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Effects of climate change and human activities on runoff in the Nenjiang River Basin, Northeast China

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Abstract

The Nenjiang River Basin (NRB) is an important grain-production region with abundant wetlands in Northeast China. Climate change and anthropogenic activities have dramatically altered the spatial and temporal distribution of regional stream discharge and water resources, which poses a serious threat to wetland ecosystems and sustainable agriculture. In this study, we analyzed 55-yr (1956–2010) rainfall and runoff patterns in the river basin to quantitatively evaluate the impact of human activities on regional hydrology. The long-term hydrologic series were divided into two periods: period I (1956–1974), during which minimum land use change occurred, and period II (1975–2010), during which land use change intensified. Kendall's rank correlation test, non-parametric Pettitt test and precipitation-runoff double cumulative curve (DCC) methods were utilized to identify the trends and thresholds of the annual runoff in the upstream, midstream, and downstream basin areas. Our results showed that the runoff in the NRB has continuously declined in the past 55 yr, and that the effects of climate change and human activities on the runoff reduction varied in the upstream, midstream and downstream area over different time scales. For the entire study period, climate change has been the dominant factor, accounting for 69.6–80.3 % of the reduction in the total basin runoff. However, the impact of human activities has been increasing from 19.7 % during the 1950s–1970s to 30.4 % in the present time. Spatially, the runoff reduction became higher from the upstream to the downstream areas, revealing an increasing threat of water availability to the large wetland ecosystem in the lower river basin. Furthermore, the sustainable development of irrigated agriculture in the NRB will be a threat to the survival of the wetlands.

1 Introduction

Climate change and human activities can affect the hydrological cycle of river basins throughout the world (e.g. Changnon and Demissie, 1996; Bronstert et al., 2002;

Legesse et al., 2003; Pfiste et al., 2004; Xu, 2005; Piao et al., 2007). Climate change has direct impacts on precipitation and evaporation (IPCC, 2007) by intensifying the global hydrological cycle (Brutsaert and Parlange, 1998). Human activities can modify temporal and spatial distribution of water resources through land use change, dam construction, river diversion, and other engineering and management practices (e.g. Govinda, 1999; Milly et al., 2005). Changes in surface runoff due to both climate change and human activities will affect natural ecosystems, agriculture, water resources management and land use planning (Miller, 1992; Ren et al., 2002; Anderson et al., 2008).

Many studies have documented concerns towards the hydrological effects of climate change and intensified human activities. The areas included in these studies ranged from a small watershed (less than 1 km^2) to large river basins ($>10\,000\,\mathrm{km}^2$) (e.g. Richey et al., 1989; Schulze, 2000; Ma et al., 2010). Studies of the climate change effect have mainly focused on the relationship between precipitation and surface runoff. For instance, researchers (e.g. Chiew et al., 1995, 2002; Wilk and Huges, 2005; Legesse et al., 2010) reported that precipitation changes would cause larger percentage changes in the runoff of a river basin (both increasing and decreasing) than temperature changes do. Studies of the land use change effect have often focused on the relationship between vegetation cover change and runoff (e.g. Bosch and Hewlett, 1982; Lane et al., 2005; Mishra et al., 2007; Scanlon et al., 2007). The methods used for evaluating the combined effect of climate change and human activities on site hydrology have varied. Ren et al. (2002) estimated the effect of human activities on the runoff by computing the impacts on each component of a water balance equation, despite the constraints of attributing the direct effect individually because the water supply and water use were complex and changed rapidly. Dooge et al. (1999) and Milly and Dunne (2002) provided a framework for evaluating the sensitivity of the annual runoff to precipitation and potential evapotranspiration. This hydrological sensitivity analysis method has in recent years been used by a number of researchers (e.g. Jones et al., 2006; Li et al., 2007; Ma et al., 2008; Jiang et al., 2011; Peng et al., 2012) to assess the combined impacts of climate change and human activities on runoff. However, these

studies treated the research areas as one large uniform unit, giving little consideration on spatial heterogeneity in the effects within the basin.

The Nenjiang River Basin (NRB) is one of the most important crop-production regions in China. Containing a large area of natural wetlands, the NRB is also one of China's most important wetland preservation areas. During the last 55 yr (1956–2010), the NRB has experienced substantial changes in climate and land use/cover, which has led to serious water resource problems. Recent studies have shown that the regional climate has become warmer and drier (Yang et al., 2008), and the runoff in the NRB has declined since the 1950s (Xu et al., 2009). Concurrently, increased demands on agricultural production have pushed an increased supply of irrigation water (Maston et al., 1997). Therefore, the conflict between the water supply and demand has become evident over the last 55 yr and is becoming a serious challenge to maintaining the highly productive agricultural system while protecting the previous wetland ecosystems. In order to develop best management strategies and practices for overcoming the challenge it is crucial to have a thorough understanding of the hydrological responses to climate and land use changes in the basin at finer temporal and spatial scales. The objectives of this study were to: (1) investigate the presence or absence of trends and change-points in the annual runoff in the NRB; (2) quantitatively evaluate the impacts of climate change and human activities on the runoff, and assess the level of impacts between the upstream, midstream and downstream regions.

2 Methodology

2.1 Study area

The Nenjiang River flows from north to south approximately 1370 km through the midwestern part of Northeastern China (Fig. 1). The river basin has a total area of $297\,000\,\mathrm{km}^2$ with extensive low-lying grasslands that provide breeding habitat for migratory birds including six of the world's fifteen crane species (Meine and George, 1996). In this study, we divided the basin into upstream, midstream and downstream basins based on altitude, topography and valley characteristics. The upstream basin is located in a hilly and mountainous area characterized by dense forests and narrow valleys. From the midstream to downstream basin, there is a transition from hills to plains, the land becomes more fertile, and the topography of the river on both banks becomes highly asymmetric. From 1956 to 2010, the upstream, midstream and downstream basins had an annual precipitation of 493 $\mathrm{mm\,yr^{-1}}$, 489 $\mathrm{mm\,yr^{-1}}$ and 414 $\mathrm{mm\,yr^{-1}}$, respectively. The annual precipitation is mainly concentrated in the rainy season from June to September, which accounts for 70–80 % of the annual total. The long-term annual average discharge of the Nenjiang River is $228 \times 10^8\,\mathrm{m^3}$.

The NRB has the highest concentration of wetlands in Northeastern China with the most diverse ecosystems in the region. The wetlands, especially those located in the downstream basin, are more vulnerable than other ecosystems to climate change (Pan, et al., 2003). Discharge of the Nenjiang River has been reported to have declined significantly in recent years (Feng et al., 2011), leading to a reduction in water sources for irrigation districts and wetlands; therefore, the analysis of the runoff variations is of great importance.

2.2 Data collection

Monthly streamflow records from five main gauging stations for the period of 1956–2010 were used in this study. Climatic data from 39 national meteorological stations located within and near the basin were collected. These data included monthly average and total precipitation, minimum and maximum air temperature, relative humidity, sunshine hours, and wind speed. We used the data to calculate monthly potential evapotranspiration with the Penman–Monteith equation, as recommended by the Food and Agriculture Organization (FAO) (Allen et al., 1998). Furthermore, we collected Landsat 7(TM) imagery (path 117–123, row 24–29) to determine land use/land cover (LULC) changes in the entire river basin.

2.3 Precipitation and runoff trend and change-point analysis

Trend and change-point analyses were conducted to separate the long-term runoff series into distinctive different time periods for assessment of climate change and human activity effects. This was done in two steps. First, we applied Kendall's rank correlation, which was based on the relative abundance of subsequent observations that exceed a particular value (Kendall and Stuart, 1973; Douglas et al., 2000), to assess the significance of trends in runoff. For a series $x_1, x_2, \ldots, x_n$, p is the number of occurrences where x_j is greater than x_i in all pairs of observations $(x_i, x_j; j > i)$, the ordered (i, j) subsets are $(i = 1, j = 2, 3, \ldots, n)$, and n is the data set record length:

$$E(p) = \frac{n(n-1)}{4} \tag{1}$$

The trend test is based on the statistic τ defined as,

$$\tau = \frac{4p}{n(n-1)} - 1 \tag{2}$$

For the random sequence,

$$E(\tau) = 0 \tag{3}$$

$$\mathrm{Var}(\tau) = \frac{2(2n+5)}{9n(n-1)} \tag{4}$$

The test defines the standard normal variety, N as

$$N = \frac{\tau}{\mathrm{Var}(\tau)^{0.5}} \tag{5}$$

The value of N converges to a standard normal distribution as n increases. At a specified level of significance of a, a standard N_a value can be obtained from the table of standard normal distributions. If $|N| > N_{a/2}$, a positive N indicates an increase in the time series, and a negative N indicates a decrease.

Secondly, we applied the non-parametric Pettitt test (Pettitt, 1979) and the precipitation-runoff double cumulative curve (DCC) to detect the change-points of the runoff series.

The Pettitt test can be derived from the Mann–Whitney U-test $U_{t,N}$, which verifies whether two samples $x_1,\ldots,x_t$ and $x_{t+1},\ldots,x_N$ are from the same population. The test statistic, $U_{t,N}$, is given as

$$U_{t,N} = U_{t-1,N} + \sum\nolimits_{j=1}^{N} \operatorname{sgn}(x_t - x_j) \qquad \text{for} \quad t = 2,\ldots,N \tag{6}$$

The test statistic counts the number of instances that a member of the first sample exceeds a member of the second sample. The null hypothesis of the Pettitt test is the absence of a change-point. The Pettitt test statistic, K_t, and the associated probabilities used in significance testing are given as

$$K_t = \max_{1 \le t \le N} |U_{t,N}| \tag{7}$$

In addition, we calculated the series of probabilities of the change-points for each year using the following formula (Kiely et al., 1998):

$$p \cong 1 - \exp\left\{-6\left(K_t^2\right)/(N^3 + N^2)\right\} \tag{8}$$

The results of which was then used for separation of time periods: if $p < 0.05$, a significant change-point exists, and the time series is divided into two parts at the location of the change-point.

The precipitation-runoff DCC analysis provides a visual representation of the consistency of the precipitation and runoff data (Matoušková, 2009). The DCC should be a straight line, and changes in the gradient of the curve may indicate that the characteristics of the precipitation or runoff have changed. In this study, we used the DCC approach to detect the change-point for precipitation and runoff series.

Overall, the runoff series can be divided into period I (where relatively less land use change and river engineering occurred) and period II (where intensive land use change and water resources management occurred). Based on the period division, the impacts of climate change and human activities on runoff were assessed using a hydrological simulation, as described below.

2.4 Quantitative evaluation of the effects of climate change and human activities on the runoff

The hydrological sensitivity analysis method can be defined as the percentage change in the mean annual runoff that occurs in response to a change in the mean annual precipitation and the potential evapotranspiration (PET) (Jones et al., 2006; Ma et al., 2008).

The water balance for a basin can be written as

$$P = E + Q + \Delta S \tag{9}$$

where P is the precipitation (mm yr^{-1}), E is the actual evapotranspiration (mm yr^{-1}), Q is the runoff (mm yr^{-1}), and ΔS is the change in the basin water storage (mm yr^{-1}). Over a long period of time (i.e. equal to or greater than 10 yr), it is reasonable to assume a zero storage change, i.e. $\Delta S = 0$.

The actual evapotranspiration (E) can be estimated based on the precipitation and PET. In 1974, Budyko developed a framework for estimating the actual evapotranspiration based on the dryness index (a ratio of PET/P). Subsequently, Fu (1981) combined the use of a dimensional analysis with mathematical reasoning and developed an analytical solution for the mean annual actual evapotranspiration:

$$\frac{E}{P} = 1 + \frac{\mathrm{PET}}{P} - \left[1 + \left(\frac{\mathrm{PET}}{P}\right)^{w}\right]^{1/w} \tag{10}$$

where w is a model parameter related to the vegetation type, soil hydraulic property, and topography (Fu, 1996).

Perturbations in both the precipitation and the PET can lead to changes in the water balance (Dooge et al., 1999). As a first-order approximation, the total change in the mean annual runoff can be estimated as

$$\Delta Q_{\text{total}} = \Delta\overline{Q}_{\text{climate}} + \Delta\overline{Q}_{\text{human}} \tag{11}$$

where ΔQ_{total} indicates the total change in the mean annual runoff (mm yr^{-1}), $\Delta\overline{Q}_{\text{climate}}$ is the change in the mean annual runoff due to climate change (mm yr^{-1}), and $\Delta\overline{Q}_{\text{human}}$ represents the change in the mean annual runoff due to human activities (mm yr^{-1}).

Precipitation and PET are the dominant factors that determine the mean annual water balance (Budyko, 1974; Zhang et al., 2001). Changes in the mean annual precipitation and PET can lead to changes in the annual runoff, and the relationship can be approximated as follows (Koster and Suarez, 1999; Milly and Dunne, 2002):

$$\Delta\overline{Q}_{\text{climate}} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial \text{PET}}\Delta\text{PET} \tag{12}$$

where, ΔP, ΔPET are changes in the precipitation and PET, respectively (mm yr^{-1}). The terms andare obtained from Eqs. (9) and (10) and can be expressed as follows:

$$\frac{\partial Q}{\partial P} = P^{w-1}(\text{PET}^{w} + P^{w})^{1/w-1} \tag{13}$$

$$\frac{\partial Q}{\partial \text{PET}} = \text{PET}^{(w-1)}(\text{PET}^{w} + P^{w})^{1/w-1} - 1 \tag{14}$$

Once $\Delta\overline{Q}_{\text{climate}}$ is determined, $\Delta\overline{Q}_{\text{human}}$ can be obtained by Eq. (11).

2.5 Land use/land cover change assessment

The Landsat imagery was interpreted to generate change maps and transition matrices. In order to reduce the number of classes and improve the accuracy, the change

characterization was done using the broader land use/cover classes such as forest or grassland.

Two sets of data have been produced: (1) a conventional statistical report of areas and its corresponding rate of change and, (2) the transition matrix, which reports the class-to-class changes observed and its mapping.

Once the areas of land use/cover types were obtained for each period, the rate of change, r, was calculated by using the following equation:

$$r = 1 - \left(1 - \frac{A_1 - A_2}{A_1}\right)^{1/t} \tag{15}$$

where A_1 is the area covered by a given land use/cover at time 1, A_2 is the area at time 2 and t is the number of years for the period of analysis.

The transition matrix was produced to perform land-use change detection. In order to analyze the nature, rate and location of land-use changes, quantitative area data of the overall land-use changes as well as gains and losses in each category between 1986 and 2000 were compiled. The two land-use maps were cross-tabulated to produce the transition matrices for the two analyzed periods. Subsequently, these matrices were derived by means of the following equation to give the annual transition rates in order to project the trends of change on an annual basis (Bell and Hinoja, 1977; Soares-Filho et al., 2002)

$$\mathbf{P}^{t} = \mathbf{H}\mathbf{V}^{t}\mathbf{H}^{-1} \tag{16}$$

where $\mathbf{P}$ is the original transition matrix, $\mathbf{H}$ and $\mathbf{V}$ are its eigenvector and eigenvalue matrices, and t is a fraction or a multiple of its time span.

We calculated the area of land in kilometers covered from each land cover into each of the remaining categories of each individual land category converted into other categories. The results will describe a land-use transition matrix between forests, water, paddy field etc. over a 15-yr period (1986–2000).

3 Results and discussion

3.1 Changes in the precipitation, PET and annual runoff

For the past 55 yr, the NRB showed an annual average precipitation of 441 $\mathrm{mm\,yr^{-1}}$ ranging from 156 $\mathrm{mm\,yr^{-1}}$ to 1111 $\mathrm{mm\,yr^{-1}}$. Annual average temperature, however, had a higher variability, ranging from $-0.7\,^{\circ}\mathrm{C\,yr^{-1}}$ to $3.6\,^{\circ}\mathrm{C\,yr^{-1}}$ with a mean of $1.5\,^{\circ}\mathrm{C\,yr^{-1}}$. The estimated PET in the NRB averaged 885 $\mathrm{mm\,yr^{-1}}$ per year, varying from 807 $\mathrm{mm\,yr^{-1}}$ to 937 $\mathrm{mm\,yr^{-1}}$. Annual surface runoff from the entire basin averaged 138 $\mathrm{mm\,yr^{-1}}$, fluctuating from 53 $\mathrm{mm\,yr^{-1}}$ to 245 $\mathrm{mm\,yr^{-1}}$ (Fig. 2). The precipitation had a significant change from 1956 to 2010, with a decreasing trend of 5.0 $\mathrm{mm\,(10\,yr)^{-1}}$, while the PET did not show obvious change (Table 1, Fig. 4). The runoff, however, showed a considerable decrease at a rate of 8.6 mm per 10 yr (with a positive significance of 0.99). The N statistic of the Kendall test was -2.31, indicating a clear decreasing trend.

The decline in the runoff is most likely due to the additional water demand from the increasing population, economic growth and agricultural development that have occurred since the 1950s. Apparently, the decline is spatially variable within the basin. To further understand the trends and change point of the annual runoff, the Pettitt test was applied to the entire NRB, while the DCC test was applied to detect the change points in the annual runoff individually for each of the upstream, midstream and downstream basins.

The results showed two change-points in the runoff series: the year of 1975 and the year of 1981 (Table 2). In addition, the DCC test demonstrated that in the upstream basin of the Nenjiang River, the precipitation and runoff were relatively consistent prior to 1975 and changed thereafter. In the midstream and downstream basins, however, the change-point occurred in 1974 (Fig. 3). The combined Pettitt and DCC test results indicate that 1975 could be the change-point reflecting the effect of human activities on runoff.

Several factors may have contributed to the change-point, including the expansion of grain production, economic crops, forestry, animal husbandry and fishery. Therefore, 1956–1974 was selected as the period I, during which the impact of human activities on the basin runoff was low. The period from 1975 to 2010 was considered the human-induced period and was further divided into three periods: 1975–1989, 1990–1999 and 2000–2010. For these periods, changes in the mean annual precipitation, PET and runoff were calculated separately for the upstream, midstream and downstream basins. In the upstream basin, the precipitation decreased by 4.4 %, −3.5 % (the negative decrease means increase) and 14.4 %, whereas the PET increased by 4.3 %, 7.7 % and 10.5 % in 1975–1989, 1990–2000 and 2001–2010, respectively, when compared with those in period I (Table 2). The observed runoff in 1975–1989, 1990–2000 and 2001–2010 decreased by 9.6 %, 2.2 % and 32.7 %, respectively, which were in a much greater change rate when compared with the precipitation and PET changes during period I. In the midstream and downstream basins, there was variation in the increase or decrease in the different periods independent of the precipitation, PET or runoff. Overall, the PET and observed runoff showed a greater rate of change in the upstream basin and the precipitation showed a greater change rate in the downstream basin. The possible reason for the change was that the runoff was affected by the snowmelt, frozen soil in the upstream basin, which was sensitive to climate change, while the downstream basin got more impact from the human activities. In the long run, these changes in the precipitation, PET and annual runoff may have a profound impact on the wetland ecological balance and sustainable agricultural development.

3.2 Quantitative evaluation of the impact of climate change and human activities on the runoff

The quantitative effects simulated in the three basin regions (Table 3) showed that the percentage changes in the runoff due to human activities were 19.7 %, 28.0 % and 30.4 % for the upstream, midstream and downstream basins, respectively. Climate change was the dominant factor in all three basin sections, while the role of human activities became increasing evident from 1975 to 2010. Moreover, the impact of human activities appeared to become stronger from the upstream basin to the downstream basin, which may be due to differences in the geomorphologic features, as well as differences in the socio-economic conditions of the three basins. The effects of climate change and human activities also varied for the different time scales. In the downstream basin, for example, the percentage changes in the runoff due to human activities were 18.2 %, 38.9 % and 34.1 % in 1975–1990, 1991–2000 and 2001–2010, respectively.

The land use and land cover in the NRB have changed substantially since 1980s (Fig. 4). The grassland and forest showed a sharp decline during this period, while the paddy field and dry land had an increasing trend. There were 10 435 km^2 of grassland in 1986 to 2000, which changed into dry land, while the grassland and dry land of 2000 were conversed from 1986 with 4075 km^2 and 5780 km^2. This would affect water storage capacity of the basin, and aggravated the soil erosion.

Changes in runoff of a river basin can be affected by both climate variability and human activities, and their role can vary spatially and temporally. Piao et al. (2007) reported that on average, land-use change has increased global runoff by 0.08 $mm\,yr^{-1}$ and its contribution is substantially larger than that of climate change in tropical regions. The results from our study reveals that climate change was the main reason for the runoff decline in the NRB from 1975–1989, whereas the contribution of human activities became more important during the periods of 1990–1999 and 2000–2009. The cause for such variation may have been a combination of the land cover changes since the late 1980s (Ye et al., 2003) and the construction of large water conservancy project in the 20th century (Ma et al., 2011). However, the quantification of the individual impacts is problematic because changes in the runoff from a large river basin are most likely associated with several factors.

3.3 Correlation between the runoff and precipitation

The correlation between the precipitation and the runoff was not very strong, especially in the downstream basin (Table 5) where the correlation coefficient was only 0.675.

However, all three basins have passed the test at the 0.01 significance level. Therefore, we selected the runoff coefficient parameter, which is defined as the ratio of the runoff to the precipitation over a given time period (Chow et al., 1988), to represent the hydro-climatic conditions of the NRB (Fig. 5). The runoff coefficients of the upstream, midstream and downstream basins were 0.41, 0.37 and 0.21, respectively.

The decreasing trend from the upstream to the downstream basin can be attributed to the steep slopes and high river network density in the upstream basin, which allows for rapid drainage and thus, a relatively high runoff coefficient. In contrast, the runoff coefficient of the downstream basin was relatively low due to the prevalence of plains. Changes in the runoff due to climate change and human activities have been shown to be sensitive to variations in the precipitation (Ma et al., 2008). As illustrated in the graph of the runoff coefficients from 1956–2010 (Fig. 5), the runoff coefficients for the period II (1975–2010) were less than that for the period I (1956–1974). We propose that the runoff was dramatically affected by the water-related human activities (e.g. agricultural irrigation) during the human-induced period (1975–2010).

3.4 The uncertainty of the hydrological simulations

There are various uncertainties in separating the effects of climate change and human activities on the runoff. The major sources of uncertainties in the hydrological sensitivity analysis method simulation may be attributed to the input data. First, the performance of this method is based on the data for a long-term period of natural runoff without the effects of human activities. However, the duration of the period I (19 yr) was insufficient for reliable statistical analyses, and there may have been human disturbances during the period I. Second, the limitations due to the number and distribution of the hydro-meteorological stations affected the accuracy of the simulation. In addition, the actual evaporation was calculated using the PET, which increases the uncertainty of the simulations relative to the use of evapotranspiration rates measured in the field. Finally, uncertainty of the model parameter can also influence the simulation results. Therefore, these uncertainties will affect the computational results to a certain extent.

4 Conclusions

We defined a conceptual framework and used a hydrological simulation to quantify the impacts of climate change and human activities on runoff in the NRB in Northeast China for a 55-yr period (1955–2010). A decrease in the annual runoff was shown using the Kendall's rank correlation method, and a change point was identified as having occurred in 1974 based on the Pettitt and DCC tests. Climate change was the dominant factor, accounting for 69.6–80.3 % of the reduction in the runoff, whereas the reduction due to human activities was 19.7–30.4 %. The impact of human activities on runoff was stronger in the downstream basin during 1975–2010, showing an increasing threat of water availability to the large area of wetlands. The results will play a key role in water resources planning and management in terms of maintaining the ecosystem integrity and the sustainable socio-economic development within the NRB.

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Table 1. Analysis of annual precipitation, PET and runoff.

Factor	Mean value ($mm\,yr^{-1}$)	Trend rate ($mm\,(10\,yr)^{-1}$)	N	Kendall test Positive significance	Pettitt change-point analysis
Precipitation	441.4	−5.0	−1.09	–	–
PET	884.8	0.8	0.01	–	–
Runoff	137.5	−8.6	−2.31	0.99	1974, 1981

Table 2. Changes in precipitation, PET and observed runoff during different periods for the upstream, midstream and downstream basins of the Nenjiang River.

Region	Period	ΔP		ΔPET		ΔQ	
		mm yr^{-1}	%	mm yr^{-1}	%	mm yr^{-1}	%
Upstream	1975–1989	−20.7	−4.4	28.9	4.3	−17.7	−9.6
	1990–1999	16.5	3.5	52.1	7.7	−4	−2.2
	2000–2009	−68.3	−14.4	71.2	10.5	−60.6	−32.7
Midstream	1975–1989	−4.5	−1.0	38.1	5.1	−10.5	−5.7
	1990–1999	34.6	7.3	7.8	1.0	22.8	13.6
	2000–2006	−38.1	−8.1	65.8	8.8	−53	−31.5
Downstream	1975–1989	39.9	8.5	17.3	1.7	−16.3	−12.2
	1990–1999	13.5	2.9	−15.3	−1.5	13.9	10.4
	2000–2009	−78.6	−16.8	16.3	1.6	−29.8	−22.2

Table 3. Effects of climate change and human activities on runoff in the Nenjiang River Basin.

Region	Period	Precip. mm	PET mm	ΔQ_{total} mm	$\Delta \overline{Q}_{\text{climate}}$ mm	%	$\Delta \overline{Q}_{\text{human}}$ mm	%
Upstream	1956–1974	475.2	676.6	–	–	–	–	–
	1975–1989	454.5	705.5	−17.7	−16.1	90.8	−1.6	9.2
	1990–1999	491.7	728.7	−4	−3.3	82.8	−0.7	17.2
	2000–2009	406.9	747.8	−60.6	−40.8	67.3	−19.8	32.7
	1975–2009	451.0	727.3	−27.4	−22.0	80.3	−5.4	19.7
Midstream	1956–1974	472.1	749.6	–	–	–	–	–
	1975–1989	467.6	787.7	−10.5	−8.6	82.3	−1.9	17.7
	1990–1999	506.7	757.4	22.8	17.9	78.3	4.9	22.8
	2000–2006	434	815.4	−53	−29.9	56.4	−23.1	43.6
	1975–2009	462.4	786.8	−13.6	−9.8	72.3	−3.8	27.3
Downstream	1956–1974	468.2	1002.3	–	–	–	–	–
	1975–1989	508.1	1019.6	−16.3	−13.3	81.8	−3	18.2
	1990–1999	481.7	987	13.9	8.5	61.1	5.4	38.9
	2000–2009	389.6	1018.6	−29.8	19.6	65.9	−10.2	34.1
	1975–2009	459.8	1008.4	−10.7	−7.4	69.6	−3.3	30.4

Table 4. The land-use transition matrix in Nenjiang River Basin from 1986–2000 (km^2).

Land use type		2000							
		Forest	Grassland	Water	Residential and industry	Unused land	Paddy field	Dry land	Total
1986	Forest	87 238	4075	91	80	798	15	5780	98 077
	Grassland	5088	50 688	198	209	1476	372	10 435	68 466
	Water	83	303	6667	10	1010	73	309	8455
	Residential and industry	57	143	15	4260	115	61	924	5575
	Unused land	744	1544	438	89	24 702	844	2147	30 508
	Paddy field	5	22	19	15	25	1642	151	1879
	Dry land	1989	2209	178	1092	991	1775	72 649	80 883
	Total	95 204	58 984	7606	5755	29 117	4782	92 395	293 843

Table 5. The correlation between precipitation and runoff for the upstream, midstream and downstream basins based on the partial correlation analysis method.

Region	Control variables			Precipitation
Upstream	PET	Runoff	Correlation	0.684
			Significance(2-tailed)	< 0.01
Midstream	PET	Runoff	Correlation	0.708
			Significance(2-tailed)	< 0.01
Downstream	PET	Runoff	Correlation	0.675
			Significance(2-tailed)	< 0.01

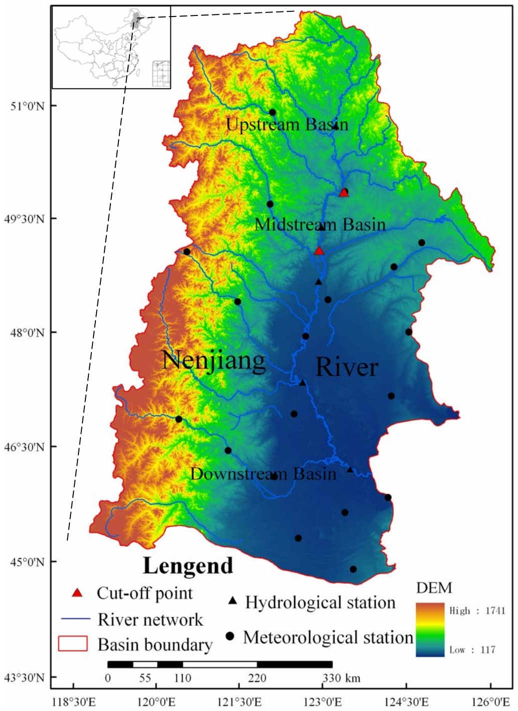

Fig. 1. Location of the study area, the distribution of hydrological and meteorological stations.

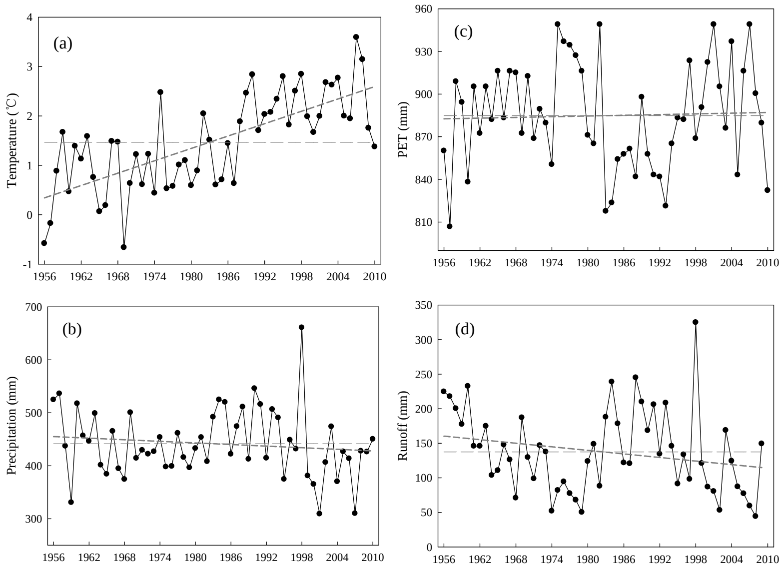

Fig. 2. Annual temperature **(a)**, precipitation **(b)**, PET **(c)** and runoff **(d)** for 1956–2010 in the Nenjiang River Basin. The long and short dashes represent the mean annual value and change, respectively, for this period.

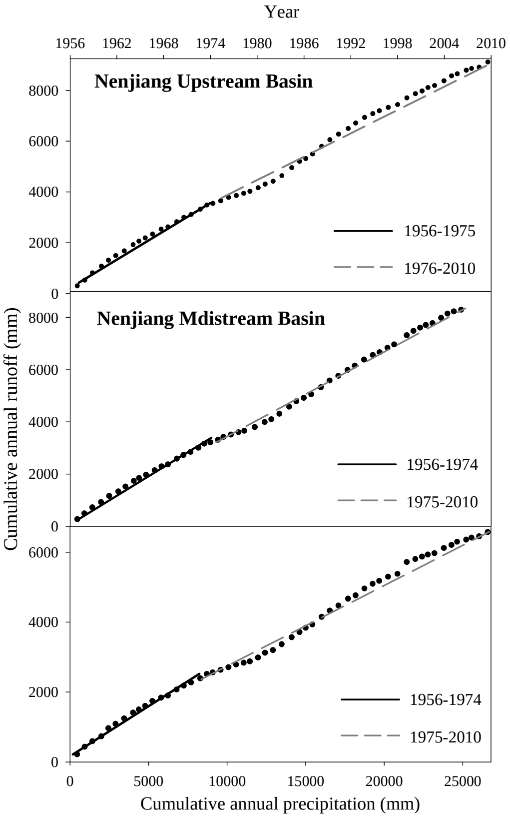

Fig. 3. DCC of annual precipitation and runoff in the Nenjiang River Basin.

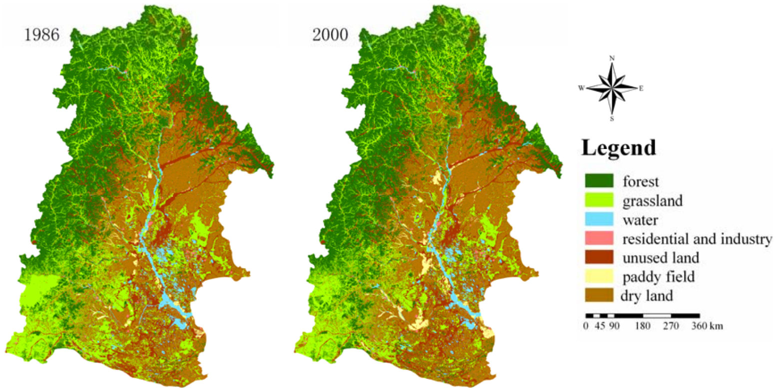

Fig. 4. The land use and land cover map of the Nenjiang River Basin in 1986 and 2000.

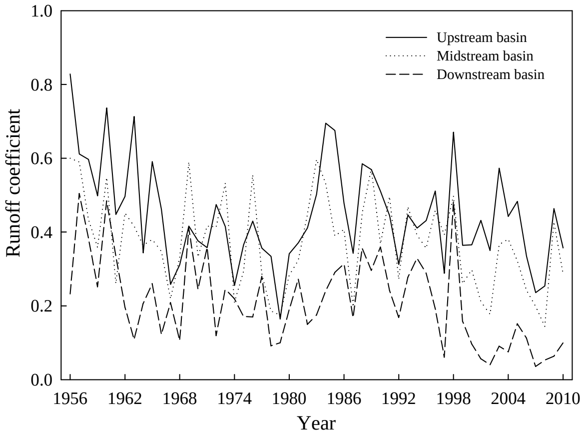

Fig. 5. Time series of the runoff coefficients for 1956–2010 within the Nenjiang River Basin.