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Surface runoff processes and sustainable utilization of water resources in Manas River Basin, Xinjiang, China

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Abstract: Water is the important resource to guarantee the existence and development of oases in arid areas. To improve the utilization efficiency of water resources in Manas River Basin, this paper investigated the trends and periods of runoff based on the runoff and climate data for the past 50 years. Subsequently, with the socioeconomic and water resources data, we studied a comprehensive evaluation on the water security in this area. The results indicated that the stream flows in the three hydrological stations of Hongshanzui, Kensiwat and Bajiahu have significantly increased and undergone abrupt changes, with periods of 18 and 20 years. According to assessment, water security in the Manas River Basin was at an unsafe level in 2008. In criterion layer, the ecological security index and the index of supply-demand situation are both at the relatively secure level; the quantity index and socioeconomic index of water resources are at the unsafe level and basic security level, respectively. Therefore, in order to achieve sustainable economic and social development within the Manas River Basin, it is vital to take a series of effective measures to improve the status of water security.

Keywords: surface runoff processes; period and trend; sustainable utilization; water resources; the Manas River Basin; fuzzy comprehensive evaluation

Water resources play the most important role of all the natural resources, especially in arid and semiarid areas (Boehmer *et al*., 2000; Chen *et al*., 2008; Meng *et al*., 2009). Due to excessive utilization and scarcity of water resources, the ecosystems are relatively fragile and social and economic development is severely restricted in such areas (Chen and Xu, 2005). The hydrological processes of inland rivers in arid and semiarid areas of Northwest China are affected by multiple synthetic factors and take on complex non-linear characteristics (Xu *et al.*, 2009).

Manas River Basin has attracted much attention from researchers owing to both its fragile ecological environment and the importance of its economic status in Xinjiang since the 1950s. In recent years, with farmland area and population increasing, water resources have been over utilized, making the basin downstream and Manas Lake become completely dry (Yao *et al*., 2007). Subsequently, the groundwater depth of the basin has fallen rapidly and the ecosystem has been badly damaged. So, sustainable utilization of water resources has become more important for water management supervisors in the Manas River Basin, given the variable annual runoff and the comprehensive evaluation of water security. However, few researchers have conducted work in this basin. In order to foster sustainable development of the socioeconomic system in the Manas River Basin, this paper revealed the changes in annual runoff processes and in climatic factors using the non-parametric test and extrapolation method of periodic variance analysis, and investigated the present status of potential water security using the methods of the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation.

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1 Study area

As the largest inland river to the north of the Tianshan Mountains, the Manas River has an estimated natural flow of 13.19×10^8 m^3, a length of about 400 km and a mountainous catchment area of 5,156 km^2. The Manas River Basin (43°05′–45°58′N, 84°42′–86°33′E) is situated between the northern foot of the Tianshan Mountains and the southern edge of the Junggar Basin (Fig. 1), facing the Gurbantunggut Desert and occupying a surface area of 3.35×10^4 km^2. The basin holds varied geomorphological types, and the terrain is high in the southern mountainous areas and low in the northern oases and deserts. Therefore, it is characterized as a mountain-oasis-desert system, which is regarded as a very typical landscape in Northwest China and even Central Asia (Cheng *et al*., 2006; Fan *et al*., 2008; Liu *et al*., 2008).

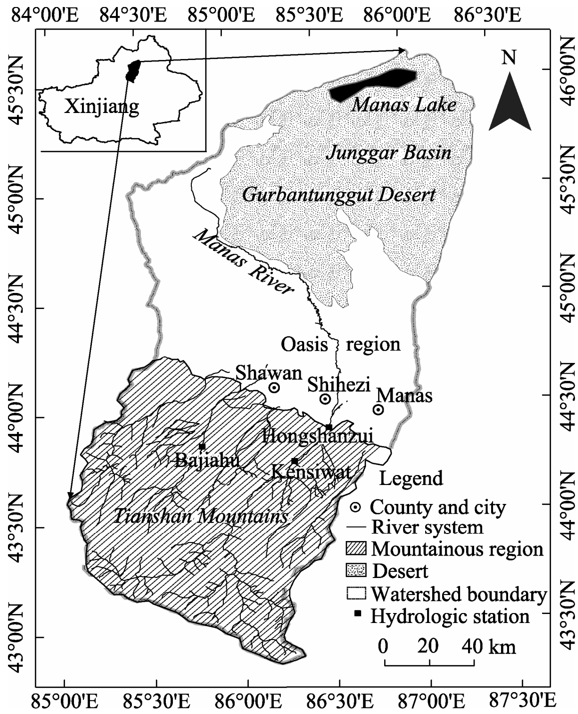

Fig. 1 The sketch map of Manas River watershed

Manas River Basin is recharged by five stream systems with a total average surface runoff of 22.98×10^8 m^3/a. From east to west, the five streams are the Taxi River, Manas River, Ningjia River, Jingou River and Bayingou River. The existence of oases depends entirely on the headwater streams from snowmelt and precipitation. The proportions of melt water (glaciers and snow), precipitation and base flow are 34.9%, 21.4% and 43.7%, respectively. Climate change has led to the variations in runoff flowing into the oases in the Manas River Basin (He and Guo, 1998).

The climate in the basin is of typical continental arid climate, with hot and dry summers, and chilly winters. The mean annual precipitation varies between 110 and 190 mm from the southern plain to the mountains. The mean annual temperature is about 6.6ºC, and mean annual evaporation ranges from 1,500 to 2,000 mm.

2 Data and methods

2.1 Data collection

In this paper, the data for the last 50 years were from 3 hydrological stations located in the mountain areas (Fig. 1), including Kensiwat (1954–2008) and Hongshanzui (1954–2008) on the Manas River, and Bajiahu (1962–2008) on the Jingou River. Meanwhile, the meteorologic and socioeconomic data for 2008 were also investigated. Temperature and precipitation data for the period of 1954–2007 were collected from 5 stations in the Manas River Basin (Shihezi, Kensiwat, Anjihai, Shawan, and Manas). The socioeconomic and water resources data were offered by the management office of the Manas River Basin. In addition, the data on land cover/land use change were gained from remote sensing images for five years (1958, 1976, 1987, 1998, and 2010).

The remote sensing data adopted in this paper came from aerial photographs in 1958, MMS images in 1976 (free from Maryland University), and TM images from American Landsat in 1987, 1998 and 2010. Because the aerial photographs of 1958 and MMS images from 1976 did not cover the whole Manas River Basin, the administrative boundary of the 1: 100,000 scale relief maps of 26 was adopted to implement masking extraction and amendment of the images. Using the ERDAS IMAGINE 9.1, Arc/Info and ArcGIS9.3, we processed remote sensing images for the five years through visual interpretation and digitization, and the topological relation was established according to land use taxonomy in China. Moreover, data from field observations were used to revise the interpretation, and acreage data of various land use patterns in the research area were attained and analysed. In addition, according to Kappa coefficients, the precisions of land cover/land use interpretation for 1958, 1976, 1987, 1998, and 2010 are respectively 55%, 64%, 81%, 86%, and 88%, which basically reflects the process of land variation.

2.2 Methods

This paper analysed the trend and abrupt change of runoff in Manas River Basin by using the Mann-Kendall monotonic trend test and Mann-Whitney abrupt change test, respectively. Subsequently, the methods of the analytic hierarchy process and fuzzy comprehensive evaluation were used to study the water security status.

2.2.1 Non-parametric statistics

(1) Mann-Kendall monotonic trend

The data ($X_1, X_2, X_3, \ldots, X_n$) was compared in turn, and the results were recorded as sgn(θ):

$$\mathrm{sgn}(\theta)=\begin{cases}1, & \theta>0\\ 0, & \theta=0.\\ -1, & \theta<0\end{cases} \tag{1}$$

The Mann-Kendall statistic was calculated by using the following formula:

$$S=\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\mathrm{sgn}(x_k-x_i). \tag{2}$$

where, x_k and x_i are the random variables, and n is the length of the selected data sequence. The test statistic is given as follows:

$$Z_c=\begin{cases}\dfrac{s-1}{\sqrt{\mathrm{var}(s)}}, & s>0\\ 0, & s=0.\\ \dfrac{s+1}{\sqrt{\mathrm{var}(s)}}, & s<0\end{cases} \tag{3}$$

With n increasing gradually, Z_c will converge to the standardized normal distribution quickly. When Z_c belongs to $-Z_{1-a/2}\le Z_c\le Z_{1-a/2}$, the null hypothesis is accepted, which indicates that there is no obvious variation trend in the samples. When the statistic Z_c is positive, the sequence is on the upward trend, and vice versa. In Mann-Kendall test, the Kendall inclination is usually used to detect the monotonic trend and indicates the variable quantity in unit time. The corresponding value is calculated as:

$$\beta=Median\left(\frac{x_i-x_j}{i-j}\right), \qquad \forall j<i. \tag{4}$$

Where, $1<j<i<n$, and a positive β denotes a rising trend while a negative β indicates a decreasing trend (Kendall, 1975; Xu *et al.*, 2006).

(2) Mann-Whitney step change

Assuming that there is a time series $X=(X_1, X_2, \ldots, X_n)$ and its subsequences $Y=(X_1, X_2, \ldots, X_{n1})$ and $Z=(X_{n1+1}, X_{n1+2}, \ldots, X_{n1+n2})$, the statistic of the Mann-Whitney abrupt-change test is calculated as:

$$Z_c=\frac{\sum_{t=1}^{n_1}r(x_t)-n_1(n_1+n_2+1)/2}{\left[n_1n_2(n_1+n_2+1)/12\right]^{1/2}}. \tag{5}$$

Where $r(x_t)$ is the rank of the observations. The null hypothesis H_0 is accepted if $-Z_{1-a/2}\le Z_c\le Z_{1-a/2}$ (Xu *et al.*, 2006).

2.2.2 Fuzzy comprehensive evaluation model

Given two finite sets $U=\{u_1, u_2, \ldots, u_m\}$, and $V=\{v_1, v_2, \ldots, v_n\}$, U represents the aggregate consisting of all the evaluation factors; V represents the aggregate consisting of all the remark grades; r_{ij} is the single judgment result of evaluation factors u_i to judgment grade v_j, and then the judgment matrix (R) with amount of m is given (Wang *et al.*, 2005):

$$R=\begin{bmatrix}r_{11}\ r_{12}\cdots r_{1n}\\ r_{21}\ r_{22}\cdots r_{2n}\\ \vdots\ \ \vdots\ \ \ \vdots\ \vdots\\ r_{m1}\ r_{m2}\cdots r_{mn}\end{bmatrix}. \tag{6}$$

If the weight coefficients of all evaluation factors can be defined as $A=[a_1, a_2, \ldots, a_m]$. A is a fuzzy subset of aggregate U, $0\le a_i\le 1$, and the sum of a_i is 1. One fuzzy subset of V can be worked out by applying the synthetic operation of fuzzy transformation, i.e. the comprehensive evaluation results can be fuzzy transformed as $B=A\times R=[b_1, b_2, \ldots, b_n]$, where B is a fuzzy set of V. Subsequently, the comprehensive score value (a) of water security is derived, and the equation is as follows:

$$a=\frac{\sum_{i=1}^{n}b_i^k a_i}{\sum_{i=1}^{n}b_i^k}. \tag{7}$$

Where a means the comprehensive score of water carrying capacity in matrix B. In order to heighten the important function of preponderant grade, we defined the k exponential of b_j as a weight to get weighted average result. In the arid region, the value of k is assumed as 1.

3 Results and discussion

3.1 Trend of annual runoff and climate factors in Manas River Basin

In the western arid region of China, many inland rivers are mainly supplied by the glacial/snow melting water in mountain areas (Chen *et al*., 2006; Xu *et al*., 2010). Therefore, the long-term trend of hydrological processes will also hold a close connection with climate change (Table 1).

The results of the non-parametric Kendall test for both runoff and climate factors (temperature and precipitation) (Table 1) have rejected the hypothesis H_0, in other words, there is a significant increasing trend (Z_c>$Z_{0.05}$=1.96) in the past 50 years for the Manas River Basin (P<0.05). The annual runoff volumes of the Bajiahu and Hongshanzui increased at the rate of 0.011×10^8 m^3/a and 0.043×10^8 m^3/a, respectively. Similarly, temperature and precipitation in this basin had an increasing rates of 0.041ºC/a and 0.932 mm/a, respectively. So, the potential impacts of climate change on water resources are to influence the runoff processes. The monthly runoff time series were used to analyze the variation characteristics of the runoff processes (Table 2).

The results in Table 2 illustrate that the higher averages of the monthly runoff volumes appear in summer (June, July and August) at the Kensiwat hydrological station of the Manas River. In the Kendall test, the monthly runoff change trends have contradicted hypothesis H_0 and the Z_c>0 at April, May, June and December since 1954. That is to say, the trends towards increasing runoff are not significant at the confidence degree of 0.05. Accordingly, the increases of runoff in the other months are significant except in these months.

Table 1 Monotonic trend of annual runoff and climate factors in the Manas River Basin

Item	Mean value	SD	CV	Z_0	β	H_0	Trend
Bajiahu (10^8 m^3)	3.09	0.42	0.137	2.44	0.011	R	Increased
Hongshanzui (10^8 m^3)	13.19	2.13	0.162	2.45	0.043	R	Increased
Temperature (ºC)	7.11	0.98	0.137	4.86	0.041	R	Increased
Precipitation (mm)	178.52	41.16	0.231	2.05	0.932	R	Increased

Note: SD, standard deviation; CV, coefficient of variation

Table 2 Monthly change trend of the runoff time series at Kensiwat of the Manas River

Month	Mean (m^3/s)	SD	CV	Z_0	β	H_0	Trend
Jan	7.62	1.64	0.216	3.45	0.05	R	Increased
Feb	6.63	1.60	0.241	2.98	0.04	R	Increased
Mar	6.85	1.22	0.179	2.97	0.03	R	Increased
Apr	9.35	1.80	0.193	1.68	0.02	A	Slightly increased
May	21.95	7.49	0.341	1.59	0.08	A	Slightly increased
Jun	71.95	19.07	0.265	1.66	0.20	A	Slightly increased
Jul	133.98	32.79	0.245	2.49	0.68	R	Increased
Aug	120.39	30.36	0.252	2.04	0.46	R	Increased
Sep	45.75	12.62	0.276	2.10	0.24	R	Increased
Oct	19.31	3.38	0.175	2.90	0.09	R	Increased
Nov	11.91	1.87	0.157	2.50	0.04	R	Increased
Dec	9.16	1.67	0.182	1.92	0.03	A	Slightly increased

Note: SD, standard deviation; CV, coefficient of variation

3.2 Abrupt change and periods of annual runoff in Manas River Basin

The accumulated difference curve is an effective method to analyze the runoff fluctuation. When the stream flow decreases, a downward gradient is represented, and vice versa. Therefore, the accumulated difference curve was used to depict the change characteristics of the annual runoff in the Manas River Basin in the past 50 years.

Figure 2 shows a monotonic decrease in accumulated flow from 1960s to mid-1990s and then a continuous increase from the mid-1990s to 2008. The Mann-Whitney statistical method was used to identify the exact abrupt change points in runoff for the Hongshanzui and Bajiahu hydrological stations. The results show that the abrupt change points occurred in 1995 at the Hongshanzui station and in 1994 at the Bajiahu hydrological station ($P<0.01$) (Fig. 2 and Table 3). Ling *et al*. (2011a, b, c) reported that the abrupt change of temperature in Manas River Basin happened in 1988. Furthermore, runoff was clearly impacted by temperature in the Manas River Basin (He and Guo, 1998), and the temperature continued to rise after 1988 and ultimately led to abrupt changes in runoff in both the Manas River and Jingou River, which occurred respectively in 1995 and 1994. In addition, the mean values for runoff at the Hongshanzui and Bajiahu hydrological stations were respectively 12.46×10^8 m^3 and 2.95×10^8 m^3 before the abrupt change, and 15.55×10^8 m^3 and 3.42×10^8 m^3 after the abrupt change.

In this paper, the extrapolation method of periodic variance analysis of hydrological time series was used to detect the period of Bajiahu on the Jingou River (Xu *et al*., 2005). The result reveals that the period for stream flow of the Bajiahu is 20 years (Table 4). Previous research (Ling *et al*., 2011a, b, c) revealed that the Manas River held a period of 18 years. Therefore, it is very important to manage water resources effectively based on the variation characteristics of hydrological periods in the Manas River Basin, especially in the low-flow season.

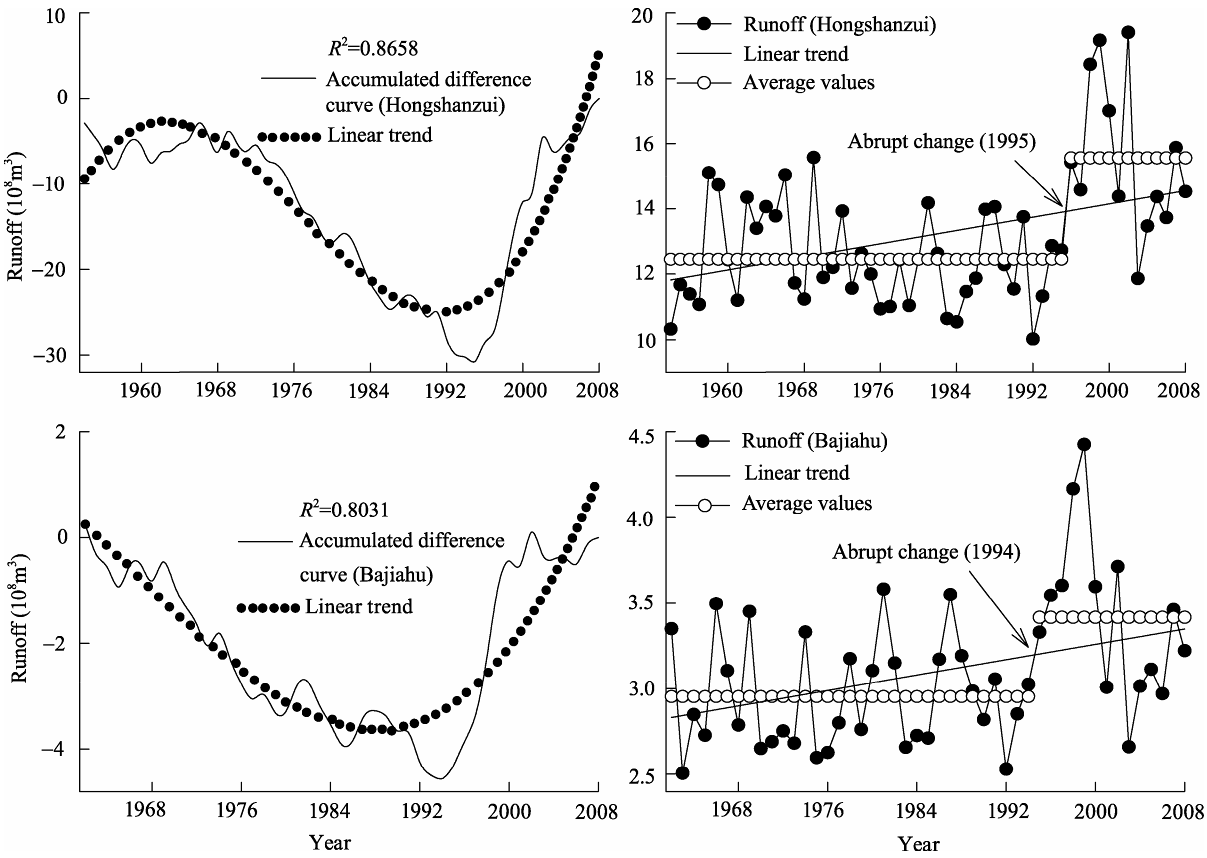

Fig. 2 Accumulated difference curve and abrupt change at two hydrological stations in the Manas River Basin during the past 50 years

Table 3 Mann-Whitney test results of abrupt change for the annual runoff in Manas River Basin

Runoff	Period	n	Mean value	CV	Z_0	H_0
Hongshanzui (Manas River)	1954–1995	42	12.46	0.116	4.10	R
	1996–2008	13	15.55	0.149		
Bajiahu (Jingou River)	1962–1994	33	2.95	0.105	3.12	R
	1995–2008	14	3.42	0.140		

Table 4 Periods of the annual runoff in Manas River Basin

River	Period of change (year)	F value	Confidence degree	CV
Bajiahu (Jingou River)	20	1.3952	0.7905	0.8739

3.3 Human activities and water use in Manas River Basin

Based on satellite remote sensing images, we acquired the data of land cover/land use change for five typical years (1958, 1976, 1987, 1998 and 2010). Human impacts were extensive and increasing with years according to investigations in the study area (Fig. 3). Figure 3 depicts the land cover/land use variations for the Manas River Basin in four years.

The results show that the Manas River Basin was primarily covered by barren deserts, semiarid grasslands and arable land. From 1958 to 2010, the area of arable land, desert, channel length and residential land increased by 150.53%, 40.70%, 31.40% and 689.08%, respectively (Fig. 3). Compared to 1958, the saline land area increased by 25.33% in 1976. Subsequently from 1976 to 2010, its area decreased substantially due to improved irrigation techniques and salt drainage measures. Land cover/land use interacts with water use. According to the data of 2008, the total population reached 211.11×10^4, which was 26.3 times that in 1958. With the population growth and the development of agriculture and industry in the Manas River Basin, the amount of water use increased accordingly. It is calculated that 96% of the available surface water resources have been used in the basin. After 1958, the water area of the Manas River Basin dwindled sharply, and particularly in 1976 it reduced by 84.46%. Therefore, further utilization of water resources is a challenge in the Manas River Basin. In addition, due to the reduction in water area, the area of forestland and grassland in 2010 has respectively decreased by 46.04% and 21.82% compared to 1958. In order to achieve the rational allocation of water resources, it is vital to evaluate the security situation of local water resources and find out the constraining factors that influence water security.

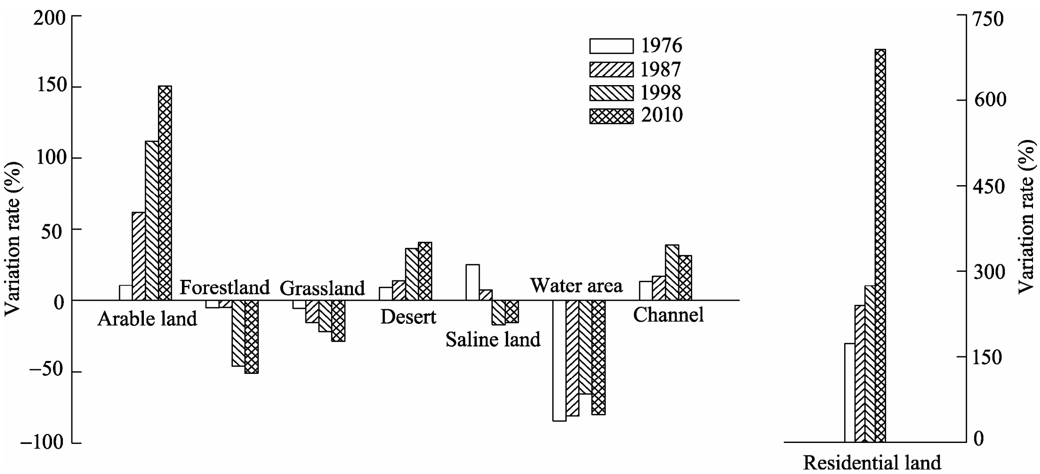

Fig. 3 Land cover/land use variations in four years (1976, 1987, 1998, and 2010) in the Manas River Basin compared to 1958

3.4 Security assessment of water resources in Manas River Basin

3.4.1 Selection and classification of evaluation factors

The evaluation factors of water security should not only denote the security situation of the water resources system, but also indicate the size and quality of the society-economy-nature multi-ecosystems (Gong and Jin, 2009). According to the water utilization characteristics in the Manas River Basin and the indication system of the national Water Supply-Demand Balance Analysis (Gong and Jin, 2009; Meng *et al*., 2009), and under the principle of measurability, independence, reliability and sufficiency in the judgment index system, we took into account the index systems of ecological security, water resources quantity, social economy and supply-demand situation. Therefore, 20 indices divided into four first-level categories were selected, which had a high influence on the water resources of the Manas River Basin and played a major role in the water security evaluation (Table 5).

Consulting other evaluation standards for water security (Li and Zhou, 2004; Meng *et al*., 2009), and combining them with the regional situation of the Manas River Basin, we defined four grades for the significance of 20 evaluation factors for water security. The intervals of each grade were defined for each factor in Table 5. The above-mentioned factors were classified into four levels, which were regarded as extreme security, relative security, basic security and insecurity (Wang *et al*., 2005; Meng *et al*., 2009).

3.4.2 Calculation of judge matrix

It is important to establish membership function fuzzily and to get a smooth transition in different grades in order to eliminate the disadvantage of slight differences in values in adjacent grades and jumping phenomenon occurring across two grades. The membership degree for the critical value between v_2 and v_3 is 1, and the membership grade attached to the two edge points is 0.5. So, the value declines linearly from the critical value to the two sides. As far as v_1 and v_4 are concerned, the longer the distance to the critical value

Table 5 Water security evaluation index system and its classification standards in the Manas River Basin

Criterion layer	Index	Unit	Degree			
			Extreme security (v_1)	Relative security (v_2)	Basic security (v_3)	Insecurity (v_4)
Indices of ecological security (U_1)	Grassland coverage rate (u_1)	%	>40	40–30	30–10	<10
	Ratio of reaching water quality standard (u_2)	%	>95	95–80	80–60	<60
	Woodland coverage rate (u_3)	%	>30	30–20	20–10	<10
	Ecological water using rate (u_4)	%	>40	40–15	15–10	<10
	Oasis desertification (u_5)	%	<5	5–15	15–25	>25
Indices of water resources quantity (U_2)	Water-producing modulus (u_6)	10^4 m^3/km^2	>70	70–50	50–30	<30
	Runoff coefficient (u_7)		>0.4	0.4–0.25	0.25–0.1	<0.1
	Aridity index (u_8)		<1	1–3	3–7	>7
	Water resources per capita (u_9)	m^3	>4,000	4,000–2,500	2,500–1,000	<1,000
	Utilization ratio of water resources (u_{10})	%	<15	15–40	40–60	>60
Indices of social economy (U_3)	GDP per capita (u_{11})	CNY/person	>5,000	5,000–3,500	3,500–1,500	<1,500
	Irrigation rate (u_{12})	%	<25	25–50	50–75	>75
	Water consumption per ten thousand yuan GDP (u_{13})	m^3	<500	500–1,000	1,000–1,500	>1,500
	Population density (u_{14})	person/km^2	<30	30–150	150–250	>250
	Average investment per m^3 of water (u_{15})	CNY/m^3	<4	4–6	6–8	>8
Indices of supply-demand situation (U_4)	Water resource supply and demand rate (u_{16})		>1.2	1.2–0.9	0.9–0.6	<0.6
	Water supply modulus (u_{17})	10^4 m^3/km^2	>20	20–14	14–8	<8
	Water supply per capita (u_{18})	m^3/person	>800	800–500	500–350	<350
	The proportion of groundwater supply (u_{19})	%	<10	10–30	30–45	>45
	Irrigation water use efficiency (u_{20})	%	>70	70–60	60–50	<50

is, the higher the membership degree is; the threshold levels of the both sides belong to the membership degree of 0.5. Based on these rules, an equation can be established to calculate the membership degree of each evaluation factor. If the critical value of v_1 and v_2 is k_1; the critical value of v_2 and v_3 is k_3; and the midpoint value of v_2 is k_2. Similarly, k_5 is the critical value, and the v_4 grade interval midpoint value is k_4. For the evaluation factor, the larger the value is, the better the evaluation result is. The equations of each membership function are as follows:

$$\mu_{v1}(u_i)=\begin{cases}0.5\,(1+\dfrac{u_i-k_1}{u_i-k_2}) & (u_i<k_1)\\ 0.5(1-\dfrac{k_1-u_i}{k_1-k_2}) & (k_2<u_i\le k_1)\\ 0 & (u_i\le k_2)\end{cases};\quad (8)$$

$$\mu_{v2}(u_i)=\begin{cases}0.5(1-\dfrac{u_i-k_1}{u_i-k_2}) & (u_i>k_1)\\ 0.5(1+\dfrac{k_1-u_i}{k_1-k_2}) & (k_2<u_i\le k_1)\\ 0.5(1+\dfrac{u_i-k_3}{k_2-k_3}) & (k_3<u_i\le k_2)\\ 0.5(1-\dfrac{k_3-u_i}{k_3-k_4}) & (k_4<u_i\le k_3)\\ 0 & (u_i\le k_4)\end{cases};\quad (9)$$

$$\mu_{v3}(u_i)\begin{cases}0 & (u_i>k_2)\\ 0.5(1-\dfrac{u_i-k_3}{k_2-k_3}) & (k_3<u_i\le k_2)\\ 0.5(1+\dfrac{k_3-u_i}{k_3-k_4}) & (k_4<u_i\le k_3)\\ 0.5(1+\dfrac{u_i-k_5}{k_4-k_5}) & (k_5<u_i\le k_4)\\ 0.5(1-\dfrac{k_5-u_i}{k_4-u_i}) & (u_i\le k_5)\end{cases};\quad (10)$$

$$\mu_{v4}(u_i)\begin{cases}0 & (u_i>k_4)\\ 0.5(1-\dfrac{u_i-k_5}{k_4-k_5}) & (k_5<u_i\le k_4)\\ 0.5(1+\dfrac{k_5-u_i}{k_4-u_i}) & (u_i\le k_5)\end{cases}.\quad (11)$$

If we turn ">" into"<" and "≤" into "≥" in Eqs. 8–11, the smaller the value is, the better the evaluation result is for the evaluation factor.

3.4.3 Calculation of the weightings of the evaluation factors

In the fuzzy comprehensive evaluation process, determining the weightings of evaluation factors is very important, and has direct impacts on the results of a comprehensive evaluation. Analytic hierarchy process (AHP) can not only achieve the unity of subjectivity and objectivity by virtue of the expert scoring method and math, but also enhance the role of critical indices in the assessment. Therefore, in this paper we chose the AHP method to weigh the indicators (Table 6). In order to better reflect the situation of water security, we identified four grades of scoring row vector, i.e. $C=(1, 0.75, 0.50, 0.25)$ according to the expert scoring.

3.4.4 Fuzzy comprehensive evaluation of the water security

Fuzzy comprehensive evaluation is a very rational and feasible method to evaluate the water security status. Based on the equations of calculating the membership and the weight of each evaluation factor, the final evaluation matrix of water security could be gained by using the fuzzy transform: $B=A\times R$. For example, the comprehensive evaluation of the ecological security index is described as:

$$\begin{aligned}B&=A\times R\\ &=[0.0479,\ 0.4440,\ 0.0719,\ 0.2671,\ 0.1691]\\ &\quad\times\begin{bmatrix}0,\ 0.4385,\ 0.5615,\ 0\\ 0.1667,\ 0.8333,\ 0,\ 0\\ 0,\ 0,\ 0.2530,\ 0.7470\\ 0,\ 0.4611,\ 0.5389,\ 0\\ 0,\ 0,\ 0.4348,\ 0.5652\end{bmatrix}\\ &=[0.0740,\ 0.5142,\ 0.2626,\ 0.1492].\end{aligned}$$

Thus the total score is as: $a=C\times B'=[1, 0.75, 0.50, 0.25]\times[0.0740, 0.5142, 0.2626, 0.1492]'=0.6283$.

For the indices of water security in the Manas River Basin in 2008, the membership degrees of ecological security in four levels are 0.0740, 0.5142, 0.2626, and 0.1492, respectively, and belong to relative security level according to the maximum membership degree principle (Table 7). Water resources can satisfy the ecological water demand under present social and economic context, and the final synthetic graded value

Table 6 The weights of evaluation factors in the Manas River Basin

Criterion layer	Weight	Index layer	Weight
		Grassland coverage rate (u_1)	0.0479
		Ratio of reaching water quality standard (u_2)	0.4440
Index of ecological security (U_1)	0.0553	Woodland coverage rate (u_3)	0.0719
		Ecological water using rate (u_4)	0.2671
		Oasis desertification (u_5)	0.1691
		Water-producing modulus (u_6)	0.1599
		Runoff coefficient (u_7)	0.0618
Index of water resources quantity (U_2)	0.5650	Aridity index (u_8)	0.4185
		Water resources per capita (u_9)	0.2625
		Utilization ratio of water resources (u_{10})	0.0973
		GDP per capita (u_{11})	0.0986
		Irrigation rate (u_{12})	0.3133
Index of social economy (U_3)	0.1175	Water consumption per ten thousand yuan GDP (u_{13})	0.3133
		Population desity (u_{14})	0.0986
		Average investment per m^3 of water (u_{15})	0.1762
		Water resource supply and demand rate (u_{16})	0.3389
		Water supply modulus (u_{17})	0.2504
Index of supply-demand situation (U_4)	0.2622	Water supply per capita (u_{18})	0.1816
		The proportion of groundwater supply (u_{19})	0.0976
		Irrigation water use efficiency (u_{20})	0.1315

Table 7 The fuzzy comprehensive evaluation results for water security in the Manas River Basin in 2008

Criterion layer	Degree				Total score
	Extreme security (v_1)	Relative security (v_2)	Basic security (v_3)	Insecurity (v_4)	
Index of ecological security (U_1)	0.0740	0.5142	0.2626	0.1492	0.6283
Index of water resources quantity (U_2)	0.2431	0.0709	0.0724	0.6136	0.4859
Index of social economy (U_3)	0.1416	0.0556	0.4746	0.3282	0.5027
Index of supply-demand situation (U_4)	0.2486	0.3695	0.2172	0.1647	0.6755
Total score of the Manas River Basin (B)	0.2233	0.1719	0.1682	0.4366	0.5455

is 0.6283. However, the synthetic graded value of the water quantity index is 0.4859 and the membership degree of the unsafe level is up to 0.6136 and has the minimum score in four criterion layers. The situation is not optimistic, so we should promote water-saving irrigation and allocate water reasonably. The synthetic graded value (0.5027) of the socio-economic indicator suggests the local social-economic development has consumed much water. Besides, traditional economic practices led to low utilization efficiency of water resources. The value for the unsafe level is 0.3282, but that of the basic security level is comparatively higher with a value of 0.4746. Thus the indicator develops positively. The index of the supply-demand situation has the highest score and is at the relatively safe level, but the membership degree is 0.3695, which is not high. The water supply quantity can basically meet local living and economic demands. Generally speaking, for the total score of the Manas River Basin, the synthetic graded value is 0.5455 and the membership degree of the unsafe level is 0.4366, indicating an insecure state. Therefore, we should strengthen the construction of water conservancy facilities, improve ecological protection and restoration, promote the transformation from a water-consuming to a water-saving pattern by using advanced techniques, and ensure the effective and rational utilization of the limited water resources.

4 Conclusions and suggestions

In the Manas River Basin, the stream flows at the Hongshanzui and Bajiahu hydrological stations have experienced increasing trends, with the periods of 18 and 20 years, and the abrupt change points occurred in 1995 and 1994, respectively.

A comprehensive assessment of water security has shown that water security in the Manas River Basin was at an unsafe level in 2008, with a membership degree of 0.4366 and a synthetic graded value of 0.5455. In criterion layer, the synthetic graded values of the ecological security index and the supply-demand situation index are both very high. However, these two indices are both at the relatively secure level, where membership degrees are 0.5142 and 0.3695, respectively. Water resources quantity index and socio-economic index are at the unsafe level and basic security level respectively, and the synthetic graded values are respectively 0.4859 and 0.5027, which are both low.

In addition, to avoid ecological threats caused by the lack of water and enhance the security and carrying capacity of the basin's water resources, our study suggested the following four measures: First, a suitable development scale in the oases of the Manas River Basin should be defined according to local water resource conditions; Second, the transport of water for ecological use from river and reservoirs to the lower reaches should be ensured; Third, groundwater resources should be utilized rationally by strict well drilling and agriculture development at desert edges; Finally, utilization of water resources should follow the periods of runoff fluctuation in the Manas River Basin.

It is important for local administrative authorities to produce a better early-warning mechanism against drought and take corresponding measures in an aim to achieve a reasonable allocation of water resources.

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