Impact of climate factors on runoff in the Kaidu River watershed: path analysis of 50-year data

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Abstract: Runoff formation is a complex meteorological-hydrological process impacted by many factors, especially in the inland river basin. Based on the data of daily mean air temperature, precipitation and runoff during the period of 1958–2007 in the Kaidu River watershed, this paper analyzed the changes in air temperature, precipitation and runoff and revealed the direct and indirect impacts of daily air temperature and precipitation on daily runoff by path analysis. The results showed that mean temperature time series of the annual, summer and autumn had a significant fluctuant increase during the last 50 years ($P < 0.05$). Only winter precipitation increased significantly ($P < 0.05$) with a rate of 1.337 mm/10a. The annual and winter runoff depthes in the last 50 years significantly increased with the rates of 7.11 mm/10a and 1.85 mm/10a, respectively. The driving function of both daily temperature and precipitation on daily runoff in annual and seasonal levels is significant in the Kaidu River watershed by correlation analysis. The result of path analysis showed that the positive effect of daily air temperature on daily runoff depth is much higher than that of daily precipitation in annual, spring, autumn and winter, however, the trend is opposite in summer.

Keywords: climate factors; runoff formation; inland river; Kaidu River watershed; path analysis

1 Introduction

Climatic parameters have been believed as the main factors to influence runoff generation. In the arid region, water resources are normally generated from mountainous areas because the precipitation occurring in oases and desert zones cannot form effective runoff. Precipitation usually takes place as snowfall in winter and early spring, and water is temporarily stored as snowpack in the lower or middle alpine region (Kuusisto, 1984; Blöschl *et al.*, 1990; Micovic and Quick, 1999). In the typical alpine area of the Tianshan Mountains from which inland rivers originate, and snowmelt and glacial melt water contribute main parts of the river runoff. The air temperature not only influences the form of precipitation, but also affects the rate of snow melting, and the timing and intensity of spring flood (Wei *et al.*, 2005). The snow cover in the Tianshan Mountains accounts for 55% of total area in winter and about 5% in summer (Dou *et al.*, 2010). Snow/glacier-melt runoff volume accounts for 40.3% of the total discharge of rivers in Xinjiang (Kang *et al.*, 2002). However, the contribution of snowmelt to runoff varies with interactions between climatic factors and environmental factors (Li and Simonovic, 2002). Temperature is identified as a critical factor that affects watershed hydrological process because of its contributions to snowmelt, evaporation, surface soil frost and thaw (Anderson 1973; Li and Simonovic, 2002; Tanasienko and Chumbaev, 2008). Air temperature shapes snowmelt runoff characteristics throughout snowmelt season (Li and Simonovic, 2002). The runoff-temperature relationship exhibits a global positive correlation (Labat *et al.*, 2004), especially in alpine watershed where snow/glacier-melt controlled by airtemperature is a major water source for runoff gen-

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eration (Fu *et al.*, 2010). Therefore, the study on the impact of air temperature on snow-dominated runoff is likely to have substantial implications for alpine regional runoff estimation.

The Tianshan Mountains extend from east to west and divide Xinjiang into two parts, i.e. Southern Xinjiang and Northern Xinjiang. Because of the block and lifting function of airflow from the Atlantic and Arctic Ocean, the precipitation in the mountainous area is abundant (Lan *et al.*, 2009). The average altitude of the Tianshan Mountains' ridge is about 4,000 m with the peak of 7,435 m, and the distances from east to west and from north to south are 1,700 km and 250 km, respectively. A large difference among the mountains exists based on the climatic characteristics. The glaciers exist on the top of mountains, both grasslands and forestlands in the mid part of mountains, and oases in the bottom of mountains. The deserts surround oases and extend the center of basins (Hu, 2004). The mean annual precipitation is about 140 mm and can reach more than 1,000 mm in the windward slope of the western Tianshan Mountains. Sixty five percent of rivers originates from the Tianshan Mountains and the discharge of these rivers accounts for 54% of the total volume of runoff in Xinjiang (He *et al.*, 1996). Previous studies showed an increase in temperature, precipitation and runoff and the positive correlation among them had been observed in Xinjiang (Wang *et al.*, 2006; Tao *et al.*, 2007; Gao, 2008; Ma, 2008).

The correlation coefficient as an important statistical indicator has been widely used for analyzing the relationship between climatic parameters and runoff. Statistically, the correlation coefficient can reflect correlation relationship between variables, but it could not clarify exactly the relationship between cause variables and effect variables, including both the direct impact of the cause variables themselves on the effect variables and the indirect effects of other variables on the effect variables. The correlation analysis discusses the relationship between two sets of data only from the statistics, and the difference between direct and indirect effects could not be partitioned. Among the relations of climatic parameters and runoff, precipitation as rainfall directly contributes to runoff, and then an interactive effect of precipitation as snowfall and temperature on runoff exists because temperature impacts runoff generation process, such as snowmelt and evaporation. As an alternative approach for analyzing the impact of precipitation and temperature on runoff formation process, the hydrological model has been proposed to simulate runoff generation process inputted by climatic parameters and others. SRM (Snowmelt Runoff Model) and MIKE–SHE (Système Hydrologique Européen) models were used to simulate runoff in the Kaidu River watershed in the Tianshan Mountains (Zhang *et al.*, 2007; Huang *et al.*, 2009). SRM mainly simulated the impact of rainfall and snowmelt water driven by temperature on runoff formation. Except for the contribution of rainfall on runoff generation process, MIKE–SHE model can also be used to estimate the temperature contribution on evaportranspiration and snowmelt. However, both of them only probe into the one-way effect of precipitation and temperature on runoff generation, and the direct effect and indirect effect of precipitation and temperature on runoff are not clearly clarified. To further explore the interactive relationship between climatic parameters and runoff, path analysis method was used in this study to investigate the role of the air temperature and precipitation on the runoff originated from the Tianshan Mountains. The study is able to provide not only evidence for hydrology and water resources, but also new train of thought for the development of hydrology in Xinjiang.

2 Study area

The Kaidu River, a main tributary that discharges into the downstream of the Tarim River, is situated at the north fringe of the Yanqi Basin on the south slope of the Tianshan Mountains in Xinjiang (42°43′–43°21′N, 82°58′–86°05′E). The river starts from the Hargat Valley and the Jacsta Valley in the Sarming Mountain with the highest altitude of 5,000 m (the middle section of the Tianshan Mountains), and ends in the Bosten Lake which is located in Bohu county of Xinjiang (Fig. 1). The lake is the largest one in Xinjiang (once the largest interior freshwater lake in China), and the beginning of another river, the Kongque River, which links to the Tarim River. The catchment area of the Kaidu River above Dashankou is 18,827 km^2, with an average elevation of 3,100 m (Tao *et al.*, 2007). In thebasin, the average annual temperature is only –4.26°C and the extreme minimum temperature is –48.1°C. The annual snow-cover days are as many as 139.3 d and the largest average annual snow depth is 12 cm (Xu *et al.*, 2008).

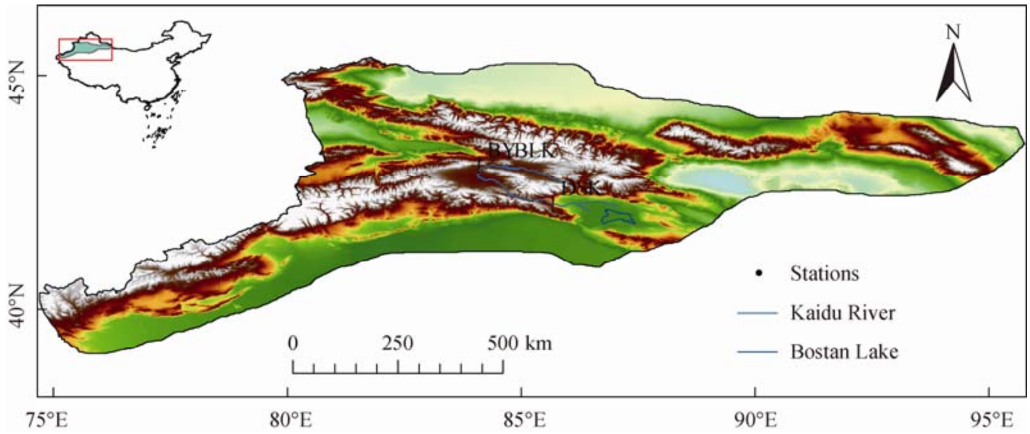

Fig.1 Location of the study area and stations (BYBLK and DSK represent Bayinbuluke meteorological station and Dashankou hydrological station, respectively.)

3 Methods

Data of daily mean air temperature, precipitation and runoff of the Kaidu River watershed were used in this study. The runoff data of the Kaidu River watershed were from Dashankou hydrological station which has a long-term observation data sequence for hydrological studies. Due to the non-inhabitant nature of the area, the daily runoff observed is basically the natural amount of runoff, with less human disturbance (Xu *et al.*, 2008). The dataset used in this study includes daily mean air temperature and precipitation time series from Bayinbuluke meteorological station and daily mean runoff time series from Dashankou hydrological station (from January 1, 1958 to December 31, 2007). Some missing daily data were interpolated on the basis of data from mean values of other years. The details of the stations and duration of data are shown in Table 1.

3.1 Regression equation to estimate hydro-meteorological variables

Regression analysis was used to describe the change in characteristics of temperature, precipitation and runoff time series in this study. The linear regression equation for estimating meteorological-hydrological parameters was developed as:

$$y = \beta_1 t + \beta_0 . \tag{1}$$

Where y is temperature (°C), precipitation (mm) or runoff depth (mm); β_1 and β_0 are regression slope and intercept, respectively; t is time (year).

3.2 Path analysis

Path analysis is a good method for partitioning correlations into direct and indirect effects (Li, 1975; Brannick, 2010). Theoretical propositions about cause and effect without manipulating variables could be tested in the method. Fig. 2 shows the basal framework of path diagram representing two effect variables (x_1, x_2) and a result variable (y) with an error source (e). There are customs about displays and names of things in path analysis. Arrows show assumed causal relations. A single-headed arrow points from cause to effect. The independent variables are called as exogenous variables, while the dependent variables as endogenous variables. A path coefficient indicates the direct effect of the variable of cause on another variable of effect. Path coefficients estimated from correlations are standardized (a path regression coefficient is unstandardized). Path coefficients are written with two subscripts. The path coefficient from the variable x_1 to the variable x_2 is written as p_{21} and note that the effect is listed first. Correlation index R^2 is a measured statistic one that reflects the reliability by which the cause variable explain the effect variable.

According to the definition of path coefficient (Li, 1975), if the correlation relationship between the effect variables (x_1, x_2) and the result variable y existes, then the following equations are established:

$$r_{10} = p_{01} + r_{12} p_{02} , \tag{2}$$

$$r_{20} = p_{02} + r_{21} p_{01} . \tag{3}$$

Where r_{10} is the correlation coefficient between the effect variable x_1 and the result variable y; r_{20} is the correlation coefficient between the effect variable x_2 and the result variable y; r_{12} is the correlation coefficient between the effect variable x_1 and the effect variable x_2; r_{21} is the correlation coefficient between the effect variable x_2 and the effect variable x_1; p_{01} is

Table 1 The hydrological and weather stations and data information in study area

Station	Longitude	Latitude	Altitude (m)	Data	Period
Bayinbuluke meteorological station	84°09′E	43°02′N	2,458	Temperature, precipitation	1958–2007
Dashankou hydrological station	85°44′E	42°13′N	1,340	Runoff	1958–2007

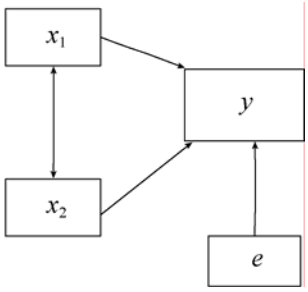

Fig. 2 The basal framework of path diagram

the path coefficient from the effect variable x_1 to the result variable y; p_{02} is the path coefficient from the effect variable x_2 to the result variable y. p_{01} and p_{02} in Eqs. (2) and (3) represent the direct effect of variable x_1 and x_2 on the result variable y, respectively, while $r_{12}p_{02}$ in Eq. (2) represents the indirect effect of variable x_1 through variable x_2 on the result variable y, and $r_{21}p_{01}$ in Eq. (3) represents the indirect effect of variable x_2 through variable x_1 on the result variable y. Path analysis technique was used to examine the relationship between temperature, precipitation and runoff depth based on available data.

4 Results and discussion

4.1 The characteristics of mean temperature, precipitation and runoff

4.1.1 Mean temperature (MT)

The varing trends of the annual mean temperature (AN-MT), the spring mean temperature (SP-MT), the summer mean temperature (SU-MT), the autumn mean temperature (AU-MT) and the winter mean temperature (WI-MT) time series during the period of 1958–2007 in the Kaidu River watershed are identified by regression analysis (Figs. 3 and 4). The mean value of AN-MT was about –4.26°C in the Kaidu River watershed. The time series of AN-MT shows totally significant increase during the last 50 years ($P < 0.05$). The increase rate was 0.26°C/10a. However, from the 1950s to the 1970s, the AN-MT values raised slowly in the 1980s and the middle 1990s; the AN-MT decreased with low values below the average value; after 2000, the AN-MT values increased rapidly and exceeded the average value. The mean values of SP-MT, SU-MT, AU-MT and WI-MT were −1.67°C, 9.87°C, –2.48°C and –23.29°C, respectively in the Kaidu River watershed. Significant increase in temperature occured in summer and autumn and did not in spring and winter in the last 50 years. The time series of SU-MT ($P < 0.01$) and AU-MT ($P < 0.05$) increased significantly during the last 50 years. The increase rates in both seasons were 0.28°C/10a and 0.35°C/10a, respectively (Fig. 4).

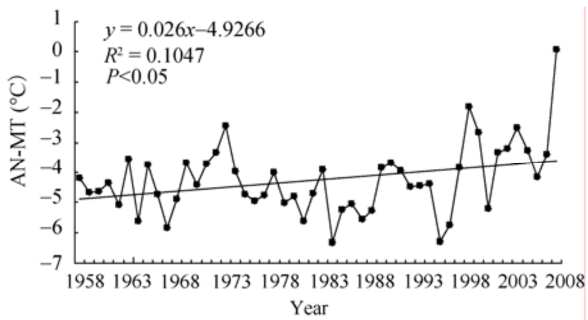

Fig. 3 The trend analysis of the annual mean temperature (AN-MT) time series during the period of 1958–2007 in the Kaidu River watershed

4.1.2 The precipitation (P)

The varying trends of the annual precipitation (AN-P), the spring precipitation (SP-P), the summer precipitation (SU-P), the autumn precipitation (AU-P) and the winter precipitation (WI-P) time series during the period of 1958–2007 in the Kaidu River watershed were identified by regression analysis (Figs. 5 and 6). The mean value of AN-AP was 275 mm and had no significant change. The mean values of SP-P, SU-P, AU-P and WI-P were 41.45 mm, 188.42 mm, 35.06 mm and 10.04 mm, respectively. The accumulated annual precipitation concentrated in summer. Only the time series of WI-P in the Kaidu River watershed increased significantly ($P < 0.05$) with a rate of 1.337 mm/10a (Fig. 6), which implies an increase in snowfall in the last 50 years.

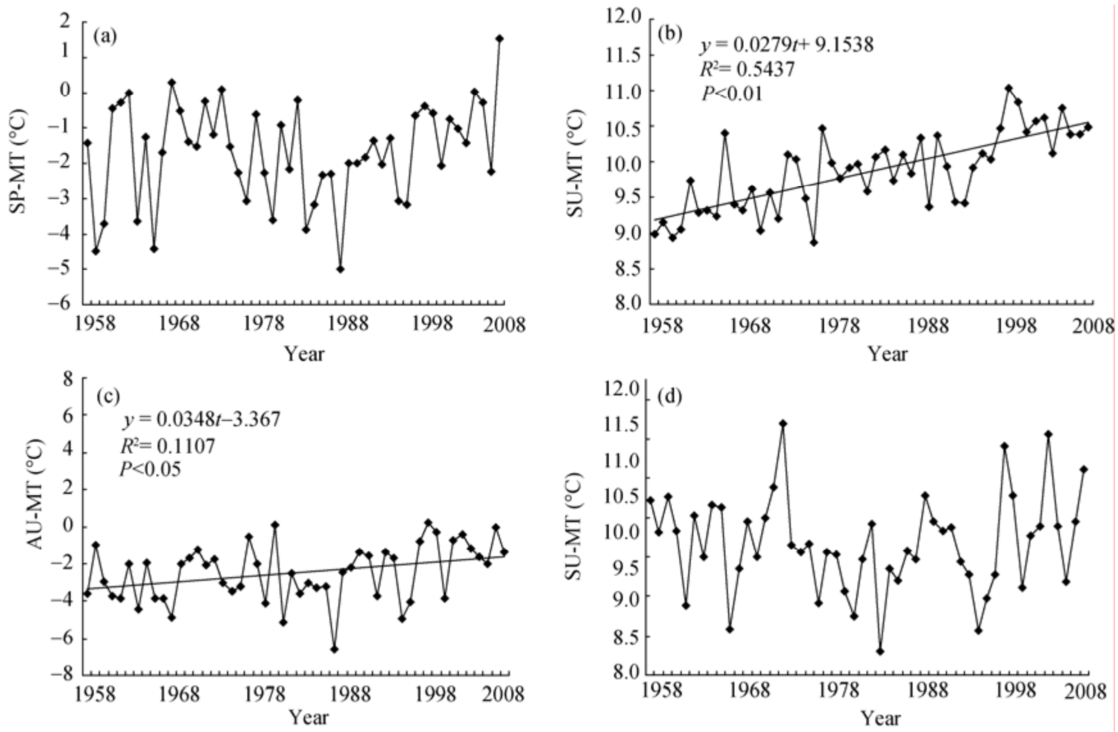

Fig. 4 The trend analyses of the spring mean temperature (SP-MT), the summer mean temperature (SU-MT), the autumn mean temperature (AU-MT) and the winter mean temperature (WI-MT) time series during the period of 1958–2007 in the Kaidu River watershed

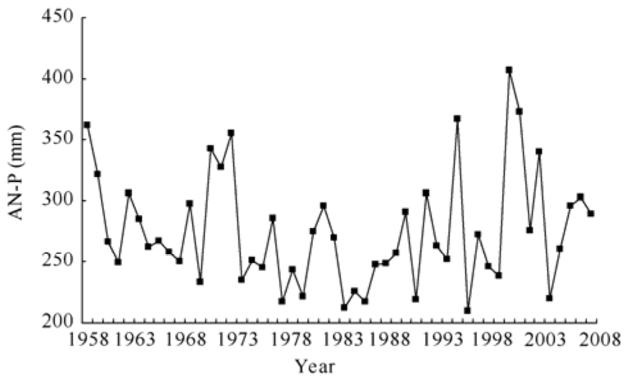

Fig. 5 The trend analysis of annual precipitation (AN-P) time series during the period of 1958–2007 in the Kaidu River watershed

4.1.3 The runoff depth (RD)

Runoff depth was calculated by dividing the runoff amount by the plot area. It is the depth (mm) of water distributed averagely into the surface of the basin. The varying trends of the annual runoff depth (AN-RD), the spring runoff depth (SP-RD), the summer runoff depth (SU-RD), the autumn runoff depth (AU-RD) and the winter runoff depth (WI-RD) time series were revealed by regression analysis (Figs. 7 and 8). The mean value of AN-RD was 183.63 mm and had a significant increase trend during the last 50 years, and the rate was 7.11mm/10a. The AN-RD values decreased from the late 1950s to the late 1960s, and then increased from the late 1960s to the early 1970s and dropped off from the mid 1970s to the early 1990s. The values of AN-RD increased rapidly with a maximum value in that year and declined after 2002. The mean values of SP-RD, SU-RD, AU-RD and WI-RD were 4.78 mm, 89.51 mm, 42.65 mm and 23.08 mm, respectively in the Kaidu River watershed. The annual runoff volume in the Kaidu River watershed concentrated in spring, summer and autumn. Only the WI-RD time series significantly increased ($P < 0.01$) with a rate of 1.85 mm/10a (Fig. 8).

4.2 The impacts of temperature and precipitation on runoff depth

4.2.1 The correlation analysis

Table 2 shows the Pearson correlation coefficients between the daily mean temperature (DMT), precipitation (DP) and runoff depth (DRD) in the Kaidu River watershed. The correlation coefficient between the annual DMT (AN-DMD) and the annual DMT (AN-DRD) and that between the annual DP (AN-DP) and the annual DRD (AN-DRD) are significant with

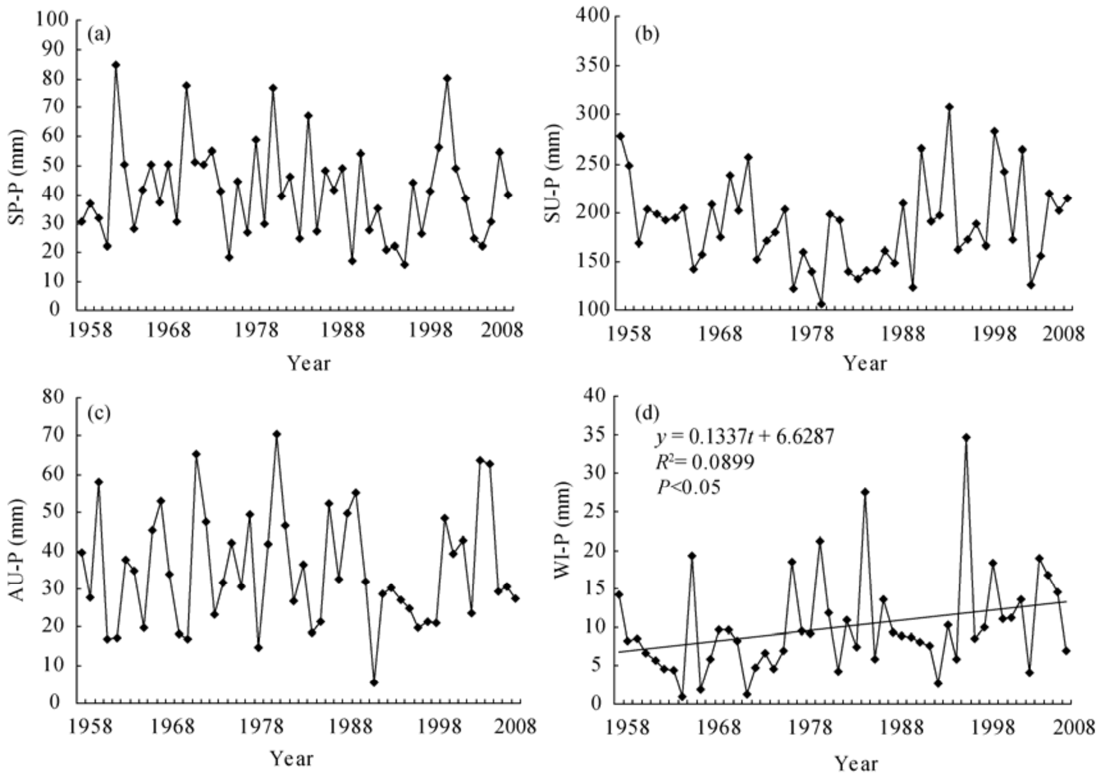

Fig. 6 The trend analyses of the spring precipitation (SP-P), the summer precipitation (SU-P), the autumn precipitation (AU-P) and the winter precipitation (WI-P) time series during the period of 1958–2007 in the Kaidu River watershed

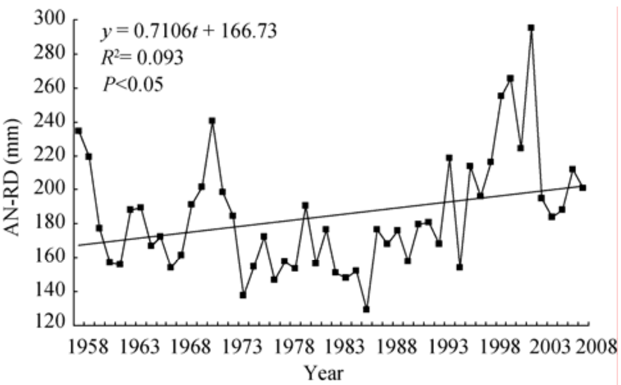

Fig. 7 The trend analysis of the annual runoff depth (AN-RD) time series during the period of 1958–2007 in the Kaidu River watershed

the values of 0.6710 ($P < 0.01$) and 0.3060 ($P < 0.01$), respectively. This indicates that the daily mean temperature and precipitation are the driving factors to the daily runoff in the Kaidu River watershed and the effect of daily mean temperature is larger than that of precipitation.

The correlation relationships between DMT and DRD and that between DP and DRD in four seasons are significant ($P < 0.01$). The correlation coefficient between SP-DMT and SP-DRD is 0.6270, which is larger than that between SP-DP and SP-DRD (0.1530). The daily mean air temperature was almost lower than 0°C in winter and went up to above 0°C in spring in which the snow/glacier-melt on the alpine began and contributes to the runoff. However, the precipitation in spring is not too high and some precipitation may take place as snowfall which might not directly contribute to runoff until the snowpack melts in the region. This explains why the contribution of temperature for runoff formation is much greater than that of precipitation in spring. In summer, the correlation coefficient between SU-DMT and SU-DRD is 0.0570, less than that between SU-DP and SU-DRD (0.1450) due to the large precipitation and strong evaporation. The correlation coefficient between DMT and DRD is larger than that between DP and DRD in both autumn and winter. This implies that the driving effect of the daily mean temperature is larger than that of the precipitation in the two seasons.

4.2.2 The path analysis

The assumption for path analysis is that a significant linear correlation relationship between cause variables and effect variables exists. The existence of significant

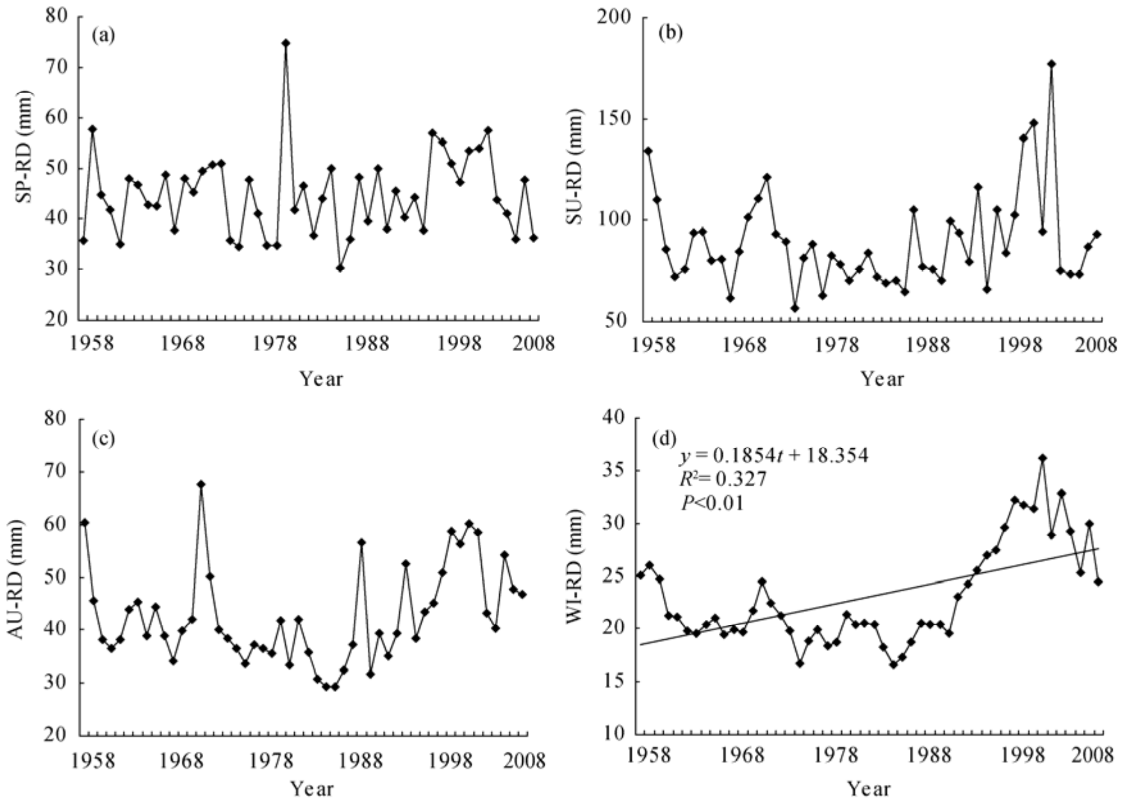

Fig. 8 The trend analysis of the spring runoff depth (SP-RD), the summer runoff depth (SU-RD), the autumn runoff depth (AU-RD) and winter runoff depth (WI-RD) time series during the period 1958–2007 in the Kaidu River watershed

linear correlation relationship between temperature, precipitation and runoff in annual and seasonal level ensures the implementation of the path analysis in the Kaidu River watershed. The path coefficient of $p_{(\mathrm{DRD,\,DP})}$ is quite small and not significant in winter (Table 3).

The path coefficients of $p_{(\mathrm{AN\text{-}DRD,\ AN\text{-}DMT})}$, $p_{(\mathrm{SP\text{-}DRD,\ SP\text{-}DMT})}$ and $p_{(\mathrm{AU\text{-}DRD,\ AU\text{-}DMT})}$ are higher than the values of $p_{(\mathrm{AN\text{-}DRD,\ AN\text{-}DP})}$, $p_{(\mathrm{SP\text{-}DRD,\ SP\text{-}DP})}$ and $p_{(\mathrm{AU\text{-}DRD,\ AU\text{-}DP})}$.

Table 2 The correlation relationship between the daily mean temperature (DMT), precipitation (DP) and runoff depth (DRD) in the Kaidu River watershed

Pearson correlation coefficients	AN-DRD	SP-DRD	SU-DRD	AU-DRD	WI-DRD
AN-DMT	0.6710**				
SP-DMT		0.6270**			
SU-DMT			0.0570**		
AU-DMT				0.6130**	
WI-DMT					0.1320**
AN-DP	0.3060**				
SP-DP		0.1530**			
SU-DP			0.1450**		
AU-DP				0.1910**	
WI-DP					0.0390**

Note: ** means that correlation is significant at 0.01 level.

Table 3 The path analysis between the daily mean temperature (DMT), precipitation (DP) and runoff depth (DRD) in the Kaidu River watershed

Period	Path coefficient		R^2
	$P_{(\mathrm{DRD,\ DMT})}$	$P_{(\mathrm{DRD,\ DP})}$	
Annual	0.6343**	0.1652**	0.3840**
Spring	0.6178**	0.0634**	0.3971**
Summer	0.0982**	0.1690**	0.0301**
Autumn	0.5978**	0.0918**	0.3840**
Winter	0.1297**	0.0106	0.0175**

Note: ** means that correlation is significant at 0.01 level.

The results imply that the impact of temperature on runoff depth is more intensive than that of precipitation in annual, spring and autumn. In summer, the impact of temperature on runoff depth was less than that of precipitation. The reliability is 38.40% if using the multi-regression function between daily mean temperature, precipitation and runoff depth during the last 50 years to estimate daily runoff depth within a year. The significant correlation index (R^2=0.3971) shows that the multi-regression function between daily mean temperature, precipitation and runoff depth in spring and autumn could explain 39.71% and 38.40% of the total variance, respectively. The multi-regression function between daily mean temperature, precipitation and runoff depth in summer could only explain 3.01% of the total variance.

Table 4 shows the direct and indirect effects of meteorological variables (temperature and precipitation) on runoff depth. It could be seen that the direct effect of daily mean temperature on runoff depth is 0.6343, and the indirect effect of daily precipitation is 0.0367 within a year, which means that the total effect of daily mean temperature on runoff depth within a year reaches 0.7751. The direct effect of daily precipitation on runoff depth is 0.1652, and the indirect effect of that through temperature is 0.1408. Total effect of daily precipitation is 0.2019. The results from path analysis also proved that the impact of mean temperature on runoff generation is much greater than that of precipitation within a year.

Table 4 The analyses of direct and indirect effects of the daily mean temperature (DMT) and the precipitation (DP) on runoff depth in the Kaidu River watershed

Variables	CC	DE	IE		Total
			by DMT	by DP	
AN-DMT	0.6710	0.6343		0.0367	0.7751
AN-DP	0.3060	0.1652	0.1408		0.2019
SP-DMT	0.6270	0.6178		0.0092	0.7074
SP-DP	0.1530	0.0634	0.0896		0.0726
SU-DMT	0.0570	0.0982		−0.0412	0.0742
SU-DP	0.1450	0.1690	−0.0240		0.1278
AU-DMT	0.6130	0.5978		0.0152	0.6970
AU-DP	0.1910	0.0918	0.0992		0.1070
WI-DMT	0.1320	0.1297		0.0023	0.1576
WI-DP	0.0390	0.0106	0.0284		0.0129

Note: CC means correlation coefficient, DE direct effect, and IE indirect effect.

In spring and autumn, the total effects of the daily mean temperature on the runoff depth are 0.7074 and 0.6970, respectively, and that of the daily precipitation are 0.0726 and 0.1070, respectively. It means that the runoff generation was mainly impacted by temperature in spring and autumn. It is different in summer and the total effect of daily mean temperature on runoff depth is 0.0742 and that of daily precipitation is 0.1278. The impact of daily precipitation on runoff generation was greater than that of the daily mean temperature in summer. The result in winter was similar to that in spring, i.e., the runoff generation is mainly impacted by daily mean temperature. The effect of temperature and precipitation on runoff formation in winter was quite small compared with that in spring and autumn.

5 Conclusion

Runoff formation is a complex meteorological-hydrological process influenced by many factors. Based on the observed data of daily mean temperature, precipitation and runoff in the Kaidu River watershed, this paper analyzed the varing trend of air temperature, precipitation and runoff depth and revealed the relationship between these climate factors and runoff. The results showed that the annual, summer and autumn mean temperature significantly increased during the last 50 years. The increase rates are 0.26°C/10a, 0.28°C/10a and 0.35°C/10a, respectively. In the case of precipitation, only the winter precipitation time series increased significantly with an increase rate of 1.34 mm/10a. The significant increase trends of the annual and winter runoff depths during the last 50 years are presented with the increase rates of 7.11 mm/10a and 1.85 mm/10a, respectively.

Correlation analysis and path analysis reveal that the positive driving effects of both daily temperature and precipitation on daily runoff generation are significant both in annual and seasonal levels in the Kaidu River watershed. In annual, spring, autumn and winter, the effect of the daily mean temperature is much greater than that of the daily precipitation, but in summer, the effect of daily precipitation is greater than that of the daily mean temperature because of precipitation occurring as rainfall and higher evaporation from high temperature.

Except for the climatic factors, potential factors including topography, land cover and human activities also impact the process of runoff generation. Further research concentrating on the mechanism analysis of runoff generation in inland rivers originated from the Tianshan Mountains may help improving runoff prediction.

Acknowledgement

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