Using runoff slope-break to determine dominate factors of runoff decline in Hutuo River Basin, North China

Fei Tian, Yonghui Yang and Shumin Han

ABSTRACT

Water resources in North China have declined sharply in recent years. Low runoff (especially in the mountain areas) has been identified as the main factor. Hutuo River Basin (HRB), a typical up-stream basin in North China with two subcatchments (Ye and Hutuo River Catchments), was investigated in this study. Mann-Kendall test was used to determine the general trend of precipitation and runoff for 1960–1999. Then Sequential Mann-Kendall test was used to establish runoff slope-break from which the beginning point of sharp decline in runoff was determined. Finally, regression analysis was done to illustrate runoff decline via comparison of precipitation-runoff correlation for the period prior to and after sharp runoff decline. This was further verified by analysis of rainy season peak runoff flows. The results are as follows: (1) annual runoff decline in the basin is significant while that of precipitation is insignificant at \( \alpha = 0.05 \) confidence level; (2) sharp decline in runoff in Ye River Catchment (YRC) occurred in 1968 while that in Hutuo River Catchment (HRC) occurred in 1978; (3) based on the regression analysis, human activity has the highest impact on runoff decline in the basin. As runoff slope-breaks in both Catchments strongly coincided with increase in agricultural activity, agricultural water use is considered the dominate factor of runoff decline in the study area.

Key words | Hutuo River Basin, Mann-Kendall test, North China, precipitation, runoff, sequential Mann-Kendall test

INTRODUCTION

Climate and land use change coupled with human water diversion have been identified as the most important factors of declining runoff and global water systems (Vorosmarty et al. 2000). Identification of major driving factors of runoff and their degree of impact on runoff change are critical for hydrological studies (Fraiture 2007; Hejazi & Moglen 2007).

Hutuo River Basin (HRB), a typical mountain basin in North China, is experiencing sharp declines in available water resources (Cui & Cui 2007; Fan et al. 2007; Yang 2007). Statistical data show that runoff declined by 71.80% in the 1980s and 62%, in the 1990s. Such declines have greatly limited runoff into Huangbizhuang (with 1.57 billion m³ storage capacity) and Gangnan (with 1.21 billion m³ storage capacity) reservoirs. These reservoirs are the main water supply for urban and industrial consumption in Shijiazhuang (a city with a population of 2.2 million). Also due to groundwater abstraction and decreasing recharge potential, groundwater levels have dropped steadily at its downstream (Yang et al. 2002). In an effort to address the deteriorating water situation in the region, a massive water transfer project (the South-to-North Water Transfer Project) has been undertaken. Upon implementation, it is estimated to deliver 0.73 billion m³ of water to Shijiazhuang, easing dependence of agriculture on groundwater (Li et al. 2007b). Hence understanding the processes and causes of runoff decline is critical for long-term water resources management in the region.

doi: 10.2166/wst.2009.578
To that end, a number of research studies have been conducted in the basin. Most of the studies have identified human activity as the main driving factor of runoff decline (Cao et al. 2000; Cui & Cui 2007; Fan et al. 2007; Yang 2007). Indeed, under the huge population pressure, tremendous human activity has occurred in the last 60 years. For instance, large reservoir operations (including Huangbzhhuang and Gangnan reservoir) started in the early 1960s (Shi 1995). Following the 1963 storm, intensive terracing was undertaken for flood control and soil conservation in Hutuo River Basin (HRB) (Miao 2001). The effect of such human activities is especially strong as they are concentrated in the mountain regions of the river basins. In 1978, a nation-wide land reform was enacted. The reform gave responsibility of reallocated lands to farmers. Though this led to increased land productivity, it also increased agricultural water utilization (Xu 2008). It is, however, yet unclear which human activity has the most impact on runoff decline in the region.

Slope-break analysis is a valuable means of detecting the occurrence of hydro-climate change and determining the dominant factors causing the change (Gerstengarbe & Werner 1999). Zhao et al. (2007) detected sharp changes in climate in the upper Yellow River Basin towards the end of the ‘80s. While Mann-Kendall test is a standard method for determining the general trend of hydro-climatic events (Douglas et al. 2000; Aziz & Burn 2006; Partal & Kahya 2006; Yue & Hashino 2007), Sequential Mann-Kendall test (Sneyers 1975) is useful in determining the period with sharp changes in hydro-climatic events (Zhang et al. 2006; Li et al. 2007a). It then follows that if the starting point of a hydro-climate event can be accurately determined, the dominate factors causing such changes can be isolated. Thus the Mann-Kendall (Mann 1945; Kendall 1975) and Sequential Mann-Kendall (Sneyers 1975) tests were used to establish non-linear trends and the period of sharp change in runoff. Attempts were also made to isolate dominate human activities behind that sharp runoff decline in Hutuo River Basin.

**STUDY AREA**

Hutuo River Basin (HRB) comprises of two catchments—Hutuo River Catchment (HRC) and Ye River Catchment (YRC). The river Hutuo originates in Shanxi Province and flows across Hebei Province before joining Haihe River in North China. Each of the two subcatchments of HRB covers an approximate area of 6,420 km² (YRC) and 15,580 km² (HRC). The study area lies between longitudes 112.14–114.37°E and latitudes 37.21–39.47°N, within an elevation of 127–3,059 m above mean sea level (Figure 1).

The climate of the study area is semi-arid with cold-dry winter and hot-rainy summer. Annual precipitation is very variable in space and time, with a long-term annual average of 525 mm. 70%–80% of the rainfall occurring in the rainy-summer months of July to September. Loess and brown earth are the dominant soil types. The parent rock predominantly consists of gneiss, then shale and limestone. Main land use types are woodland, grassland and farmland. Woodland is mainly deciduous broad-leaved (e.g. Robinia pseudoacacia, species of Quercus family) and coniferous (e.g. Pinus tabulaeformis, Platycladus orientalis) forests, shrubs (e.g. Vitex negundo and Zizyphus jujuba) and herbs (e.g. Themed japonica and Bothriochloa ischaemum). Winter-wheat and summer-maize are the main crops (cultivated in a continuous crop rotation system) in the area.

![Figure 1](https://iwaponline.com/wst/article-pdf/60/8/2135/447636/2135.pdf)
MATERIALS AND METHODS

Data

Daily meteorological data from 5 national standard stations (three in YRC and two in HRC) were obtained from China Meteorological Administration (CMA) for the period spanning from 1 January 1960 to 31 December 1999. Daily precipitation data (from three stations inside YRC) were averaged to get monthly and annual precipitation for YRC. For HRC, monthly and annual precipitation was obtained by averaging precipitation data from two (Pingshan and Yangquan) stations inside the catchment (Figure 1).

Daily runoff for 1960–1999 was also collected from the main outlets of YRC at Weishui gauge station and HRC at Xiaojue gauge station. Runoff was monitored in rectangular weirs designed by ISO (International Standards Organization) for liquid flow measurement in open river systems.

Land use/land cover data are obtained from Chinese Natural Resources Database (CNRD) for the 1980s and 1990s. To simply the analysis, land use was grouped into grassland, forest and farmland. The composition of the different land use classes is given in Table 1.

In addition, a 90 m x 90 m DEM (Digital Elevation Model) obtained from NASA (National Aeronautics and Space Administration) was used to generate slope, drainage network, and catchment boundary.

Mann-Kendall test

Non-parametric Mann-Kendall test was used to determine the trends of the hydro-climate variables of runoff and precipitation. This technique is widely used in testing for randomness in hydro-climate time-series (Zhu & Day 2005; Novotny & Stefan 2007). In non-parametric Mann-Kendall test, the null hypothesis $H_0$ of deseasonalized data $(x_1, \ldots, x_n)$ is a sample of $n$ independent and identically distributed random variables. The alternative two-sided test hypothesis $H_1$ states that $x_k$ and $x_j$ are not identical when $k$ and $j \leq n$ ($k \neq j$). The test statistic $S$, with zero mean and computed variance from Equation (3), is asymptotically normal and is calculated by Equations (1) and (2) (Hirsch & Slack 1984) as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k)$$

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases}$$

$$\text{var}(S) = [n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)/18]$$

The notation $t$ is the extent of any given tie and $\sum_t$ is the summation over all ties. In the case where the sample size $n > 10$, the standard normal variate $Z$ is computed in Equation (4) (Douglas et al. 2000) as:

$$Z = \begin{cases} \frac{S}{\sqrt{\text{var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S}{\sqrt{\text{var}(S)}} & \text{if } S < 0 \end{cases}$$

Thus in two-sided trend tests, $H_0$ is accepted if $|Z| \leq Z_{\alpha/2}$ at $\alpha$ level of significance. Positive $S$ indicates ‘upward trend’ while negative $S$ indicates ‘downward trend’.

Sequential Mann-Kendall test

The sequential Mann-Kendall test (Sneyers 1975) is used to test an assumption about the beginning of the development of a trend within a sample $(x_1, \ldots, x_n)$ of random variable $x$ based on rank series of progressive and retrograde rows of the sample. The magnitudes of the annual mean time-series
\( x_j \) \((j = 1, \ldots, n)\) are compared with \( x_k \) \((k = 1, \ldots, j - 1)\). At each point, the number of cases \( x_k < x_j \) is counted and denoted as \( n_j \). The test statistic

\[
t_j = \sum_{i}^{j} n_j \quad (j = 2, 3, \ldots, n)
\]

is normally distributed, with mean and variance respectively given as

\[
E(t) = \frac{n(n - 1)}{4}
\]

and

\[
\text{Var}(t_j) = \frac{[j(j - 1)(2j + 5)]}{72}
\]

The sequential values of the statistic \( U(t) \) are calculated as

\[
U(t) = \frac{t_j - E(t)}{\sqrt{\text{Var}(t_j)}}
\]

which is the forward sequence, and the backward sequence \( U'(t) \) is calculated using the same equation but in the inverse series of data.

In two-sided trend tests, the null hypothesis is accepted at \( \alpha \) significance level if \( |U(t)| \leq U(t)_{1-\alpha/2} \), where \( U(t)_{1-\alpha/2} \) is the critical value of standard normal distribution with probability exceeding \( \alpha/2 \). Positive \( U(t) \) denotes positive trend and negative \( U(t) \) denotes negative trend. In this study, \( \alpha \) was set at 0.05. The sequential version test enables detection of the approximate time of occurrence of a trend by locating the intersection point of the forward and backward curves of the test statistic. If the intersection point is significant at \( \alpha = 0.05 \), we infer that the critical point of the analyzed time-series occurs at that time (Moraes et al. 1998; Gerstengarbe & Werner 1999). Hence Sequential Mann-Kendall test is considered an effective way of locating the beginning point of a trend.

**Driving factor assessment**

The impact of human activity and climate change on runoff in the study area was assessed using regression analysis. Based on the Sequential Mann-Kendall test, runoff data for each catchment was divided into two sets—‘natural period’ and ‘post-natural period’. Runoff-precipitation correlation comparisons for both the natural and post-natural periods give an indication of the effect of human activity on runoff. This is because under similar precipitation, the comparison reflects the extent to which runoff is influenced by human activity.

Furthermore, change in runoff in the two catchments was compared for the rainy season. The assumption is that augmentation of human water use is facilitated by peak flow harvest in post-natural period. The stronger the human activity, the faster is peak flow decline in the catchment.

**RESULTS**

**Annual precipitation and runoff**

Time-series (1960–1999) of annual precipitation and runoff for YRC and HRC are illustrated in Figure 2. As observed in the figure, annual precipitation is relatively stable with minimal decline. Annual runoff, on the other hand, has experienced drastic decline in especially YRC. Furthermore, runoff increases with increase in precipitation and vice versa. However, the rate of change of precipitation is not necessarily equal to that of runoff.

In YRC (Table 2), for instance, while precipitation dropped by 11.5%, 24% and 16.7% from the 60s to ‘70s, ‘80s and ‘90s, runoff respectively dropped by 54.7%, 80.3% and 71.8%. Also compared with the 70s, precipitation only dropped by 14.1% while runoff dropped by 56.4% in the 80s; three times higher than precipitation decline. Table 1 shows some increase in runoff in the 1990s. With precipitation rise by 9.6% from the 80s to ‘90s, runoff also rose by 42.9%. However, increase in runoff was due largely to the extensive 1996 flooding (the second wettest years in the last half-century). During the flood, a peak flow of \( 1.3 \times 10^4 \) m\(^3\)/s was recorded. In fact annual runoff for 1996 is at least six times higher than that for normal years.

In HRC, runoff also experienced a sharp decline. However, it is not as strong as that for YRC. For instance, precipitation declined by 8.4%, 13.7% and 21.3% from 60s to ‘70s, ‘80s and ‘90s while runoff disproportionally dropped...
by 26.2%, 50.2%, and 62% over the same period. From the 70s to the 90s, 14.1% decline in precipitation resulted in 48.4% runoff decline. Also from the 80s to 90s (which is a decade later), 8.8% decline in precipitation led to 22.6% decline in runoff. It is then evident that runoff decline between the 70s and 80s is stronger. When precipitation dropped by only 5.9%, runoff dropped by 32.5%.

Mann-Kendall test for precipitation

Annual precipitation is declining in both catchments, though statistically insignificant at 0.05 significant level. However, while Mann-Kendall Z-value (−1.81) for HRC is barely significant at 0.05 significance level (−1.96), that for YRC (−1.27) is far below the 0.05 significance level.

Mann-Kendall test for runoff

There is significant downward trend in annual runoff for YRC with Z = −5.09. Though a significant downward

Table 2 | Comparison of precipitation and runoff for Ye and Hutuo River Catchments for the period 1960–1999

<table>
<thead>
<tr>
<th>Variable</th>
<th>Period</th>
<th>Appt</th>
<th>Arof</th>
<th>Period</th>
<th>Difference Value</th>
<th>Pvrof (%)</th>
<th>Difference Value</th>
<th>Pvppt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YRC</td>
<td>1960–1969</td>
<td>606</td>
<td>21.3</td>
<td>70s–60s</td>
<td>−11.7</td>
<td>−54.7</td>
<td>−69.7</td>
<td>−11.5</td>
</tr>
<tr>
<td></td>
<td>1970–1979</td>
<td>536.3</td>
<td>9.6</td>
<td>80s–60s</td>
<td>−17.1</td>
<td>−80.3</td>
<td>−145.1</td>
<td>−24</td>
</tr>
<tr>
<td></td>
<td>1980–1989</td>
<td>460.9</td>
<td>4.2</td>
<td>80s–70s</td>
<td>−5.4</td>
<td>−36.4</td>
<td>−75.4</td>
<td>−14.1</td>
</tr>
<tr>
<td></td>
<td>1990–1999</td>
<td>504.9</td>
<td>6.0</td>
<td>90s–60s</td>
<td>−15.3</td>
<td>−71.8</td>
<td>−101.1</td>
<td>−16.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−</td>
<td>−</td>
<td>90s–70s</td>
<td>−3.6</td>
<td>−37.8</td>
<td>−31.4</td>
<td>−5.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−</td>
<td>−</td>
<td>90s–80s</td>
<td>1.8</td>
<td>42.9</td>
<td>44.0</td>
<td>9.6</td>
</tr>
<tr>
<td>HRC</td>
<td>1960–1969</td>
<td>643.6</td>
<td>30.9</td>
<td>70s–60s</td>
<td>−8.1</td>
<td>−26.2</td>
<td>−53.9</td>
<td>−8.4</td>
</tr>
<tr>
<td></td>
<td>1970–1979</td>
<td>589.8</td>
<td>22.8</td>
<td>80s–60s</td>
<td>−15.5</td>
<td>−50.2</td>
<td>−88.4</td>
<td>−13.7</td>
</tr>
<tr>
<td></td>
<td>1980–1989</td>
<td>555.3</td>
<td>15.4</td>
<td>80s–70s</td>
<td>−7.4</td>
<td>−32.5</td>
<td>−34.5</td>
<td>−5.9</td>
</tr>
<tr>
<td></td>
<td>1990–1999</td>
<td>506.5</td>
<td>11.8</td>
<td>90s–60s</td>
<td>−19.1</td>
<td>−62.0</td>
<td>−137.2</td>
<td>−21.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−</td>
<td>−</td>
<td>90s–70s</td>
<td>−11.0</td>
<td>−48.4</td>
<td>−83.3</td>
<td>−14.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−</td>
<td>−</td>
<td>90s–80s</td>
<td>−3.6</td>
<td>−22.6</td>
<td>−48.8</td>
<td>−8.8</td>
</tr>
</tbody>
</table>

Appt = annual precipitation (mm), Arof = annual runoff (m³/s), Pvrof = percent difference in runoff for given periods, Pvppt = percent difference in precipitation between given periods.

Note: negative values denote runoff or precipitation decline.
trend ($Z$-value of −3.67) is also noted for HRC, the trend is not as strong as that for YRC.

On the monthly scale, there is a downward trend in runoff for both catchments (Figure 4). In YRC, runoff decline is significant for all the months of the year, with the weakest and strongest $Z$-values of −3.06 and −6.33 respectively. In HRC, on the other hand, the monthly runoff decline is significant; except for May and June with respective $Z$-values of −1.08 and −1.55. This explains the increasing trend of surface water dry-up or zero-runoff at the gauge stations in both catchments in the last four decades.

**Sequential Mann-Kendall test for runoff**

Figure 5 vividly shows the results of forward/backward application of Sequential Mann-Kendall test for YRC and HRC. There is a drastic decline in runoff in both catchments, and especially in YRC. The intersection point of the forward and backward curves indicate the starting time (which is 1968) of sharp runoff decline in YRC. The decline became significant by 1974 and the trend accelerated since 1978. In HRC, runoff decline started in 1970 and it got drastic in 1978. By 1984, the trend of runoff decline has become significant.

**Human impact assessment**

Based on the results for Sequential Mann-Kendall test, runoff was divided into two periods (‘natural period’ and ‘post-natural period’). For YRC, the natural period is defined as the period from 1960 to 1967, while the post-natural period is from 1968 to 1999. Similarly for HRC, the natural period spans from 1960 to 1977 and the post-natural period spans from 1978 to 1999. Figure 6 shows the comparisons of the precipitation-runoff correlations for the two periods. In both catchments, a stronger correlation is noted for the natural period than the post-natural period. The regression line for natural period also lies above that for the post-natural period. This implies that under similar
precipitation, runoff under the post-natural period is much weaker. It is therefore reasonable to state that human activity, rather than climate or precipitation change, is the main driving factor of runoff decline in the basin.

To quantify the impact of human activity on runoff in both catchments, rainy season (July-Sept) runoff was analyzed for the period 1960–1999 and the result plotted in Figure 7. At Z-value of $-1.74$ (YRC) and $-1.58$ (HRC), there is no observable significant downward trend in precipitation. On the other hand, there is a significant decline in runoff at Z-value of $-3.76$ for YRC. A significant downward runoff tendency is also noted for HRC at Z-value of $-2.11$. The trend of runoff decline in HRC is not as strong as in YRC, indicating that human activity in HRC may not be as strong as in YRC.

In YRC, flow has significantly dropped since 1968, and nearly ceased in dry years during the 80s and 90s (Figure 7). Decline in peak runoff is much less in HRC, than in YRC. For instance, runoff decline in the 1970s is not so severe. In the 1980s or since 1978, this is obvious decline in runoff for dry years. The change in runoff is therefore best explained by human activity.

**DISCUSSION AND CONCLUSIONS**

**Human impact on runoff**

Based on our analysis, runoff has been declining in HRB, consistent with other research findings in the basin (Cao et al. 2000; Fan et al. 2007). While no significant decline in annual precipitation is noted in both catchments from Mann-Kendall test, runoff has declined significantly at an average Z-value of $-5.09$ (YRC), and $-3.67$ (HRC). Runoff increases with increase in precipitation and vice versa. However, the rate of precipitation decline is far less than runoff. For instance, precipitation decline in YRC and HRC form the 60s to 90s, is only 16.70% and 21.3% while that of runoff is 71.8% and 62% respectively.

Further analysis suggests that runoff decline is mainly driven by human activity. Regression analysis for the natural and post-natural periods points to human activity, rather than climate change, as the most dominant factor of runoff decline in the basin. For similar precipitation, lower runoff is noticeable from the regression lines under the post-natural period (Figure 6). Furthermore, rainy season runoff...
is artificially kept low. This is especially the case for YRC where rainy season runoff for the dry years is very weak in the 70s and nearly non-existent in the 80s and 90s. Though rainy season runoff decline is weaker in HRC, the trend is generally very similar to that for YRC. It is therefore reasonable to conclude that human activity is the dominant driving factor of runoff decline in the study area. Several other runoff studies in HRC (Cui & Cui 2007; Yang 2007) and in nearby regions have come to the same conclusion (Gao et al. 2002; Ren et al. 2002; Yao et al. 2003).

**Dominant factor and sharp runoff decline**

Abrupt changes in time-series events could give an indication of the dominant drivers of such changes (Gerstengarbe & Werner 1999). By selecting two catchments of HRB, we investigated the occurrence of abrupt runoff decline and the time the decline became statistically significant. Results show that in YRC, sharp declines in runoff started in 1968 and became significant in 1974. Regarding HRC, sharp declines in runoff started in 1978 and became significant in 1984. While it is generally known that human activity is a major driving factor of runoff change in most basins, sharp runoff declines occurring at different periods may give an indication of the dominate factors causing the change in periods.

Different forms of human activity occurred in the study area at different points in time. The earliest forms of human activity that seriously influenced natural runoff started in 1958. In 1956–1965, a number of reservoirs including Guozhuang reservoir, Shiban reservoir, and Xiaguan reservoir were constructed at the headwater areas of the measurement gauge stations (Shi 1995). The second stage commenced in 1964, soon after the catastrophic 1963 flooding. During the time, terraces were constructed to conserve soils and water resources and to augment agricultural production. In 1964, ‘Dazhai’ montane transformation style was overwhelmingly encouraged by the Chinese government (Miao 2001). Dazhai village, the central of the transformation, is located in YRC. By construction of terraces and hydro-projects for agricultural irrigation, grain yield doubled from 1966 to 1969 in Xiyang county—the county where Dazhai is located (Zhang & Li 2007). The increase in grain yield was triggered mainly by intensive agricultural irrigation. In the other county of Pingding (YRC), percent irrigated area increased by 270% from 1962 to 1977, resulting in 230.2% increase in grain production from 43 million kg to 142 million kg (Wang et al. 2004). For the same basin, Jin et al. (1993) ascribed the increase in grain yield to both intensive and extensive farmland irrigation. Then in 1978, China’s land reform policy was enacted. It gave farmers full management responsibilities of reallocated communal lands. The land reform greatly motivated farmers to augment agricultural production (Xu 2008).

Our analysis shows that abrupt runoff decline in the catchments of HRB coincided with the two reforms mentioned above; i.e. the ‘Dazhai’ land transformation and then China’s land reform policy. Because YRC is the central location of ‘Dazhai’, it is undoubtedly the most intensive human land transformation and agricultural development region. This is more evident when assessed under similar percent agricultural land (Table 1), where sharp declines in runoff started much earlier and became
significant in YRC than in HRC. In HRC, runoff decline is evident during the ‘Dazhai’ period; even though it is insignificant (Figure 5). Then after farmland reallocation to individual farmers, runoff declined sharply and became significant in 1984. It is therefore reasonable to conclude that runoff decline in the catchments of HRB is strongly driven by agricultural/human activity. Our conclusion is further confirmed by the fact that agricultural water use accounted for 90% total water use in 1983 in most of the montane counties (HSWR 1984).

ACKNOWLEDGEMENTS

We acknowledge the financial support of Key Innovative Project from Chinese Academy of Sciences (KZCX1-YW-08-03-04) and Natural Science Foundation Committee (40871022). We appreciate the suggestions from editor and reviewers. We are also grateful to Dr. Paul J. Moiwo for reviewing and restructuring the manuscript.

REFERENCES

Xu, Q. 2008 Variance, characteristic and direction of the household contract responsibility system. World Econ. Papers 1, 93–100 (in Chinese).


