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Xingmin Mu[1,2,*]
Ying Li[1]
Peng Gao[1,2]
Hongbo Shao[3,4]
Fei Wang[1,2]

[1]Northwest A&F University, Yangling, P. R. China
[2]Institute of Soil and Water Conservation, Chinese Academy of Sciences (CAS), Yangling, P. R. China
[3]The CAS/Shandong Provincial Key Laboratory of Coastal Environmental Process, Yantai Institute of Costal Zone Research, Chinese Academy of Sciences (CAS), Yantai, P. R. China
[4]Institute for Life Sciences, Qingdao University of Science & Technology (QUST), Qingdao, P. R. China

Research Article

The Runoff Declining Process and Water Quality in Songhuajiang River Catchment, China under Global Climatic Change

The runoff in Songhuajiang River catchment has experienced a decreasing trend during the second half of the 20th century. Serially complete daily rainfall data of 42 rainfall stations from 1959 to 2002 and daily runoff data of five meteorological stations from 1953 to 2005 were obtained. The Mann–Kendall trend test and the sequential version of Mann–Kendall test were employed in this study to test the monthly and annual trends for both rainfall and runoff, to determine the start point of abrupt runoff declining, and to identify the main driving factors of runoff decline. The results showed an insignificant increasing trend in rainfall but a significant decreasing trend in runoff in the catchment. For the five meteorological stations, abrupt runoff decline occurred during 1957–1963 and the middle 1990s. Through Mann–Kendall comparisons for the area-rainfall and runoff for the two decreasing periods, human activity, rather than climatic change, is identified as the main driving factor of runoff decline. Analysis of land use/cover shows that farmland is most related with runoff decline among all the land use/cover change in Nenjiang catchment. From 1986 to 1995, the area of farmland increased rapidly from 6.99 to 7.61 million hm^2. Hydraulic engineering has a significant influence on the runoff decline in the second Songhuajiang catchment. Many large-scale reservoirs and hydropower stations have been built in the upstream of the Second Songhuajiang and lead to the runoff decline. Nenjiang and the Second Songhuajiang are the two sources of mainstream of Songhuajiang. Decreased runoff in these two sub-catchments then results in runoff decrease in mainstream of Songhuajiang catchment. It is, therefore, concluded that high percent agricultural land and hydraulic engineering are the most probable driving factors of runoff decline in Songhuajiang River catchment, China.

Keywords: Human activity; Land use/cover; Mann–Kendall trend test; Sustainable development; Water monitoring

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1 Introduction

There is a decreasing trend of runoff in most river basins in China in recent 50 years under global climatic change [1–4]. Many investigations have been conducted and reported runoff decline in different catchments [5–7]. Climate change and human activity are considered the main factors driving runoff decline in most river basins. Therefore, the role that climate change and human activities play in this decrease is currently of interest [8, 9].

Identifying the influence of climate change on runoff using regression method [10, 11], runoff coefficient method [12, 13], or the more complex hydrological models [14–16] is relatively easy. As to the human activities, several forms has been noticed, however, how to quantify the effect of various human activities on runoff has so far not been fully understood [17–20]. All these processes influence water quality and manipulation of water management performance in the catchment in the world [21–25].

Some human activities have significant effects on runoff decline in China. Hydraulic engineering is one of the important reasons of runoff decline. In Yangtze River, reservoirs have great impacts on runoff and the impacts vary with the capacity and operation pattern of reservoirs and their distance to the measurement stations [26, 27]. Reservoirs are also the cause of runoff decline in the hilly area of Haihe catchment [28]. Land use/cover change due to human activity is another important factor influencing runoff decline in some catchments. In the last 50 years, large area of natural forest/grassland was transformed into farmlands. In Huaihe catchment, agricultural irrigation is the most significant factor of runoff decline from 1958 [29–31]. Also in the plain area of Haihe catchment, farming styles increased the agricultural water use and thus decrease the

Correspondence: Professor H.-B. Shao, Institute for Life Sciences, Qingdao University of Science & Technology, Qingdao 266042, P. R. China
E-mail: shaohongbochu@126.com

*Additional corresponding author: Professor X.-M. Mu, xmmu@yahoo.com

runoff [32, 33]. Soil and water conservation measures also have significant effects on runoff decline [32–34].

Many methods have been developed for detecting jump points in hydro-phenomena. For instance, scholars used order cluster analysis to determine the abrupt change years of runoff in Huaihe catchment which was noted in 1957 and 1985, the double mass curve method to investigate sediment and runoff change in Fenhe catchment after 1959 and noted significant change in runoff in 1964, using the Hubert and the Pettitt test for detesting the first jump year of annual precipitation in some stations in Jordan [6, 10, 15, 22]. Sequential Mann–Kendall test was employed to detect the abrupt changes of runoff in Naolihe and Nenjiang catchments [11]. Among these methods, sequential Mann–Kendall test is efficient for identifying periods with significant hydrological changes and has huge an advantage over other methods in terms of time and precision [3–6, 21–27, 30–32].

Although, several studies have pointed out the abrupt change years of runoff change and the main forms of human activities that have significant effects on runoff decline have been highly understood in China, motivation for this study comes from the fact that a few are devoted to determining the abrupt change and driving factors on runoff in Songhuajiang River catchment. In this study, according to the daily rainfall data (1959–2002) and daily runoff data (1959–2005), abrupt runoff decline and the main driving factors in Songhuajiang River catchment are investigated for considering water quality and sustainable development under global climate change.

2 Materials and methods

2.1 Study area

Songhuajiang River flows through Jilin, Inner Mongolia, Heilongjiang, and Liaoning provinces. Songhuajiang River catchment is one of the seven major river catchments in China with the area of 5.57 million km^2, stretching between longitudes 119°52′–132°31′ and latitudes 41°42′–51°38′ (Fig. 1). The predominant climate is the north temperate monsoon climate with cold and long winters and hot and rainy summers. Annual average rainfall is approximately 500 mm, about 60–80% of which falls in the months of June–September. The dominant cultivated crops in Songhuajiang River catchment are soybean, corn, sorghum, and wheat. Songhuajiang River catchment has abundant water resource. There are 71 channels whose theory reserves of hydropower are more than 10 000 kW. In additions, eight large-scale hydropower stations have been built, with annual average generated energy of 56.69 kW/h. And until 1998, there are total 6551 large, medium, and small-scale reservoirs in Songhuajiang River catchment, with total storage capacity of 25.73 billion m^3.

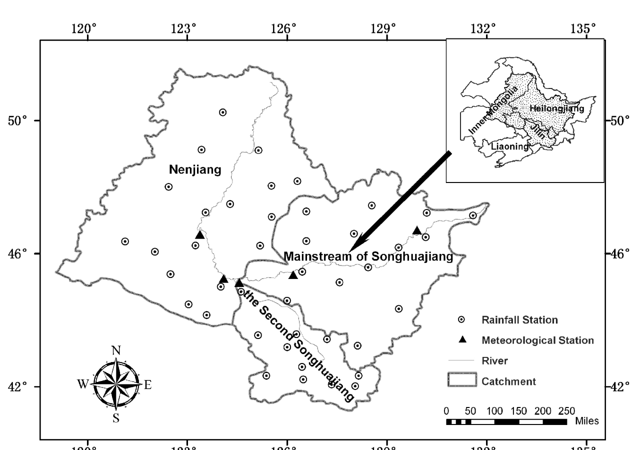

Figure 1. Location of Songhuajiang River catchment, distribution of rainfall stations, and meteorological stations over the study area.

Songhuajiang River catchment is divided into three sub-catchments – Nenjiang, the Second Songhuajiang, and mainstream of Songhuajiang catchments. Nenjiang is the north source of Songhuajiang River, the total length of its mainstream is 1370 km. Nenjiang catchment covers an area of 297 000 km^2. The middle and down reaches of this sub-catchment is a part of Songnen Plain which is the main agricultural area of Songhuajiang River catchment. The south source is the Second Songhuajiang, it flows 958 km. The area of this sub-catchment is 734 000 km^2. The upstream of this sub-catchment has abundant water resource and the drop height is 1556 m. The Second Songhuajiang catchment, therefore, has great theory reserves of hydropower as 802 900 kW. Nenjiang and the Second Songhuajiang flow together at Fuyu County, and then flow to the east, which is Mainstream of Songhuajiang.

2.2 Data collecting

Serially complete daily rainfall information of 42 evenly distributed rainfall stations in Songhuajiang River catchment during the 44-year period 1959–2002 were obtained to analyze the monthly and annual rainfall changes. Seventeen stations are located in Nenjiang catchment, 11 in the Second Songhuajiang catchment, and 14 in mainstream of Songhuajiang catchment.

Five meteorological stations were selected to be used in this study. The record period covers 53 years from 1953 to 2005. Nenjiang and Dalai stations are in Nenjiang catchment, Fuyu station is in the second Songhuajiang catchment, and Harbin, Jiamusi stations are in mainstream of Songhuajiang catchment.

2.3 Methods

The time-series trend for rainfall and runoff was established in this study mainly using the Mann–Kendall trend test and the sequential version of Mann–Kendall test.

The Mann–Kendall trend test tests whether there is a trend in the time series data. It is a non-parametric test. The n time series values ($x_1, x_2, x_3, \ldots, x_n$) are replaced by their relative ranks ($R_1, R_2, R_3, \ldots, R_n$) (starting at 1 for the lowest up to n). The test statistic S is:

$$S = \sum_{i=1}^{n-1} \left[\sum_{j=i+1}^{n} \mathrm{sgn}(R_j - R_i) \right] \qquad (1)$$

where $\mathrm{sgn}(x) = 1$ for $x > 0$, $\mathrm{sgn}(x) = 0$ for $x = 0$, and $\mathrm{sgn}(x) = -1$ for $x < 0$.

If the null hypothesis H_o is true, then S is approximately normally distributed with:

$$\mu = 0 \qquad (2)$$

$$\sigma = \frac{n(n-1)(2n+5)}{18} \qquad (3)$$

The *Z*-statistic is therefore:

$$Z = |S|\sigma^{0.5} \quad (4)$$

The sequential version of Mann–Kendall test is used to test assumptions about the start of a trend within the sample x_1, x_2, x_3, …, x_n from set of random variable x based rank series of progressive and retrograde rows of the sample. The magnitudes of x_j annual mean time-series and $j = 1, 2, 3, \ldots, n$ are compared by x_k, where $k = 1, 2, 3, \ldots, j-1$. For each comparison, the number of cases $x_k > x_j$ is counted and denoted by n_j. The test statistic:

$$i_j = \sum_{1}^{j} n_j \quad j = 2, 3, \ldots, n \quad (5)$$

is normally distributed with mean:

$$E(i) = \frac{n(n-1)}{4} \quad (6)$$

and variance as:

$$\mathrm{Var}(i_j) = \frac{[j(j-1)(2j+5)]}{72} \quad (7)$$

The sequential values of the statistic *U*(*i*) are calculated as:

$$U(i) = \frac{i_j - E(i)}{\sqrt{\mathrm{Var}(i_j)}} \quad (8)$$

which is the increasing sequence, and the decreasing sequence *U*(*d*) is calculated using the same equation but in the reverse data series.

In two-sided trend test, a null hypothesis is accepted at α significance level if $|U(i)| \leq U(i)_{1-\alpha/2}$; where $U(i)_{1-\alpha/2}$ is the critical value of the standard normal distribution with a probability exceeding $\alpha/2$. A positive *U*(*i*) denotes an increasing trend while the reverse denotes a decreasing trend. In this study, α is set at 0.05 significant level. The sequential Mann–Kendall test enables detection of the approximate time of occurrence of a trend from the intersection point of the increasing and decreasing curves of the test statistic. If the intersection point is significant at $\alpha = 0.05$, then the critical point of change is at that period. Hence, the sequential Mann–Kendall test is an efficient way by which the starting time of a trend is pinpointed.

3 Results

3.1 Annual rainfall trend

Observed annual rainfall for the three sub-catchments (for 1959–2002) is presented in Fig. 2 with the statistical characteristics given in Tab. 1. Average rainfall of the three sub-catchments is 438.3–698.8 mm. Rainfall in all these sub-catchments, whose critical value (CV) are no more than 2.0, is relatively stable.

Mann–Kendall trend test statistics calculated for each sub-catchment from 1959 to 2002 are given in Tab. 2, together with critical values corresponding to 5% significant level. Results suggest that annual trends of rainfall (1959–2002) for all the three sub-catchments are positive, but no one shows evidence of a significant positive trend. A negative trend appeared in these 3three sub-catchments from 1980s, but these are statistically insignificant, apart from Nenjiang (1990–2002), with Mann–Kendall value of −2.07.

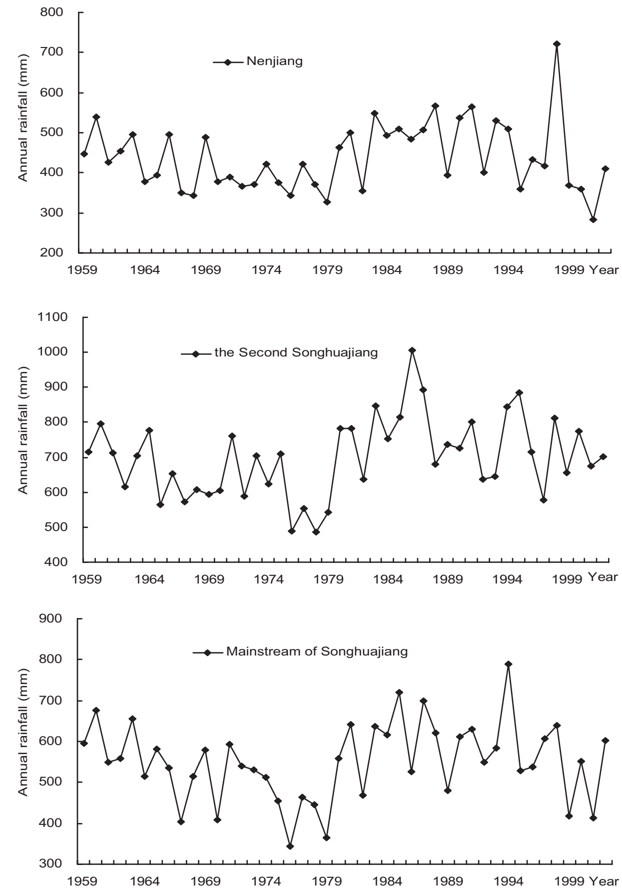

Figure 2. Annual rainfall for the three sub-catchments of Songhuajiang River catchment from 1959 to 2002.

Figure 3 depicts annual rainfall trend for each rainfall station in Songhuajiang River catchment from 1959 to 2002. Only 12 of the 43 stations have a decreasing trend, but none of them is significant. All of the rest 30 stations have an increasing trend, and only Daxing'anling station has significant increase with Mann–Kendall value of 2.91.

3.2 Monthly rainfall trend

The Mann–Kendall trend test was also used to determine monthly rainfall trends for the three sub-catchments (Fig. 4). All the three sub-catchments exhibit an increasing trend in most months for rainfall,

Table 1. Statistical characteristics of annual rainfall for the three sub-catchments of Songhuajiang River catchment from 1959 to 2002

Sub-catchment	Mean (mm)	Max (mm)	Year	Min (mm)	Year	CV
Nenjiang	438.3	721.8	1998	282.6	2001	0.19
The Second Songhuajiang	698.8	1004.6	1986	486.2	1978	0.16
Mainstream of Songhuajiang	551.3	790.3	1994	344.9	1976	0.17

Table 2. Mann–Kendall trend test for annual rainfall in the three sub-catchments of Songhuajiang River catchment

Sub-catchment	Mann–Kendall value				Critical value
	1959–2002	1970–2002	1980–2002	1990–2002	
Nenjiang	0.47	1.08	−1.35	−2.07	1.96
The Second Songhuajiang	1.58	1.46	−1.40	−0.24	1.96
Mainstream of Songhuajiang	0.49	1.39	−1.29	−1.22	1.96

i.e., generally significant. There is a decreasing trend for monthly rainfall in summer, but, i.e., statistically insignificant. Results obtained in this study are in accordance with the findings of J [16, 19, 23, 27]. However, they contradicted [29] that no trend was found for spring rainfall in division and of Northeast China which covers Songhuajiang River Basin. In order to compare the results, the method used for trend analysis in [29] was repeated here using the data set in this study. Obvious increasing trend was found for spring rainfall in Nenjiang, the Second Songhuajiang and mainstream Songhuajiang with linear regression significance level of 94.83, 99.73, and 97.73%, respectively, confirming the contradiction [29].

3.3 Annual runoff trend

Table 3 depicts decreasing runoff for the five selected meteorological stations in all the sub-catchments (Fig. 5). Annual runoff has been declining at the rate of 0.12, 0.16, 0.13, 0.27, and 0.50 billion m^3/year in Jiangqiao, Dalai, Fuyu, Harbin, and Jiamusi meteorological stations, respectively, from 1953 to 2005. From the 1950s to the 1970s, runoff declined by 51.92, 53.56, 36.95, 37.58, and 39.14%, respectively. From the 1980s to the early 21st century, runoff in Jiangqiao, Dalai, Fuyu, Harbin, and Jiamusi stations, declined by 42.45, 50.31, 21.34, 38.98, and 38.44%.

3.4 Monthly runoff trend

The Mann–Kendall test was used to determine monthly runoff trend for five meteorological stations and the results presented in Fig. 6. Monthly runoff generally exhibits a decreasing trend, aside from April in Jiangqiao station, February and March in Dalai station, March in Fuyu station, and December–April in Jiamusi station.

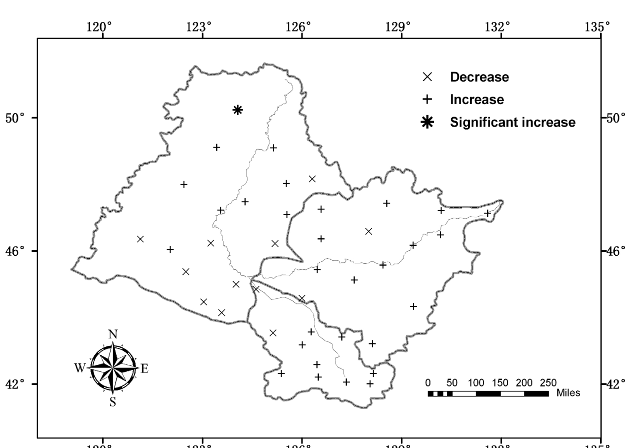

Figure 3. Mann–Kendall trend test for annual rainfall at 95% confidence level in 43 rainfall stations in Songhuajiang River catchment.

The decreasing trend of runoff is significant for all the five stations in at least 3 months of the year. Although the annual runoff trend is insignificant for Jiangqiao station, there are several months in autumn for which the downward trend is significant.

3.5 Abrupt runoff decline

The sequential Mann–Kendall test was used to graphically illustrate the increasing and decreasing trends of runoff for the five meteorological stations for the period 1953–2005 (Fig. 7). The separation point of the increasing and decreasing curves indicates the starting point of abrupt runoff change in each meteorological station. Abrupt change in runoff is significant ($p < 0.05$) at the point of curves fall outside the dashed lines. There is abrupt decline in runoff in

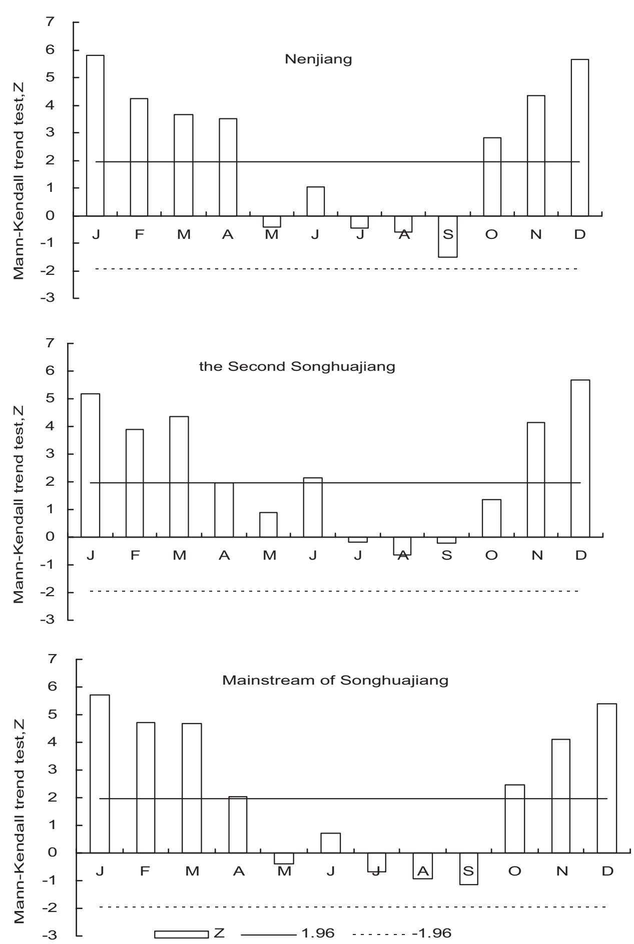

Figure 4. Mann–Kendall trend test for monthly rainfall in the three sub-catchments of Songhuajiang River catchment (1959–2002).

Table 3. Variation in runoff for the five meteorological stations in the three sub-catchments of Songhuajinag River catchment (billion m^3)

Station	Nenjiang		The Second Songhuajiang	Mainstream of Songhuajiang	
Period	Jiangqiao	Dalai	Fuyu	Harbin	Jiamusi
1953–2005	24.54	21.84	15.10	42.57	74.50
1950s	31.77	29.38	20.23	53.08	91.94
1960s	26.43	24.20	16.50	46.16	84.73
1970s	15.28	13.64	12.76	33.13	55.95
1980s	27.97	24.15	15.42	47.03	82.51
1990s	28.51	26.00	13.90	44.95	78.58
2000–2005	16.10	12.00	12.13	28.69	50.79

The Mann–Kendall test analysis shows significant declines in annual runoff trend for Dalai, Fuyu, Harbin, and Jiamusi stations, with respective *Z*-values of −2.21, −2.59, −2.51, and −2.35 as shown in Fig. 5. For meteorological station of Jiangqiao, annual runoff decline is insignificant.

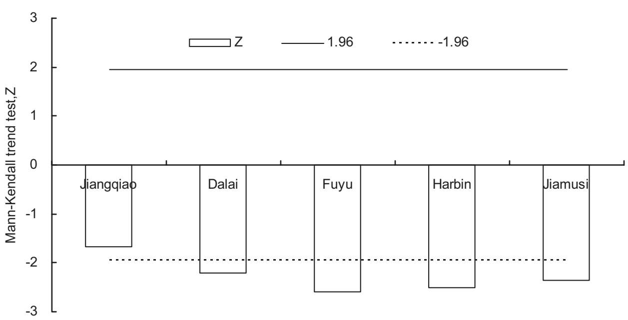

Figure 5. Annual runoff trend test for the five meteorological stations of Songhuajiang River Catchement (1953–2005).

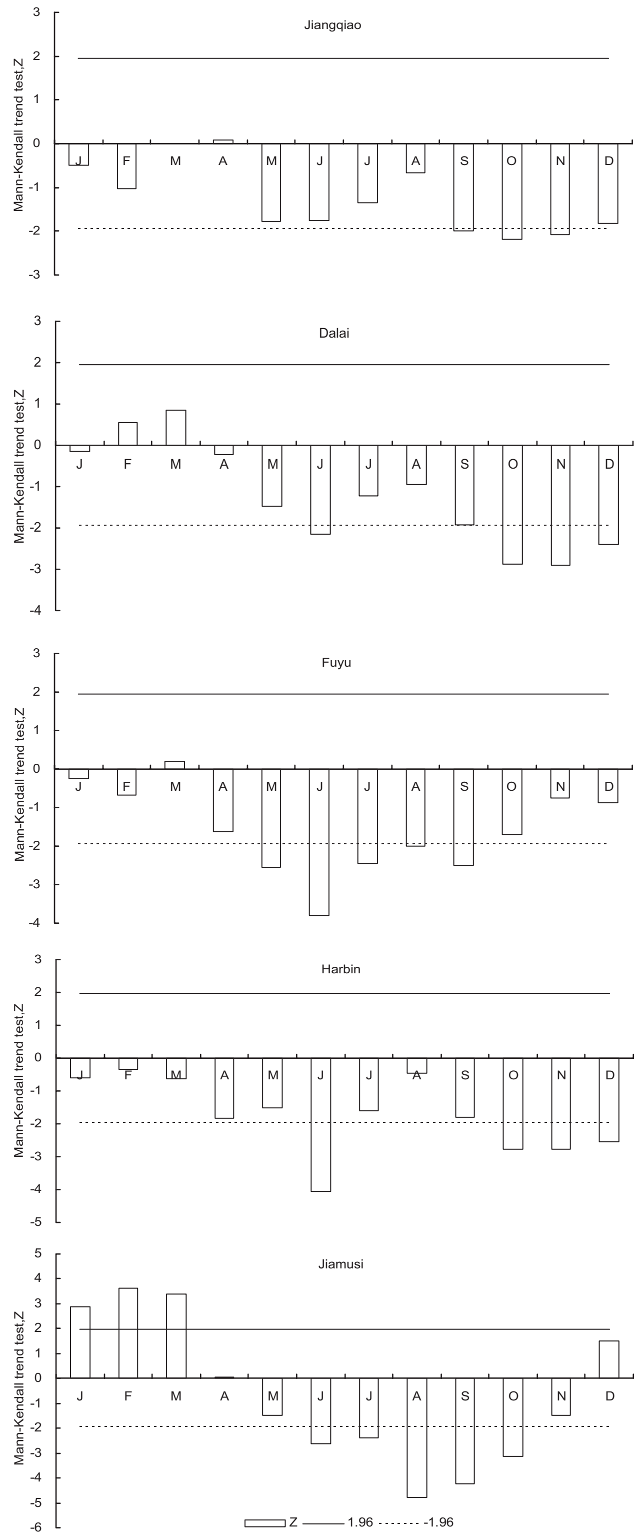

Figure 6. Mann–Kendall trend test for monthly runoff in the five meteorological stations of Songhuajiang River catchment (1953–2005).

all the five meteorological stations. However, none of them is significant.

In general, there are two abrupt decline periods in runoff from 1953 to 2005. 1957–1966 is the first period with abrupt decline in runoff in the study area. Fuyu is the station with the earliest runoff decline which started as early as 1957. The first runoff decline in Jiangqiao, Dalai, Harbin, and Jiamusi started in 1963, 1963, 1964, and 1966, respectively. There is an increasing trend in 1980s apart from Fuyu station. However, the separation points are outside the dashed lines, so it is not an abrupt increase. The second abrupt decline occurred in around 1995, but runoff in Fuyu station only experienced abrupt decline once.

3.6 Correlation analysis between rainfall and runoff

Based on the results of the sequential Mann–Kendall test analysis, runoff has two decline periods. The first is from early 1960s to middle 1980s, and the second is from middle 1990s to early 21st century. Figure 8 illustrates Mann–Kendall comparison of area-rainfall and runoff for the two periods for Jiangqiao, Dalai, Harbin, and Jiamusi meteorological stations. The rainfall data we obtained only start from 1959, but runoff decline in Fuyu station happened in 1957, so Mann–Kendall comparison of area-rainfall and runoff from 1959 to 2002 was made for Fuyu meteorological station. Results show that area-rainfall in Fuyu has an increasing trend, with Mann–Kendall value of 1.54. On the contrary, runoff in Fuyu station has a decreasing trend, with Mann–Kendall value of −1.19. This implies that rainfall is not the driving factor of declining runoff in Fuyu station.

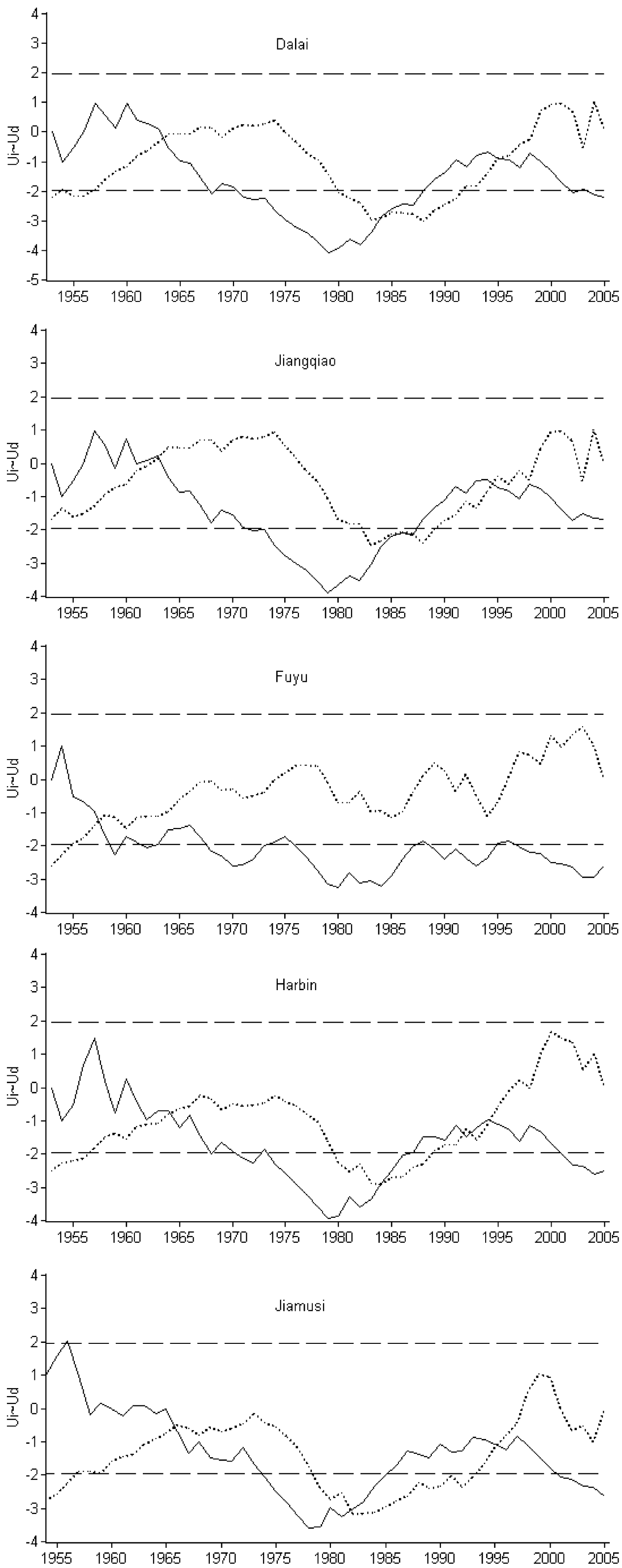

Figure 7. Sequential Mann–Kendall test for annual runoff with increasing trend *U*(*i*) – solid line, and decreasing trend *U*(*d*) – dotted line. Dashed horizontal lines represent critical values corresponding to the 95% significance level.

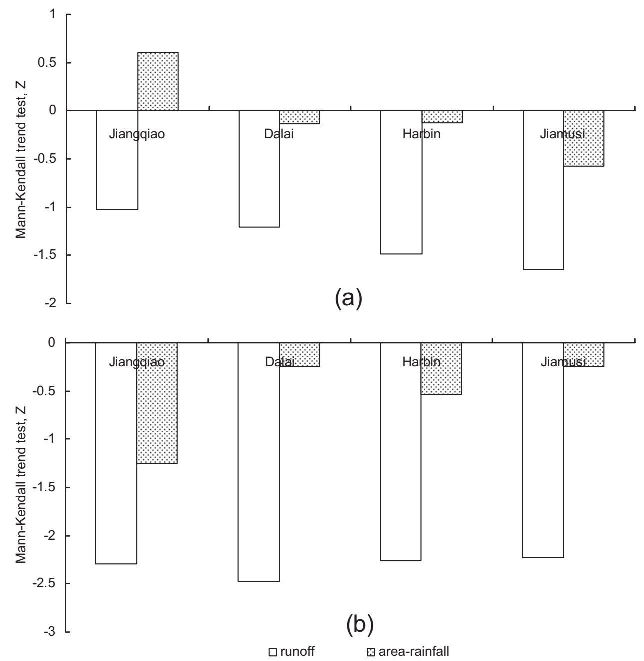

Figure 8. Mann–Kendall comparison of area-rainfall and runoff for the first (a) and the second runoff decline periods (b).

In the remaining four meteorological stations, apart from Jiangqiao (the first decline period) where opposite trend exist in area-rainfall and runoff, Mann–Kendall values for area-rainfall are negative, the same as runoff, but much smaller than that for runoff in all the four meteorological stations in both decline periods. This suggests that runoff decreased with the decrease of area-rainfall; however, the change amplitude of runoff is much bigger than that of area-rainfall, so runoff decline is not only influenced by area-rainfall, and could therefore be driven by human activity. It could be deduced that human activity is the main driving factor of declining runoff in the study area.

3.7 Driving factors of runoff decline

Correlation analysis suggests that human activity is possible the main cause of runoff decline. Furthermore, the sequential Mann–Kendall test clearly shows abrupt decline in runoff in all the five meteorological stations started in 1957–1963 and middle 1990s (apart from Fuyu station). Thus considerable human activity in these two periods is considered the most possible drive of runoff decline in the catchments.

3.7.1 Land use/cover change effect

Years 1958–1960 are the period of Great Leap Forward Movement that aimed to rapidly transform China from a primarily agrarian economy into a modern communist society through the process of agriculturalization and industrialization. As a result, large area of grass land, forest land, marshland, and wasteland were changed into farmland to develop grain production. On the other hand, the area of construction land also sharply increased in this period due to the large-scale resource development, especially the industrial and mining enterprises construction. Increased agricultural and industrial activity then results in increased water use.

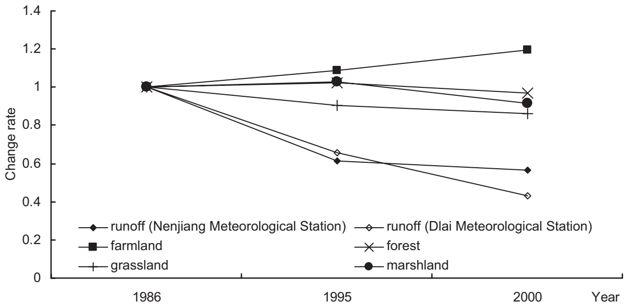

Figure 9. Land use/cover change and the trend of runoff of Nenjiang catchment.

Land use/cover change is much stronger after 1980s. Take, e.g., the sub-catchment Nenjiang. Land use/cover change and the trend of runoff of Nenjiang catchment is shown as Fig. 9. Some scholars pointed that how land use/cover change affect river runoff is complicate, and it is not the result of unique land use/cover change [1–4, 6–10, 17, 23, 28]. According to Fig. 9, the change of farmland is most effective. The area of farmland increased rapidly from 6.99 million hm^2 in 1986 to 7.61 million hm^2 in 1995 which account for 28.1% of the whole area of Nenjiang catchment. The area of upland field increased by 374.9 thousand hm^2 during these 10 years and paddy field also has a significant increase amplitude; it was almost three times larger in 1995 compared to that in middle 1980s which implies the fierce reclamation in the study area.

3.7.2 Hydraulic engineering effect

From 1950s, some large-scale water diversion projects, such as Northern, Central, Southern Conveyance Projects, were built in Nenjiang catchment in order to solve the agricultural, industrial, and domestic water use. These projects decrease the runoff in Nenjiang downstream region. Further, Chaersen Reservoir, with a total storage capacity of 1.25 billion m^3, was built in 1990 in Nenjiang catchment.

Hydraulic engineering has a greater influence on runoff decline in the Second Songhuajiang catchment. In late 1950s, Xinlicheng, Hailong, Shitoukoumen Reservoirs were built in upstream region of the Second Songhuajiang. In 1953, Fengman Hydropower Station was basically completed also in upstream region. The control area is 42 500 km^2 and the total storage capacity is as high as 10.99 billion m^3. In late 1970s and early 1980s, Baishan, Hongshi, and Jingpo Lake Hydropower Stations were then built in the Second Songhuajiang, with total storage capacity of 7.07 billion m^3, further intensified the runoff decline in the Second Songhuajiang.

3.7.3 Runoff influencing effect

Nenjiang and the Second Songhuajiang are the two sources of mainstream of Songhuajiang. A decreased runoff in these two sub-catchments then results in runoff decrease in mainstream of Songhuajiang catchment. To further prove this claim, runoff correlation between mainstream of Songhuajiang catchment and the total runoff of the other two sub-catchments was analyzed using Kendall test (The meteorological stations selected here are Dalai, Fuyu, and Jiamusi stations, located in the downstream areas of the three sub-catchments). Result shows that correlation coefficient is 0.778, which is significant at the 0.01 level. Thus runoff decline in Nenjiang and the Second Songhuajaing could be an important factor driving runoff decline in mainstream of Songhuajiang.

4 Discussion and conclusions

There is an insignificant increasing trend in rainfall for most of the rainfall stations, but the Mann–Kendall test analysis shows significant decline in runoff in the sub-catchments of Songhuajiang River catchment for the period of 1953–2002. It suggests that rainfall should not the driving factor of significant runoff decline [1–10, 19–27, 30, 34].

Based on the sequential Mann–Kendall test, an abrupt runoff decline (1957) is detected for Fuyu meteorological station and two abrupt declines (early 1960s and middle 1990s) are for Nenjiang, Dalai, Harbin, and Jiamusi meteorological stations. Further analysis reveals that although the trend of change in rainfall is the same as that in runoff in almost all the stations in the two decline periods, the rainfall Mann–Kendall values are much smaller than runoff values. This confirms that human activity, rather than change in rainfall, is the main driving factor of abrupt runoff decline [11–19, 28–32].

Analysis of land use/cover shows that farmland is most related with runoff decline among all the land use/cover change in Nenjiang catchment. From 1986 to 1995, the area of farmland increased rapidly from 6.99 to 7.61 million hm^2, of which the area of upland field increased by 374 900 hm^2 and paddy field increased more than two times. Hydraulic engineering has a significant influence on runoff decline in the Second Songhuajiang catchment. The upstream of the Second Songhuajiang is in mountain area, with abundant water resource. Many large-scale reservoirs and hydropower stations, therefore, built in this region and lead to the runoff decline in the Second Songhuajiang catchment. Nenjiang and the Second Songhuajiang are the two sources of Mainstream of Songhuajiang. Decrease runoff in these two sub-catchments then results in runoff decrease in Mainstream of Songhuajiang catchment. The above results provide better basis for protecting water quality and environmental policy-makers [32–34].

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