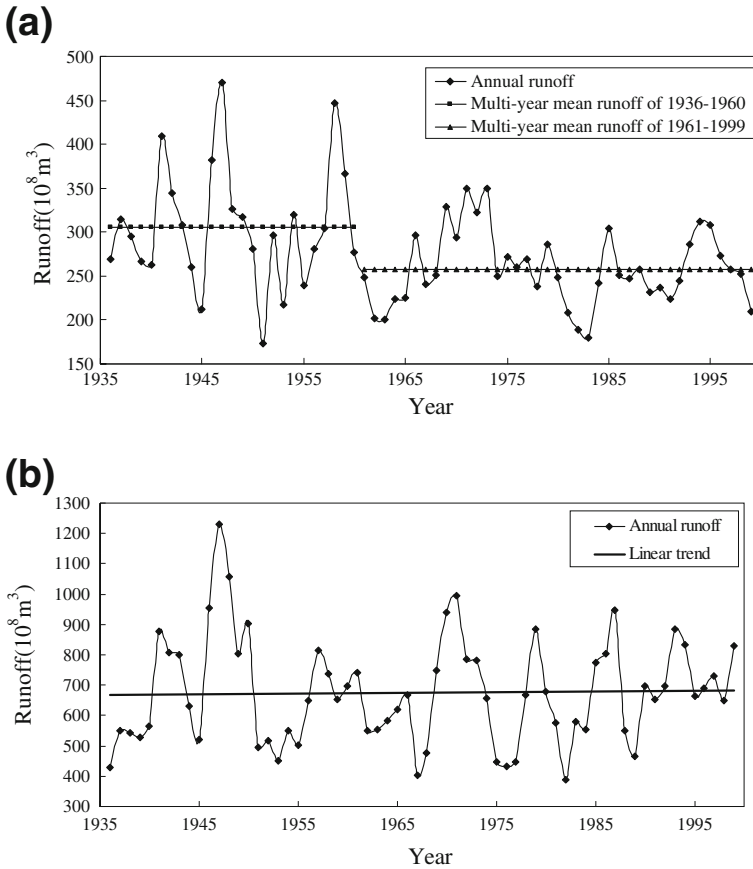
Fig. 2 a. Changes of the annual runoff (Omsk hydrometric station). b. Changes of the annual runoff (Tobolsk hydrometric station)

(except April), but is increased in January-April and December. D-values 2 show that the flow is further decreased in May-July, but is further increased in the dry season and April.

For Tobolsk hydrometric station, no abrupt change was detected in the series of annual runoff and its distribution features. Located at the lower reaches, the hydrological regime of Tobolsk hydrometric station is influenced by the hydrological regime of Omsk hydrometric station. So the monthly flow series were divided at 1961 when the abrupt change was occurred in the series of the annual runoff and its distribution features of Omsk Hydrometric station. Figure 6 shows the changes in the monthly flow of Tobolsk hydrometric station which are similar with the changes at the middle reaches. D-values, the difference between the mean values of 1961–1999 and 1936–1960, show that the flow is decreased in June-October but is increased in the dry season and April.

3.4 Climate Changes and the Possible Influence

Table 4 shows the temperature changes of the Irtysh River Basin. The temperature increased at some meteorological stations in January-March, May-July, October and December. The form of precipitation in winter is snow. Though the temperature increased in some winter
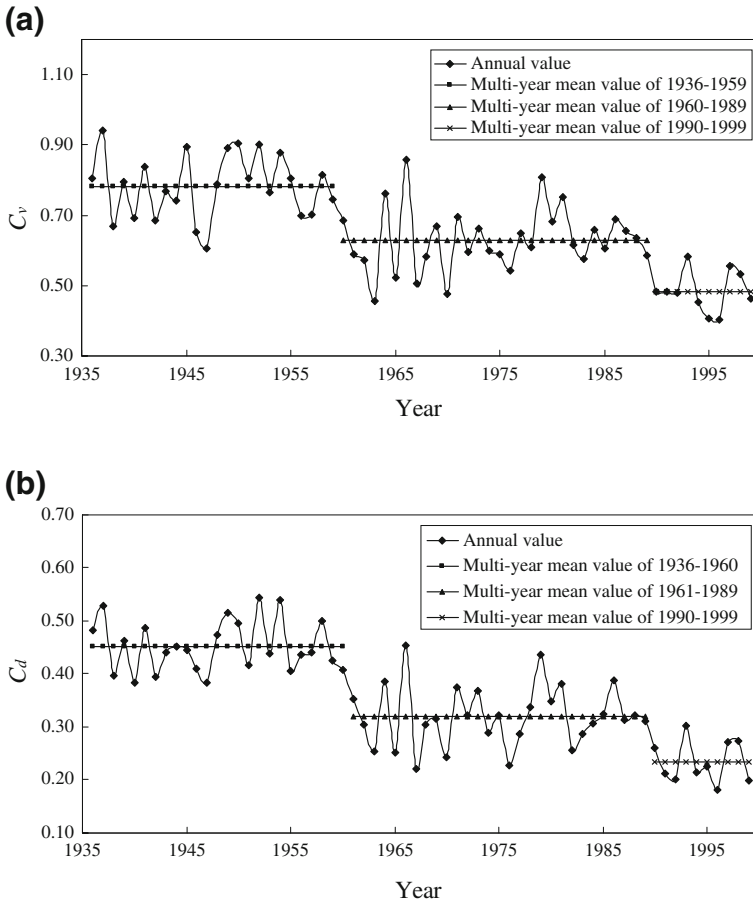
Fig. 3 **a**. Changes of the runoff variation within a year of Omsk hydrometric station. **b**. Changes of the runoff concentration within a year of Omsk hydrometric station

months, little influence may be induced to hydrological changes because the form of precipitation remains to be snow which would not increase the runoff in the dry season. In some months of the flood season, the increased temperature may increase the evaporation and then decrease the runoff.

Table 5 shows the precipitation changes of the Irtysh River Basin. At some meteorological stations, the precipitation increased in winter which would lead to a thicker snow cover and consequently a higher snowmelt runoff in spring. At only one meteorological station, the precipitation decreased in July. At seven meteorological stations, the annual precipitation increased which should increase the annual runoff.

3.5 Possible Causes of the Hydrological Changes

The hydrological changes of the Irtysh River may be partially attributed to the climate changes. The increased runoff of April may be partially attributed to the increased precipitation in winter. The decreased runoff of the flood season may be partially attributed to the increased temperature and the decreased precipitation. However, the climate changes are not
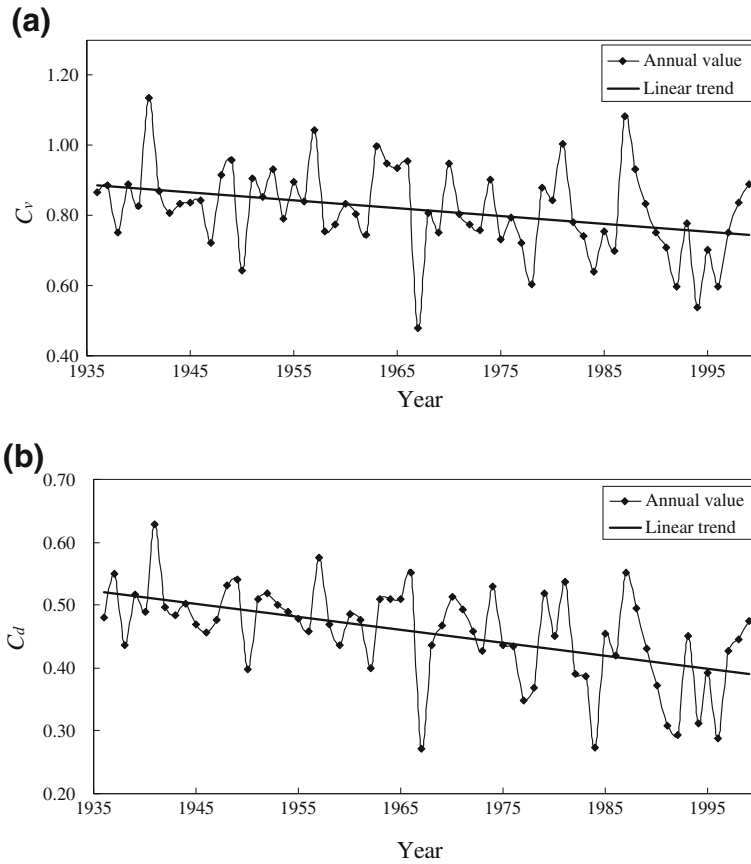
(a)

(b)

Fig. 4 **a**. Changes of the runoff variation within a year of Tobolsk hydrometric station. **b**. Changes of the runoff concentration within a year of Tobolsk hydrometric station

sufficient enough to explain all hydrological changes and some hydrological changes are even opposite to the changes that the climate changes should lead to.
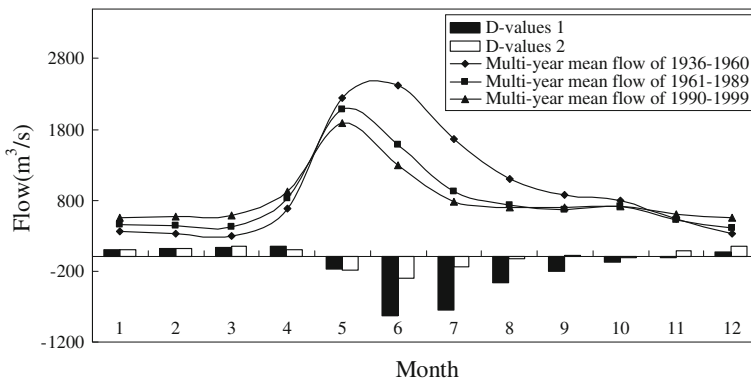

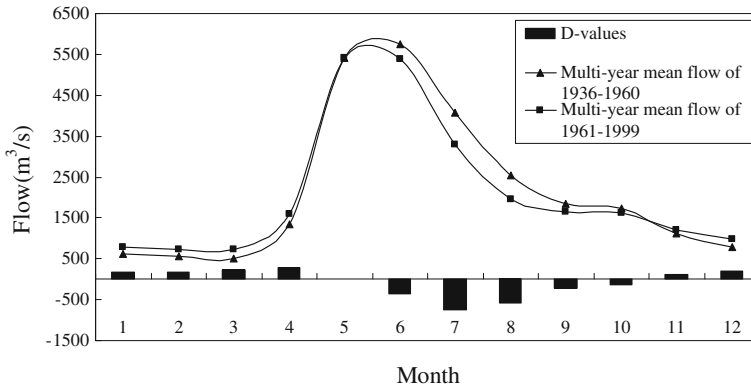Fig. 5 Changes of the monthly flow of Omsk hydrometric station

Fig. 6 Changes of the monthly flow of Tobolsk hydrometric station

Human activities, especially the reservoir operation, may be another important factor. At the middle reaches, the annual runoff was changed abruptly at 1961 when the Bukhtarma reservoir began to operate and it was decreased sharply. The runoff reduction may be mainly attributed to the evaporation of the reservoirs. The original water surface area of the Zaysan Lake was about 1810 km^2. After the operation of the Bukhtarma reservoir, which is located close to the down stream of the Zaysan Lake, the water surface area is increased to

Table 4 Temperature change of the Irtysh River Basin

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
36665	Z	2.58	1.95	0.49	0.62	1.15	0.62	1.08	1.81	1.81	1.65	1.76	2.72
	change	↑*	-	-	-	-	-	-	-	-	-	-	↑*
29807	Z	2.43	1.95	1.77	1.07	1.57	1.52	1.95	1.37	0.42	2.35	0.51	2.30
	change	↑*	-	-	-	-	-	-	-	-	↑*	-	↑*
29612	Z	2.52	2.00	2.50	0.60	1.65	0.01	2.29	1.51	-0.49	1.78	1.12	2.51
	change	↑*	↑*	↑*	-	-	-	↑*	-	-	-	-	↑*
28698	Z	2.54	2.11	2.55	0.93	1.64	1.32	2.14	1.45	-0.53	2.17	0.74	2.29
	change	↑*	↑*	↑*	-	-	-	↑*	-	-	↑*	-	↑*
28493	Z	1.94	1.51	3.37	0.76	1.75	0.81	3.18	1.35	-0.35	1.89	0.39	1.93
	change	-	-	↑*	-	-	-	↑*	-	-	-	-	-
35188	Z	2.75	2.13	1.60	1.70	1.70	2.36	1.76	1.18	1.81	2.58	1.51	2.57
	change	↑*	↑*	-	-	-	↑*	-	-	-	↑*	-	↑*
28679	Z	2.51	1.98	1.88	1.08	2.09	2.22	2.05	0.41	-0.27	2.51	0.48	2.21
	change	↑*	↑*	-	-	↑*	↑*	↑*	-	-	↑*	-	↑*
28952	Z	2.69	2.42	1.69	1.40	1.54	2.49	1.59	0.46	0.85	3.30	1.00	2.31
	change	↑*	↑*	-	-	-	↑*	-	-	-	↑*	-	↑*
28661	Z	2.02	1.91	1.87	0.94	1.15	1.14	1.43	-0.48	-0.80	2.11	0.24	1.92
	change	↑*	-	-	-	-	-	-	-	-	↑*	-	-
28275	Z	0.82	-0.16	1.89	-0.10	0.92	0.79	1.79	-1.16	-1.68	1.41	-0.24	1.23
	change	-	-	-	-	-	-	-	-	-	-	-	-

The symbol "↑" denotes the increasing change; "↓" denotes the decreasing change; "-" denotes no change; "*" denotes the significance of change past 0.95 confidence level

Table 5 Precipitation change of the Irtysh River Basin

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
36665	Z	0.80	3.05	0.41	-1.27	-0.42	-0.75	1.45	-0.46	1.61	1.11	1.96	1.11	1.68
	change	-	↑*	-	-	-	-	-	-	-	-	↑*	-	-
36177	Z	0.70	1.37	-0.16	-1.26	0.75	-0.93	1.68	0.85	-0.67	-1.78	0.27	0.72	0.71
	change	-	-	-	-	-	-	-	-	-	-	-	-	-
29807	Z	3.27	2.95	0.30	0.82	0.59	0.02	-0.76	1.46	0.03	1.95	2.28	2.03	1.85
	change	↑*	↑*	-	-	-	-	-	-	-	-	↑*	↑*	-
29612	Z	3.92	2.90	2.25	1.27	-0.43	-0.45	-1.72	0.29	0.66	1.76	3.95	4.54	2.27
	change	↑*	↑*	↑*	-	-	-	-	-	-	-	↑*	↑*	↑*
28698	Z	6.49	5.94	3.26	0.76	-0.41	-0.90	-0.08	0.53	1.45	1.55	4.72	5.93	3.24
	change	↑*	↑*	↑*	-	-	-	-	-	-	-	↑*	↑*	↑*
28493	Z	4.44	3.42	0.52	1.28	-1.35	-0.67	-2.02	1.40	0.92	1.45	3.24	3.86	2.03
	change	↑*	↑*	-	-	-	-	↓*	-	-	-	↑*	↑*	↑*
35188	Z	4.18	4.71	2.53	0.97	0.61	0.43	0.00	-0.45	-0.20	0.71	4.08	4.37	3.52
	change	↑*	↑*	↑*	-	-	-	-	-	-	-	↑*	↑*	↑*
35078	Z	4.01	4.30	1.53	1.09	0.21	0.91	-0.34	0.64	0.93	0.47	2.86	4.59	4.21
	change	↑*	↑*	-	-	-	-	-	-	-	-	↑*	↑*	↑*
28679	Z	5.65	5.09	3.42	0.95	-0.02	-1.19	0.69	0.23	1.61	1.66	4.44	5.32	3.77
	change	↑*	↑*	↑*	-	-	-	-	-	-	-	↑*	↑*	↑*
28952	Z	4.25	2.89	1.42	1.16	0.96	0.08	0.38	1.04	0.02	-0.91	2.60	3.96	3.19
	change	↑*	↑*	-	-	-	-	-	-	-	-	↑*	↑*	↑*
28661	Z	2.76	1.61	-0.17	-0.39	0.14	1.65	-1.05	0.96	1.49	-0.58	1.73	2.11	1.68
	change	↑*	-	-	-	-	-	-	-	-	-	-	↑*	-
28275	Z	3.27	0.85	-1.89	0.09	-0.74	-1.18	-0.81	0.21	0.54	0.67	0.55	1.01	-0.13
	change	↑*	-	-	-	-	-	-	-	-	-	-	-	-

The symbol "↑" denotes the increasing change; "↓" denotes the decreasing change; "-" denotes no change; "*" denotes the significance of change past 0.95 confidence level

5490 km^2. The Shul'binsk reservoir began to operate at 1989 and its water surface area is 507 km^2. The increased water surface area aggravates the evaporation and leads to the runoff reduction. The runoff distribution features within a year (C_v and C_d) were changed abruptly two times around the years when the Bukhtarma and Shul'binsk reservoir began to operate. And accordingly, the change pattern of monthly flow was the expected pattern that the reservoir operation would lead to. The reservoirs store water in the flood season and release water in the dry season, and consequently decrease the intra-annual variation and concentration of the runoff. So the changes of runoff distribution within a year may be mainly attributed to the Bukhtarma and Shul'binsk reservoir.

The hydrological regime at the lower reaches is affected relative mildly by the reservoirs at the upper reaches. Under the opposite influences of climate changes and human activities, the annual runoff remains steady. The runoff distribution within a year is also influenced by the reservoir operation. The runoff is decreased in the flood season and is increased in the dry season.

It should be noted that other human activities (e.g. water extraction, agricultural irrigation and land use) may also change the hydrological regime, besides the reservoir operation. But only the influence of the reservoir operation was discussed in this paper due to the limited data.

4 Conclusions

For Omsk hydrometric station at the middle reaches of the Irtysh River, the annual runoff was decreased by 48×10^8 m^3 after an abrupt change at 1961. The values of the intra-annual runoff distribution features measured by coefficient of variation and concentration degree were decreased after two abrupt changes occurring around 1961 and 1990. For Tobolsk hydrometric station at the lower reaches, the annual runoff remained steady and the values of its distribution features were decreased gradually. For the two hydrometric stations, the runoff of the flood season (except April) was decreased and that of the dry season and April was increased.

The hydrological changes of the Irtysh River may be partially attributed to climate changes. The increased precipitation in winter may increase the runoff of April. The increased temperature and the decreased precipitation in some months of the flood season may decrease the runoff. Human activities, especially the reservoir operation, are another important factor. The increased water surface area of the reservoirs aggravates the evaporation and reduces the annual runoff at the middle reaches. The reservoirs store water in the flood season and release water in the dry season, and consequently decrease the runoff of the flood season and increase the runoff of the dry season.

References

Chen GC, Xie P (2008) Change point analysis of hydrologic time series based on heuristic segmentation method. Acta Scientiarum Naturalium Universitatis Sunyatseni 47(5):122–125

Dou L, Huang MB, Hong Y (2008) Statistical assessment of the impact of conservation measures on streamflow responses in a watershed of the Loess Plateau, China. Water Resour Manag 23(10):1935–1949. doi:10.1007/s11269-008-9361-6

Feng GL, Gong ZQ, Dong WJ, Li JP (2005) Abrupt climate change detection based on heuristic segmentation algorithm. Acta Physica Sinica 54(11):5494–5499

Fukuda K, Eugene Stanley H, Nunes Amaral LA (2004) Heuristic segmentation of a nonstationary time series. Physical Review E 69(2):1–12. doi:10.1103/PhysRevE.69.021108

Gong ZQ, Feng GL, Wan SQ, Li JP (2006) Analysis of features of climate change of Huabei area and the global climate change based on heuristic segmentation algorithm. Acta Physica Sinica 55(1):477–484

Hao XM, Chen YN, Xu CC, Li WH (2007) Impacts of climate change and human activities on the surface runoff in the Tarim River Basin over the last 50 years. Water Resour Manag 22(9):1159–1171. doi:10.1007/s11269-007-9218-4

Hrkal Z, Gadalia A, Rigaudiere P (2006) Will the river Irtysh survive the year 2030? Impact of long-term unsuitable land use and water management of the upper stretch of the river catchment (North Kazakhstan). Environ Geol 50(5):717–723. doi:10.1007/s00254-006-0244-y

Li L, Hao ZC, Wang JH, Wang ZH, Yu ZB (2008) Impact of future climate change on runoff in the head region of the Yellow River. J Hydrol Eng 13(5):347–354. doi:10.1061/(asce)1084-0699(2008) 13:5(347

McClelland JW, Holmes RM, Peterson BJ, Stieglitz M (2004) Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. J Geophys Res 109(D18102):1–12. doi:10.1029/2004JD004583

Mix K, Lopes VL, Rast W (2012) Environmental drivers of streamflow change in the upper Rio Grande. Water Resour Manag 26(1):253–272. doi:10.1007/s11269-011-9916-9

Ouyang W, Hao F, Song K, Zhang X (2011) Cascade dam-induced hydrological disturbance and environmental impact in the upper stream of the Yellow River. Water Resour Manag 25(3):913–927. doi:10.1007/s11269-010-9733-6

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime. BioScience 47(11):769–784. doi:10.2307/1313099

Wu H, Soh L-K, Samal A, Chen XH (2007) Trend analysis of streamflow drought events in Nebraska. Water Resour Manag 22(2):145–164. doi:10.1007/s11269-006-9148-6

Xu ZX, Chen YN, Li JY (2004) Impact of climate change on water resources in the Tarim River basin. Water Resour Manag 18(5):439–458. doi:10.1023/B:WARM.0000049142.95583.98

Yang DQ, Ye BS, Kane D (2004a) Streamflow changes over Siberian Yenisei River Basin. J Hydrol 296(1–4):59–80. doi:10.1016/j.jhydrol.2004.03.017

Yang DQ, Ye BS, Shiklomanov A (2004b) Discharge characteristics and changes over the Ob River watershed in Siberia. J Hydrometeorol 5(4):595–610. doi:10.1175/1525-7541(2004) 005<0595:dcacot>2.0.co;2

Ye BS, Yang DQ, Kane DL (2003) Changes in Lena River streamflow hydrology: human impacts versus natural variations. Water Resour Res 39(7):SWC 8-1-14. doi:10.1029/2003wr001991

Ye HC, Ladochy S, Yang DQ, Zhang TJ, Zhang XB, Ellison M (2004) The impact of climatic conditions on seasonal river discharges in Siberia. J Hydrometeorol 5(2):286–295. doi:10.1175/1525-7541(2004) 005<0286:TIOCCO>2.0.CO;2

Yue S, Pilon P, Cavadias G (2002) Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. J Hydrol 259(1–4):254–271. doi:10.1016/s0022-1694(01)00594-7

Zhang Q, Xu CY, Yang T (2008) Variability of water resource in the Yellow River basin of past 50 years, China. Water Resour Manag 23(6):1157–1170. doi:10.1007/s11269-008-9320-2