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Detecting runoff variation in Weihe River basin, China

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Abstract Dramatic changes in hydrological factors in the Weihe River basin are analysed. These changes have exacerbated ecological problems and caused severe water shortages for agriculture, industries and the human population in the region, but their drivers are uncertain. The Mann-Kendall test, accumulated departure analysis, sequential clustering and the sliding t-test methods were used to identify the causes of changes in precipitation and runoff in the Weihe basin. Change-points were identified in the precipitation and runoff records for all sub-catchments. For runoff, the change in trend was most pronounced during the 1990s, whereas changes in precipitation were more prominent earlier. The results indicate that human activities have had a greater impact than climate change on the hydrology of the Weihe basin. These findings have significant implications for the establishment of effective strategies to counter adverse effects of hydrological changes in the catchment.

Keywords Weihe River; runoff series; Mann-Kendall test; variation changes; attribution

1 INTRODUCTION

Global warming and the increasingly large-scale of human activities (IPCC, 2007) are causing major changes to hydrological cycles of river basins and affecting their physical conditions on a regional scale (Wei, 2007). For example, Barnett *et al.* (2008) and Szilagyi (2001) highlighted extensive changes to the hydrological cycles of western USA during the last half of the 20th century. In recent decades, hydrological studies have focused on runoff, in particular (Labat *et al.*, 2004; Liu and Xia, 2004; Fraiture, 2007; Hejazi and Moglen, 2007). In northern China, substantial reductions in runoff in recent decades have been observed (*inter alia*) in the Haihe River catchment (Yang and Tian, 2009), the Yellow River basin (Fu *et al.*, 2004) and the Sanggan River catchment (Zhang 2003). This is a serious concern in the semi-humid and semi-arid regions of the country as they are exacerbating major ecological problems and causing severe water shortages for agriculture, industries and the huge human population (Kling *et al.*, 2012). Thus there is a clear need to identify the causes in order to formulate effective mitigation strategies.

Runoff volumes in a catchment are known to be influenced by numerous factors, including climatic variables (particularly precipitation), human activities, subsurface drainage patterns and various other geographical and hydrological variables (Huang *et al*., 2003; Chen *et al.*, 2007; Zhang *et al.*., 2008; Kumar *et al.*, 2009). Changes in any of these variables can profoundly affect runoff, but the main factors driving runoff decline in most Chinese rivers basins are believed to be climate change and human activities (Yang and Tian, 2009, plus other references). Quantifying the impact of climate change on runoff is relatively straightforward, using either traditional regression methods (e.g. Fan *et al.*, 2007) or more complex hydrological models, such as SWAT (Soil and Water Assessment Tool; Yao *et al.*, 2008). In contrast, quantifying changes in runoff caused by human activity is more complex and they are not yet fully understood (Yang and Tian, 2009). However, several methods have been recently developed and applied to detect trends and changes in hydrological records (Wei, 2007; Xie, 2012) and facilitate attempts to identify the main drivers. These include the Mann-Kendall test (Sneyers, 1975; Sulkava *et al*., 2007; Zhao *et al.*, 2007; Zhang *et al*., 2008; Fan *et al.*, 2013), Rammer's method (Wei, 2007), the Yamamoto method (Tan *et al.*, 2008), the Pettitt test (Mu *et al.*, 2007), accumulated departure analysis (Zhang *et al.*, 2010), sequential cluster analysis (Yan *et al.*, 2003), and the sliding t-test (Yin *et al.*, 2009).

Although there have been numerous studies on hydrological changes, and several attempts to identify change-points in time series of hydrological data, few have focused on both precipitation and runoff, or attempted to identify the main factors driving the changes. Thus, this study analyses changes in precipitation and runoff, and the factors controlling them, in the Weihe River basin, China, where the water shortage problems mentioned above have increased in recent years. Key objectives are to identify change-points in precipitation and runoff series using four methods (the Mann-Kendall test, accumulated departure analysis, sequential cluster analysis and sliding t-test), and the main factors that caused the shifts at the identified change-points.

2 STUDY AREA AND DATA

2.1 Study area

The Weihe River rises in the Niaoshu hills, Gansu province, and flows into the Yellow River in Shaanxi province. Its basin is located in the semi-humid and semi-arid climate regions and comprises hills, loess terraces and alluvial, mountainous and plateau areas. The basin covers 0.135×10^6 km^2 (103º39′–110º37′E to 33º42′–34º14′N; Fig. 1) and is divided between three provinces: Shaanxi (49.8% of the catchment area), Gansu (44.1%) and Ningxia (6.1%).

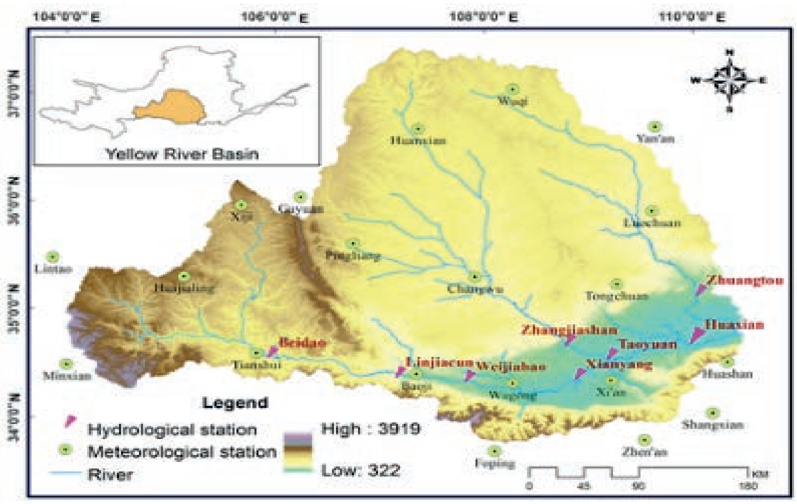


Fig. 1. Map of the Weihe River Basin and its location within the Yellow River basin (insert).

2.2 Data

Meteorological and runoff data were collected from 18 precipitation stations and 8 hydrological stations in the Weihe River basin (Fig. 1). Measured variables included areal precipitation and areal potential evaporation and runoff (Fig. 2).

Annual runoff data for January 1960 to December 2010 were provided by six hydrological stations in the mainstream (Beidao, Linjiacun, Weijiapu, Xianyang, Lingtong and Huaxian) of Weihe River. The monthly precipitation data for this period were obtained from the Chinese Meteorological Data Sharing System. Total annual surface precipitation and potential evaporation values (Fig. 2) were calculated from the area-weighted precipitation data collected at the 18 meteorological stations using the Tessellation Polygon Analysis methods.

Area-average precipitation ranged from 366 to 807 mm/year (mean 494.6 mm/year), potential evaporation from 720 to 935 mm/year (Fig. 2). Mean annual runoff was 7.28×10^6 m³, with a maximum of 208×10^6 m³ recorded in 1964 and a minimum of 21.00×10^6 m³ recorded in 1995.

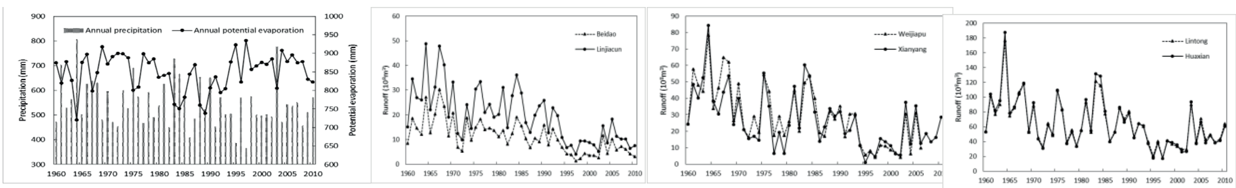


Fig. 2 Area annual precipitation (mm), area potential evaporation (mm), annual runoff (10^8 m³) in the Weihe River.

3 METHODS

3.1 Variation points analysis methods

Four methods are used to analyse the variation points; each method has different attributes.

The sequential Mann-Kendall test (Mann, 1945; Sneyers, 1975) was used to detect variation changes in precipitation recorded at the 18 hydrological stations listed in Table 1 and in runoff (annual, seasonal and monthly) from 1919 to 2011 at the Huaxian hydrological station. The Mann-Kendall test is used to detect trends in time series. The null hypothesis is that the data are independent and randomly distributed, i.e. there is no trend in the dataset. The alternative hypothesis is that there is a monotonic trend in the dataset. Accumulated departure analysis is a commonly applied method that allows for intuitive evaluation of trends in time series. Sequential cluster analysis is a method that clusters observations, while preserving their order. To identify the most likely change-point, τ, an appropriate threshold value is required. The threshold value is optimized by minimizing the sum of quadratic dissimilarity within clusters, while maximizing between-cluster dissimilarity. A shortcoming of this method is that the outcome of the analysis is affected by the sequence endpoints. The moving t-test (MTT) detects climate jumps in a series by assessing the significant differences between averages of two groups of samples. This method has been widely used in China to detect climate jump events.

3.2 Slope change ratio of cumulative quantity (SCRCQ)

The difference in curve slope before and after a change-point can be used to calculate contributions of selected factors to the change. If the curve slopes for cumulative precipitation *versus* time before and after the variation points are S_{Pa} and S_{Pb}, respectively, and the curve slopes for cumulative runoff *versus* time before and after the change-point are S_{Ra} and S_{Rb}, respectively, then the contribution rate from precipitation to runoff, C_P (%), after the variation point can be expressed as a percentage of the contribution rate before the change-point:

$$C_P = 100 \times \left(\left| S_{Pa} - S_{Pb} \right| - 1 \right) / \left(\left| S_{Ra} - S_{Rb} \right| - 1 \right) \tag{1}$$

Similarly, the contribution rate from potential evaporation to runoff, C_{PE} (%), after the change-point compared to before the change-point can be expressed as:

$$C_{PE} = 100 \times \left(\left| S_{PEa} - S_{PEb} \right| - 1 \right) / \left(\left| S_{Ra} - S_{Rb} \right| - 1 \right) \tag{2}$$

where S_{PEa} and S_{PEa} are the cumulative potential evaporation *versus* time before and after the variation point.

Thus, the contribution rate from climate change to runoff after the variation point compared to that before the variation point (C_C, %) can be expressed as:

$$C_C = C_P + C_{PE} \tag{3}$$

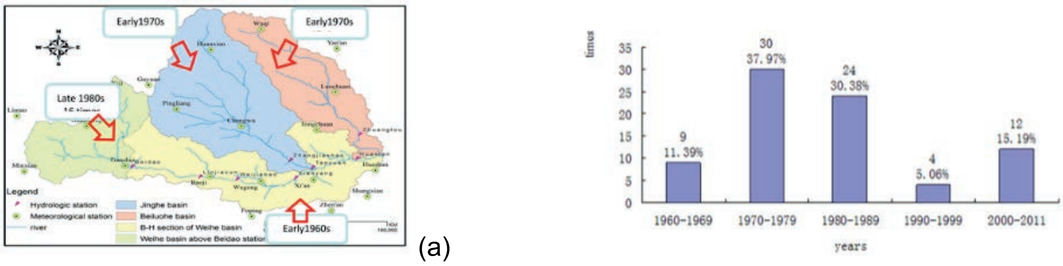
Based on the principle of water quantity balance, the contribution rate from human activities to runoff (C_H, %) can be expressed as:

$$C_H = 100 - C_P - C_{PE} \tag{4}$$

4 RESULTS AND DISCUSSION

4.1 Results of Mann-Kendall

Precipitation time series The Weihe River basin is divided into four sub-basins. The areas covered by the sub-basins and locations of hydrological and meteorological stations are shown in Fig. 3(a). The Mann-Kendall test was used to identify change-points in the annual precipitation series recorded at each station from 1960 to 2011. In total 79 variation points were identified in the Weihe River catchment, 30 of which occurred in the Beidao to Huaxian section of the mainstream. An analysis of the temporal distribution revealed that most change-points (54, nearly 70% of the total) occurred during the 1970s and 1980s (Fig. 3(a)). There was a clear, spatial element to the temporal variation in hydrological change, with most change-points occurring earlier in the southwestern parts and later in the northwestern parts (Fig. 3(b)). There was also a gradual delay in the change-points moving from downstream to upstream.



(a) (b)

Fig. 3 (a) Time periods change in each sub-basin. (b) Temporal distribution in precipitation records.

Runoff time series The Mann-Kendall test was also used to detect variation points in the runoff records from seven stations along the mainstream Weihe River. Five change-points were found, of which two occurred during the 1980s and three during the 1990s (Table 1). The higher number of change-points in the 1990s suggests that the runoff changes were more dramatic during this decade than during the previous decades.

4.2 Results of accumulated departure analysis

Accumulated departure analysis was used to identify change-points in runoff data from each section of the mainstream Weihe River. In total, 11 variation points were identified (Table 2). There was substantial temporal variation in the numbers of these events, with 18% occurring in the 1960s, 27% in the 1970s, 27% in the 1980s and 37% in the 1990s.

4.3 Results of sequential cluster analysis

Sequential cluster analysis was also used to detect change-points in the runoff data from each section of the mainstream Weihe River. In total 17 change-points were identified, with the 1990s having the highest number of events (6) of any decade (Table 3). Thus, changes in runoff were most pronounced during the 1990s.

4.4 Sliding T test results

The analysis of runoff data by the sliding t-test identified 17 variation points: four in the 1960s, three in the 1970s, one in the 1980s, five in the 1990s and four in the 2000s (Table 4). The results confirm that the 1990s was a period of major changes in runoff.

4.5 Variation results

Table 5 shows the percentage of runoff variation changes in each decade; the changes in runoff over five decades were analysed using four methods. Each method clearly indicates that hydrological changes in the Weihe River basin occurred most frequently in the 1990s.

4.6 Attribution

SCRCQ analysis indicated that climate change contributed substantially less strongly than human activities to the shifts in runoff during the 1990s (32.9% and 67.1%, respectively). The contributions from precipitation and potential evaporation were 29.8% and 3.1%, respectively. In the 2000s, the influence of human activities further increased, resulting in an 81.1% contribution, while the contribution from climate change declined to 18.9%, mainly due to a decrease in the contribution of precipitation to 12%. During the same period, the contribution from potential evaporation increased slightly to 6.95%.

Table 1 Mann-Kendall test results.

Station	Variation points
Linjiacun	-
Weijiapu	-
Xianyang	1985
Lintong	1989
Huaxian	1990
Zhangjiashan	1997
Zhuangtou	1993

Table 2 Accumulated departure analysis results.

Section	Variation points	
Above Beidao	1986	-
Beidao-Linjiacun	1969	1993
Linjiacun-Xianyang	1971	1993
Xianyang-Lintong	1969	1990
Lintong-Huaxian	1970	1986
The entire basin	1970	1993

Table 3 Sequential cluster analysis results.

Section	Variation points		
Above Beidao	1970	1985	1993
Beidao-Linjiacun	1968	1990	1993
Linjiacun-Xianyang	1968	1985	1993
Xianyang-Lintong	1968	1990	-
Lintong-Huaxian	1966	1985	1988
The entire basin	1968	1985	1990

Table 4 Sliding t-test results.

Section	Variation points		
Above Beidao	1970	1994	2002
Beidao-Linjiacun	1968	1974	1994
Linjiacun-Xianyang	1968	1994	2002
Xianyang-Lintong	1968	1992	2002
Lintong-Huaxian	1970	1988	-
The entire basin	1968	1993	2002

Table 5 Variation changes in runoff (%) over five decades detected using four analytical methods

Method	1960s	1970s	1980s	1990s	2000s
Mann-Kendall test			40%	60%	
Accumulated departure analysis	18%	27%	18%	36%	
Sequential cluster analysis	29%	6%	29%	35%	
Sliding t-test	24%	18%	6%	29%	24%

Table 6 Contributions to runoff and slope change ratio of cumulative quantity (SCRCQ) results for the time periods before, during and after shifts in the hydrological regime.

Period	S_R	S_{PE}	S_P	C_{PE}	C_P	C_H	C_C
1960–1989	63.88	849.22	566.99				
1990–1999	34.506	861.33	489.24	3.10%	29.82%	67.08%	32.92%
2000–2010	41.652	869.75	543.4	6.95%	11.96%	81.10%	18.90%

Note: S_R, S_{PE}, S_P are the curve slopes of cumulative runoff, potential evaporation and precipitation versus time; C_{PE}, C_P, C_H, C_C are the contribution rates from potential evaporation, precipitation, human activities and climate change to runoff.

The result of calculating the rainfall and streamflow values in the two periods (divided by 1990) is shown in Table 7. At Huaxian station, rainfall had slightly increased, 3%, while the runoff had a significantly fall, 32.3%, confirming the substantial divergence between changes in precipitation and runoff before and after 1990.

Total annual consumption increased by 56% from 2.793 billion m^3 (2383 × 10^6 m^3 of surface water, and 410 × 10^6 m^3 of groundwater) before 1990s, to 4.263 billion m^3 (2.05 billion m^3 of surface water and 2.213 billion m^3 of groundwater) after 1990s. Soil and Water Conservation in Weihe River Basin with an increase of 184 million m^3, the average annual runoff from 116 × 10^6 m^3 (before 1990s) to 300 × 10^6 m^3 (after 1990s).

Table 7 Changes in mean precipitation (mm) and runoff (108m³) from 1956–1989 to 1990–2011.

Period	Mean precipitation	Mean change	Percent change	Mean runoff	Specific value (10^8 m^3)	Migration rate
1956–1989	506.02			69.04		
1990–2011	521.11	15.10	3.0%	46.73	−22.31	−32.3%

5 CONCLUSIONS

Variation points were identified in the precipitation and runoff records for all Weihe River sub-catchments, using the Mann-Kendall test, accumulated departure analysis, sequential cluster analysis and sliding t-test. For runoff, the change in trend was most pronounced during the 1990s, whereas changes in precipitation were more noticeable earlier in the time series. Human activities were shown to be the main driving force behind these changes. Our findings are in agreement with those of previous studies (e.g. Gao, *et al*., 2002; Yao *et al*., 2003; Cui and Cui, 2007) and suggest that human activities have had a greater impact than climate change on the hydrology of the Weihe River basin. Given the changing environment, further work on runoff variation for hydrographic computation in engineering is necessary.

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