Chin. Geogra. Sci. 2012 Vol. 22 No. 2 pp. 144–153
doi: 10.1007/s11769-012-0525-1
www.springerlink.com/content/1002-0063

Runoff Change of Naoli River in Northeast China in 1955–2009 and Its Influencing Factors

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Abstract: Runoff change and trend of the Naoli River Basin were studied through the time series analysis using the data from the hydrological and meteorological stations. Time series of hydrological data were from 1957 to 2009 for Bao′an station, from 1955 to 2009 for Baoqing station, from 1956 to 2009 for Caizuizi station and from 1978 to 2009 for Hongqiling station. The influences of climate change and human activities on runoff change were investigated, and the causes of hydrological regime change were revealed. The seasonal runoff distribution of the Naoli River was extremely uneven, and the annual change was great. Overall, the annual runoff showed a significant decreasing trend. The annual runoff of Bao′an, Baoqing, and Caizuizi stations in 2009 decreased by 64.1%, 76.3%, and 84.3%, respectively, compared with their beginning data recorded. The wet and dry years of the Naoli River have changed in the study period. The frequency of wet year occurrence decreased and lasted longer, whereas that of dry year occurrence increased. The frequency of dry year occurrence increased from 25.0%–27.8% to 83.9%–87.5%. The years before the 1970s were mostly wet, whereas those after the 1970s were mostly dry. Precipitation reduction and land use changes contributed to the decrease in annual runoff. Rising temperature and water project construction have also contributed important effects on the runoff change of the Naoli River.

Keywords: runoff change; hydrological parameters; wetland; land use; human activities; Naoli River

Citation: Song Xiaolin, Lu Xianguo, Liu Zhengmao, Sun Yonghe, 2012. Runoff change of Naoli River in Northeast China in 1955–2009 and its influencing factors. *Chinese Geographical Science*, 22(2): 144–153. doi: 10.1007/s 11769-012-0525-1

1 Introduction

The formation and variation law of runoff in a basin are generally influenced by natural and human factors. Natural factors mainly refer to climate change (Yang *et al.*, 2010). Human factors manifested through deforestation, forestation, land reclamation, urban development, and other types. Human activities, the predominant driving force affecting runoff change (Roland, 2000; Booth *et al.*, 2004; Chen *et al.*, 2006), have attracted increasing attention (Zhang *et al.*, 2004; Li and Li, 2008; Tang *et al.*, 2009). Land use change is one of the main causes of decreasing runoff (Bronstert *et al.*, 2002), it alter the characteristics of the underlying surface, affecting all aspects of the hydrological cycle. At regional scale, land use change has also been the primary factor affecting hydrological regimes and ecological succession processes. One of the principal issues in the research programs of land use/cover change constructed by the International Geosphere-Biosphere Program and International Human Dimensions Program is to reveal the influences of land use and cover changes on hydro-

Received date: 2011-03-22; accepted date: 2011-11-23

Foundation item: Under the auspices of National Natural Science Foundation of China (No. 40830535, 41001110, 41101092, 41171092), National Basic Research Program of China (No. 2010CB951304), the CAS/SAFEA (Chinese Academy of Sciences/State Administration of Foreign Experts Affairs) International Partnership Program for Creative Research Teams, 'Eleventh Five-Year' Key Technological Projects of Heilongjiang Province Farm Bureau (No. HNK10A-10-01, HNK10A-10-03)

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logical processes and water resources. Land use change will alter temperature, moisture of soil and evaporation and transpiration process, resulting in regional climate change. Land use often interacts with climate, and consequently influence river hydrological regimes in together. Therefore, the causes, processes, and influences of climate and land use change are crucially important in studying runoff change and its influencing factors in regional scale.

The Naoli River is one of the typical rivers in the Sanjiang Plain, Northeast China. A large-scale reclamation has happened in the Naoli River Basin in the past 50 years, which has resulted in a significant change in landscape types and ecological environment; this reclamation also brought a profound effect on the hydrological regime of the Naoli River (Wu *et al.*, 2006). With the increasing global atmospheric temperature, meteorological features of the Naoli River Basin have changed because of the combined effects of natural condition changes and human activities. In the past 50 years, atmospheric temperature and precipitation manifested an increasing and decreasing trends, respectively (Yao *et al.*, 2009). These manifestations may cause a series of changes in the hydrological conditions and water resources of the Naoli River and would have a dramatic influence on the environment and socio-economic development. The Naoli River supplies most of the water for this region and plays an important role in the local development. Therefore, the causes of hydrological and water resources change in the Naoli River Basin are necessary to investigate.

In recent years, many scholars have conducted several researches on water conditions as well as land use and climate changes in the Naoli River Basin (Cui and Liu, 2001; Hou *et al.*, 2004; Yao, 2009). After decades of reclamation, the ecological and environmental characteristics in the Naoli River Basin have changed greatly, which decreased the wetlands and expanded the farmlands (Cui and Liu, 2001; Luo *et al.*, 2002; Wu *et al.*, 2006). This profoundly changed the hydrological regime of the Naoli River in space and time; in addition, both annual runoff amount and runoff depth continuously decreased. Agricultural activities are speculated to be the main causes of decreasing runoff in the Naoli River, wherein human activities contribute to 62%–71% of decreasing runoff in the Naoli River (Luan *et al.*, 2007).

However, previous studies focused on some hydrological parameters, such as annual runoff amount and runoff depth, to reveal hydrological regime changes. Less systemic work has addressed the hydrological cycle change and runoff allocation characteristics, which is significant for further understanding about how river hydrological regimes respond to human activities. In the present work, the runoff change tendency and hydrological cycle change law of the Naoli River over the past 50 years were analyzed systematically, and the main driving forces of runoff change were discussed to provide scientific basis for the sustainable utilization of water resources and reveal water cycle comprehensively.

2 Materials and Methods

2.1 Study area

The Naoli River Basin, located in the hinterland of the Sanjiang Plain in Northeast China, has a temperate humid and semi-humid continental monsoon climate. The average annual temperature and annual precipitation in the basin are 3.5℃ and 518 mm, respectively; the rainfall from March to September accounts for 72% of the annual precipitation. The total area of the basin is 24 863 km^2, occupying a quarter of the total area of the Sanjiang Plain. The Naoli River, the primary tributary of the Wusuli River, originates from the Qliga Mountain of the Wanda Mountain in Boli County, Heilongjiang Province and flows into the Wusuli River in the Dong′an Town of Raohe County. Its overall length is 283 km. The basin is low-lying and flat, with extensive floodplains. Poor surface runoff facilitates the formation and development of wetlands.

Agricultural reclamation in the Naoli River Basin has been active since the foundation of the People′s Republic of China in 1949, especially after 1980, when the economy developed quickly. Food production in this region was a quarter of the total food production in the Sanjiang Plain in the early 1990s, making this region an important commodity grain base of China. Large-scale land exploitation in the Naoli River Basin decreased the wetland area, of which ecological characteristics obviously changed (Liu, 1995; Han *et al.*, 1996). The degeneration and loss of massive wetlands would certainly affect the hydrological process of wetlands and consequently have a profound effect on the hydrological regimes of marshy rivers (Jansen *et al.*, 2001; Maltchik *et al.*, 2007; Chaouche *et al.*, 2010).

2.2 Data sources

A long series of observation data exist in the hydrological and meteorological stations of the Naoli River Basin. In the present study, the hydrological data used were the monthly runoff data of the Baoqing, Bao′an, Caizuizi and the Hongqiling stations (Fig. 1). Time series of hydrological data were from 1957 to 2009 for Bao′an station, from 1955 to 2009 for Baoqing station, from 1956 to 2009 for Caizuizi station and from 1978 to 2009 for Hongqiling station. The data from 2002 to 2004 were lacking. Meteorological data were collected from the Baoqing region, including the average annual precipitation, average annual atmospheric temperature (AAT), average annual highest atmospheric temperature (AHT), and average annual lowest atmospheric temperature (ALT) from 1957 to 2005. The meteorological data were from the Heilongjiang Meteorological Data Sharing Center and the Heilongjiang Statistical Yearbook (2006). The land use data of six periods from 1954 to 2005 were from the Wetland Database of Northeast China, which is affiliated to the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences.

2.3 Hydrological parameters

The uneven coefficient of annual runoff distribution (C_{vy}) can comprehensively reflect the changes in runoff distribution characteristics. Its formula is as follows (Shi, 1964):

$$C_{vy} = \sqrt{\frac{\sum_{i=1}^{12}\left(\frac{K_i}{\overline{K}} - 1\right)^2}{12}}$$

where K_i is the ratio of monthly runoff to annual runoff in month i (%) and $\overline{K}$ is the percentage of average monthly runoff of a year (8.33%).

Runoff module ratio (K) is the ratio of runoff in a certain period to the average annual runoff. $K = 1$ suggests that runoff in this period is equal to the average annual runoff, and $K < 1$ indicates that runoff is decreasing. The formula is as follows (Shi, 1964):

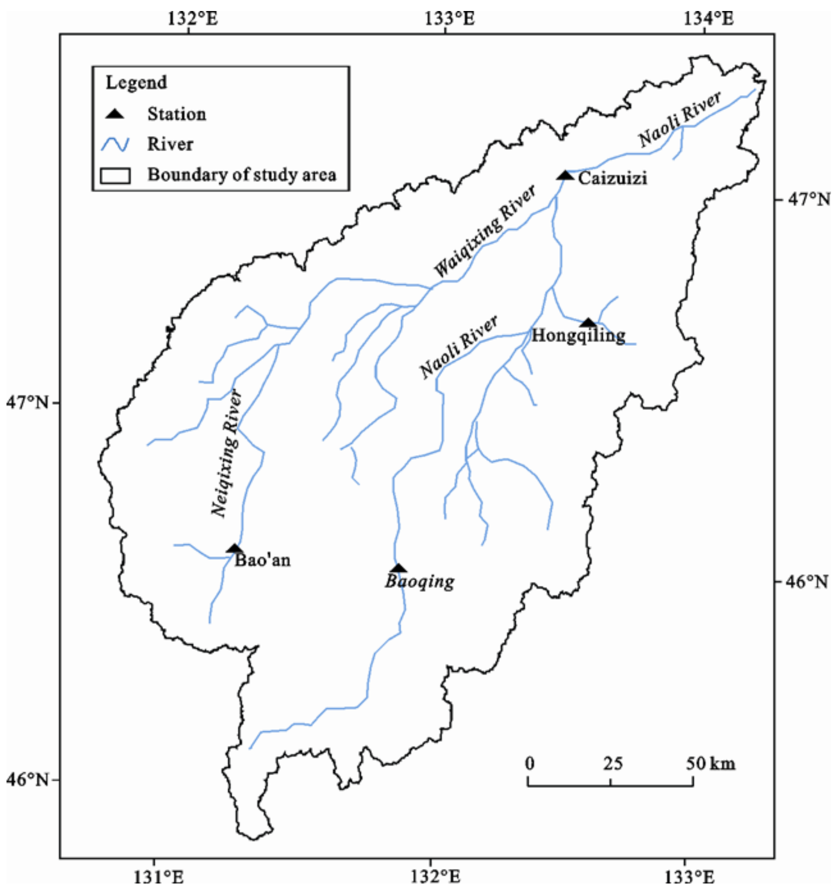


Fig. 1 Locations of hydrological stations in study area

$$K = \frac{Q_i}{Q_0}$$

where Q_i is the runoff in period i and Q_0 is the average annual runoff.

3 Results

3.1 Tendency of annual runoff

For the study period of 1955–2009, the order of the average annual runoff of the four hydrological stations is as follows: Caizuizi > Baoqing > Hongqiling > Bao′an (Fig. 2). The runoff generally followed a decreasing trend; however, the rate of decrease varied. Hongqiling station had the lowest rate. In 2009, the runoff volumes in Bao′an, Baoqing, and Caizuizi stations were 1.79×10^9, 2.80×10^9, and 8.30×10^9 m^3, respectively, and had decreased by 64.1%, 76.3%, and 84.3% compared with those in 1957. Caizuizi station showed the largest decrease rate of 4.15×10^8 m^3/yr followed by Baoqing station, 1.21×10^8 m^3/yr. Bao′an station was the third, 3.70×10^7 m^3/yr.

3.2 Distribution characteristics of seasonal runoff

Similar with other rivers in Northeast China, two flood seasons occur every year in the Naoli River, exhibiting a ′bimodal′ distribution (Fig. 3). The first flood season usually stars from March and ends in late June and early July, and the peak appears in May. The second flood season occurs from late July to October when the runoff volume is larger than the first flood because the runoff is mostly concentrated, and the peaks appear in August for Baoqing, Bao′an and Hongqiling station and in October for Caizuizi station. Runoff during flood seasons has decreased since the 1950s, especially during the secondary flood seasons. In the 2000s, no obvious flood was observed from March to July in Baoqing and Bao′an stations, and the runoff of Baoqing and Bao′an stations in August decreased by 77.5% and 78%, respectively, compared with that in the 1950s. In Caizuizi station, only one remarkable flood peak was observed in May of the 2000s and the secondary flood peak disappeared. The runoff of Caizuizi station in May of the 2000s had decreased by 62.1% compared with that in the 1950s. In Hongqiling station, although the runoff in August somewhat decreased from the 1970s to the 2000s, the summer flood was still obvious. Runoff change and flood appearance seemed simultaneous in the Baoqing and Bao′an stations. The monthly runoff in Caizuizi station was more uniform, and its flood season occurrence

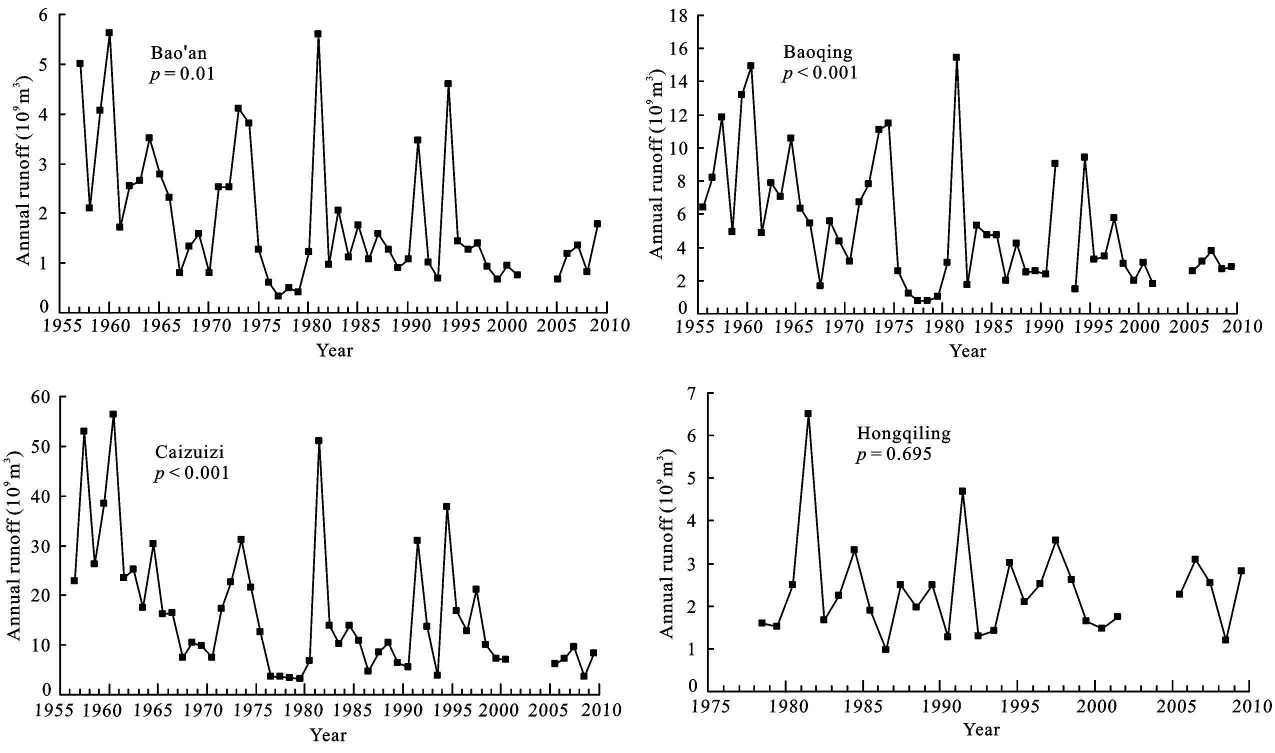


Fig. 2 Runoff variation of Naoli River in study period

was later than the other stations, which may result from flood regulation and the storage role of shore side wetlands along the Naoli River.

3.3 Distribution characteristics of annual runoff

The analysis of uneven coefficient of annual runoff distribution (C_{vy}) at Bao′an, Baoqing, Caizuizi, and Hongqiling showed that the C_{vy} of the four hydrological stations was 0.64–2.25, wherein the average value was 1.22. The C_{vy} of the Naoli River was higher than those of other rivers because the area of Naoli River Basin is smaller, and its supply mode is single.

The C_{vy} analysis of the annual runoff in a 10-year interval indicated that C_{vy} differed greatly with stations and increased, with some fluctuations, in all four hydrological stations for the past 50 years (Fig. 4). The variability coefficients of Bao′an, Baoqing, Caizuizi, and Hongqiling stations were 25.26%, 22.09%, 22.67%, and 20.12% respectively. This result indicates that the largest and smallest fluctuations occurred in Bao′an and Hongqiling stations, respectively. In the sub-basin of Bao′an station, reclamation activities were widespread

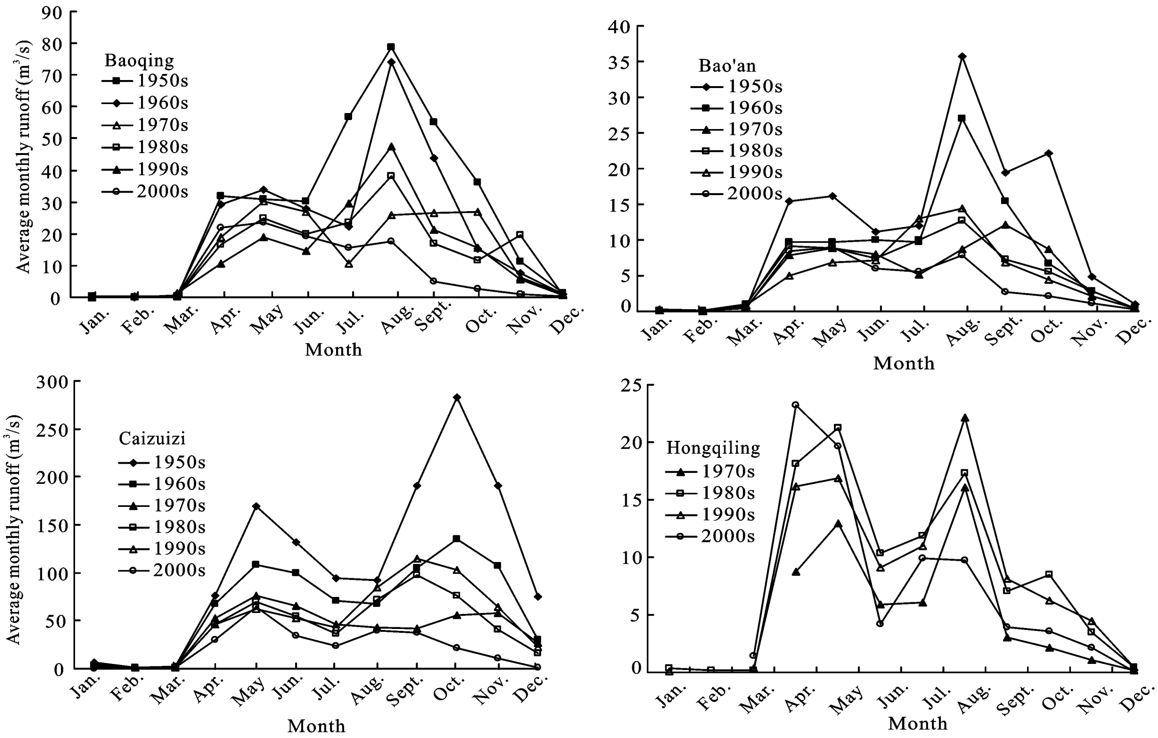


Fig. 3 Seasonal runoff variation of Naoli River

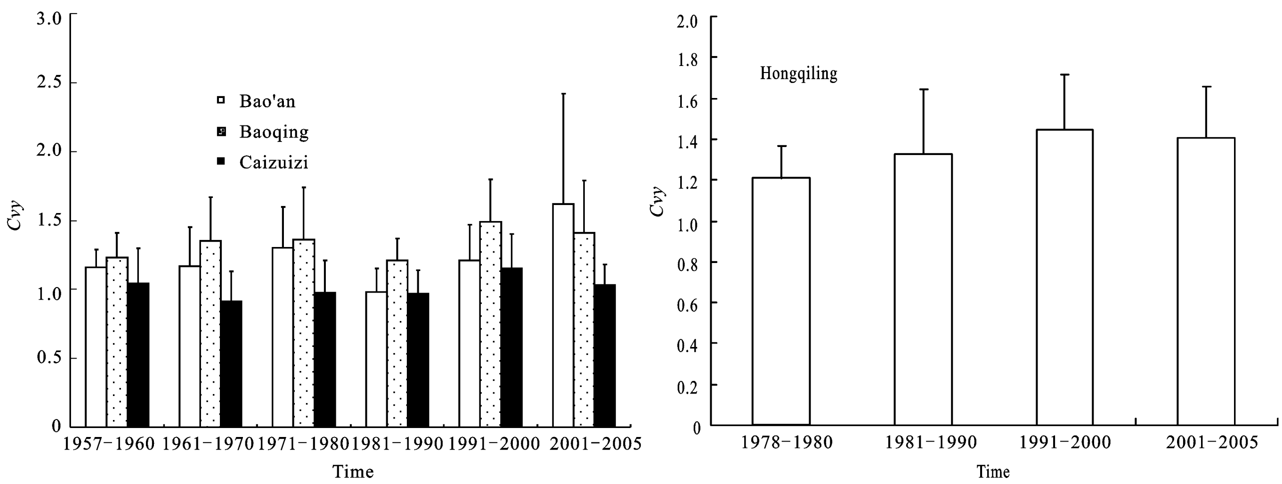


Fig. 4 Change of uneven coefficient of annual runoff distribution (C_{vy}) of four hydrological stations in study period

and wetland areas were almost lost, which decreased the runoff adjustment abilities of the wetlands and increased the fluctuations of C_{vy} in the area. By contrast, human activity in the Hongqiling watershed is the slightest among the four stations and wetland area is greater, resulting in strong adjustment ability on runoff and a relatively less fluctuating C_{vy}.

3.4 Change characteristics of runoff module ratio (*K*) in past 50 years

K has decreased for the past 50 years in the Naoli River Basin, which suggests that the runoff is lower than the average annual runoff (Fig. 5). Among the four hydrological stations, 51.7%–64.0% of the total years were recorded with $K < 1$, wherein Caizuizi station had the highest percentage. $K < 1$ occurred the most after the 1970s. During the beginning years to 1969 in the Bao′an, Baoqing, and Caizuizi stations, four years were recorded with $K < 1$, which is only approximately 12.9% of the total recorded years, whereas all other records occurred after the 1970s.

3.5 Changes of wet and dry years

In hydrology, wet year is defined as the year when runoff is greater than normal annual runoff, whereas dry year refers to the opposite. Wet and dry years often appear continuously in alternating cycles. For the past 50 years, the dry years of the Naoli River occurred much longer than the wet years (Table 1). The average module ratios of Baoqing, Bao′an, and Caizuizi stations were all larger than 1 when the time step from 1957 to 1967 was set as 10 years. This result suggests that wet years are predominant in that period. During 1968–1977, 1978–1987, 1988–1997, and 1998–2009, the average module ratios of the three hydrological stations were all less than 1. This result indicates that most years after the 1970s are dry.

The average module ratio in the Bao′an station during

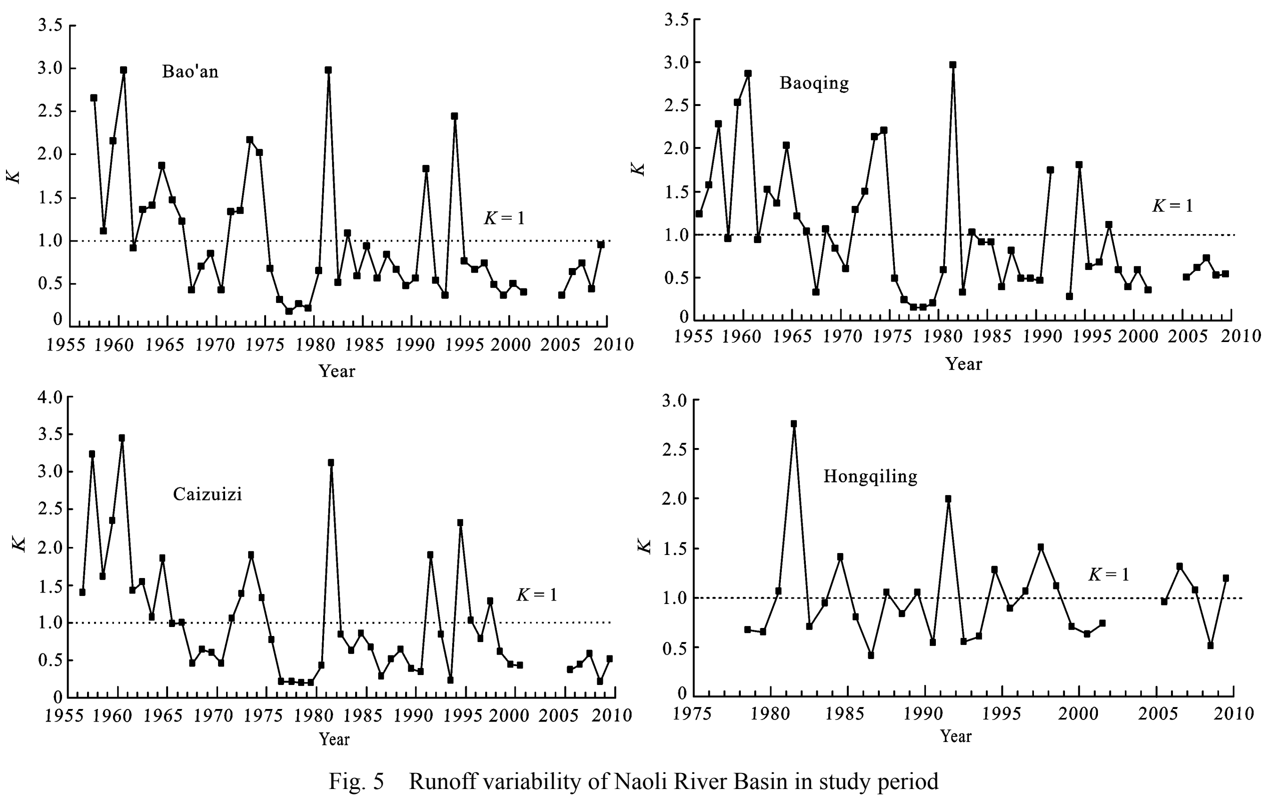


Fig. 5 Runoff variability of Naoli River Basin in study period

Table 1 Change of continuous wet and dry years in Naoli River Basin

Station	Dry years	Wet years	Continuous dry years	Continuous wet years
Bao′an	33	17	1975–1980, 1984–1990, 1992–1993, 1995–2009	1957–1966, 1971–1974
Baoqing	31	20	1975–1980, 1984–1990, 1995–1996, 1998–2009	1955–1960, 1962–1966, 1971–1974
Caizuizi	31	19	1975–1980, 1982–1990, 1992–1993, 1998–2009	1956–1964, 1971–1974

1957–1966 was 1.71. This result suggests that the years during this period were continuously wet. However, the average module ratio during 1967–1970 was 0.60. This result indicates that these four years were continuously dry. The years from 1971 to 1974 were continuously wet, wherein the average module ratio was 1.72. However, the wet years halted from 1975 to 2009, and four series of dry years occurred (Table 1). The average module ratio was 0.74 in period 1975–2009. This result suggests that the dry years appeared more frequently, and cycle time was becoming shorter. The wet years continued to decrease, and the cycle time became longer. The occurrence of consecutive wet years decreased. In 1957–1975, the frequency of dry year occurrence was 27.8%, but this frequency increased to 87.5% in 1975–2009 (data not shown for 2002–2004).

Data from the Baoqing station indicate that continuous wet years occurred in 1955–1966 (except 1961), wherein the average module ratio was 1.63. Dry years were found between 1966 and 1970, wherein the average module ratio was 0.71, except for 1968, when it was 1.03. The years of 1971–1974 were continuously wet, wherein the average module ratio was 1.78. The average module ratio in 1975–2009 was 0.70. No continuous wet years were found during this period, but four series of continuous dry years occurred (Table 1) (data not shown for 2002–2004). The frequency of dry year occurrence was 25% in 1955–1974, which increased to 83.9% in 1975–2009.

Data from the Caizuizi station indicate that continuous wet years occurred in 1956–1964, wherein the average module ratio was 1.99. The years of 1965–1971 were continuously dry, wherein the average module ratio was 0.69. The years during 1971–1974 were wet, wherein the average module ratio was 1.41. No continuous wet years occurred during 1975–2009, but four series of dry years occurred (Table 1) (data not shown for 2002–2004). The frequency of dry year occurrence increased from 26.3% in 1956–1974 to 83.9% in 1975–2009.

The cycle periods of wet and dry years of the Naoli River have changed for the past 50 years. The frequency of wet year occurrence reduced, and the cycle period became longer. The frequency of dry year occurrences increased from 25.0%–27.8% to 83.9%–87.5% from 1955 to 2009. Before the 1970s, wet years were predominant. However, dry years accounted for majority of the records after the 1970s.

4 Discussion

4.1 Effect of precipitation and temperature on runoff

Precipitation is a direct water source of the Naoli River and the main source of summer flood formation. The magnitude and strength of precipitation and its changes in space and time directly affect the hydrological regime of the Naoli River. For instance, the correlation coefficient between annual precipitation and runoff in Baoqing station was 0.91, and the significance level (P) was lower than 0.01. This result suggests that precipitation plays a determinant role in runoff change. The analysis based on meteorological data in Baoqing station indicates that precipitation in the area has decreased for the past 50 years, suggesting the same tendency with runoff changes (Fig. 6).

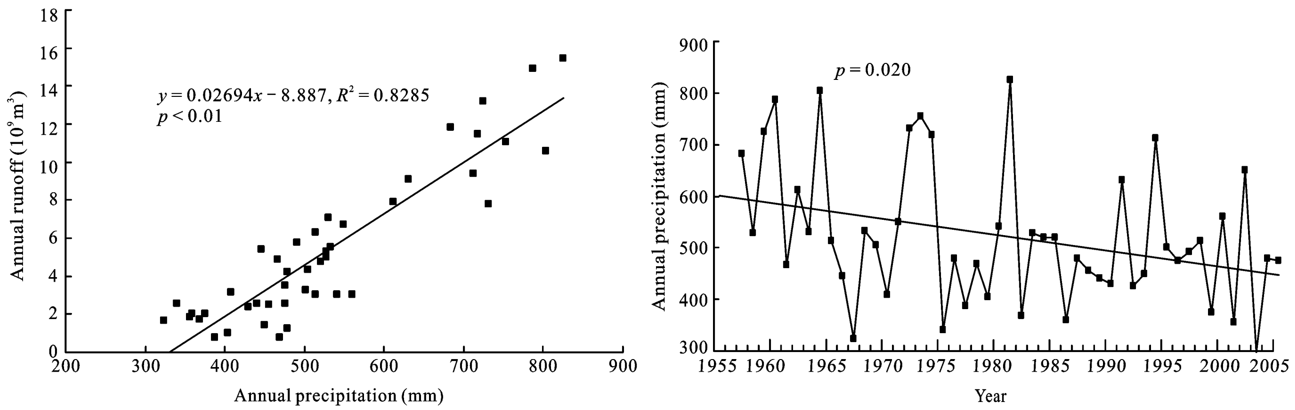
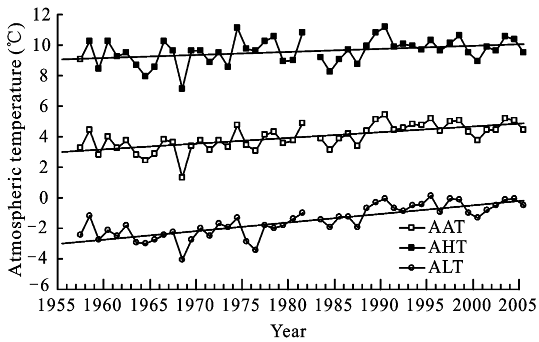


Fig. 6 Relationship between annual precipitation and annual runoff at Baoqing station in study period

Results showed that AAT, AHT, and ALT have all increased in the Baoqing region for the past 50 years (Fig. 7). The AAT, ALT, and AHT in 1957–2005 increased from 3.27℃ to 4.46℃, –2.43℃ to –0.49℃, and 9.06℃ to 9.53℃, respectively. ALT increased the largest. The increasing rates of ALT, AHT, and AAT were 0.0199, 0.0566, and 0.0386 ℃/yr, respectively. Although correlation analysis showed no significant correlation between increasing atmospheric temperature and decreasing runoff, the melting of ice and snow and evaporation due to increasing atmospheric temperature would consequently affect runoff change in the Naoli River.



AAT, average annual atmospheric temperature; AHT, average annual highest atmospheric temperature; ALT, average annual lowest atmospheric temperature

Fig. 7 Atmospheric temperature changes of Baoqing station in 1957–2005

4.2 Effect of land use change

Land use change is the main cause of runoff decrease at the regional scale (Li *et al.*, 2007). From 1954 to 2005, the main characteristics of land use change in the Naoli River Basin were as follows: fast growth of cultivated land and rapid decrease of unused land (Fig. 8). For the past 50 years, the area of cultivated land has increased more than three times, whereas the area of unusedland has decreased by 82.9%. The analysis on the sub-classification land use of unused land indicates that marshes account for the majority of lost unused land, which resulted from the strategic requirement for grain in the early stage of People's Republic of China, when a large quantity of demobilized soldiers marched to the Sanjiang Plain and established many large state-owned farms. Four farm administrations exist, two of which are located in the Naoli River Basin, which accelerated wetland reclamation. Large-scale wetland loss changed the underlying surface characteristics and consequently affected hydrological regime of the Naoli River. However, the great increase of farmland required more water for irrigation, which further decreased runoff.

Runoff change and trends in the wetland area of Caizuizi station were studied. Results show that runoff significantly fluctuated with reducing wetland area (Fig. 9). From the 1950s to the mid 1980s, runoff decreased sharply because of weak adjustment abilities of wetland on hydrological regimes caused by wetland loss and reclamation. Runoff had decreased from 2.74×10^{10} m^3 in the 1950s to 5.00×10^9 m^3 in the mid 1980s. Since the mid 1980s, national policies of reducing wetland reclamation in the Sanjiang Plain were implemented, and reclamation happened mostly on some small and scattered wetlands. In addition, wetland protection and restoration have caused increasing attention during this period, resulting in improved adjustment abilities of

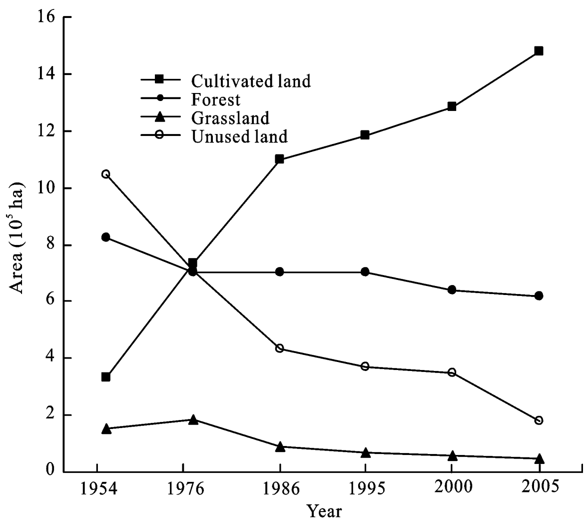


Fig. 8 Land use changes of Naoli River Basin in 1954–2005

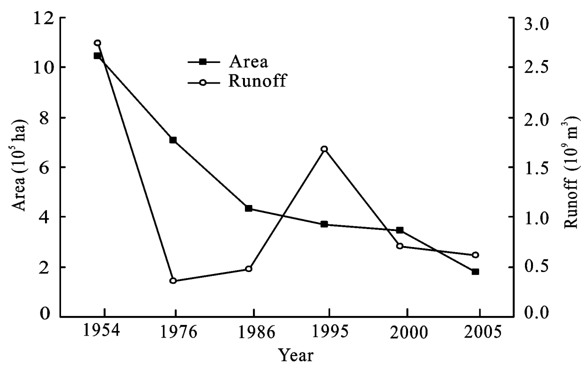


Fig. 9 Change of unexplored land area and runoff of Caizuizi station in study period

wetlands on the runoff. The runoff significantly increased from the mid 1980s to the mid 1990s. At the end of the 1990s, a large area of dry farmland was changed into paddy field, and agricultural water increased greatly, which sharply decreased runoff.

The exploitation and utilization of water resources are direct influencing factors for runoff decrease in the Naoli River Basin. Since the late 1950s, a series of water logging elimination and drought prevention engineering projects were constructed in the basin, including intensive drainage channels, irrigation systems, flood detention districts, levees, and dams, among others (Liu and Li, 2005). A drainage system of 1215 km^2 is currently present in the Naoli River Basin. The flood detention district of the Heiyu Pond was built at the upstream of the Waiqixing River; some new water conservancy projects, such as the new Waiqixing River and the Zhi River in Fujin County, were constructed. Forty big and small reservoirs were built in the basin (Liu, 2005), five of which are relatively large (Table 2). These dams and reservoirs have changed hydrological regimes and river habits to some extent; they served as a partial runoff storage, which played a certain role in runoff reduction in the Naoli River. By 1998, some dams of 1009.3 km length were also built along the channels of the Naoli River for flood prevention (Liu *et al.*, 2007). A good number of drainage ditches were built, which further affected the spatial and temporal processes of hydrological regimes (Hopkinoson and Vallino, 1995).

Table 2 Five reservoirs and their controlling area in Naoli River Basin

Reservoir	Controlling area (km^2)
Longtouqiao	1730
Xiamutong	472
Qing River	265
Jubaoshan	142
Jinsha River	104

5 Conclusions

The Naoli River Basin was selected as the study area. Annual and seasonal changes in the features of runoff and its driving mechanisms were analyzed according to the data from four hydrological stations. Findings of the current study could provide scientific basis for regional water resources management. The following conclusions were obtained throughout the current study:

(1) During the study period of 1957–2009 for Bao′an station, 1956–2009 for Caizuizi station, 1955–2009 for Baoqing station, and 1978–2009 for Hongqiling station, Naoli River runoff has generally decreased and was more obvious during the summer flood. After the 2000s, no significant summer flood was observed in the Baoqing, Bao′an, and Caizuizi stations. Compared with other large rivers, the seasonal runoff distribution in the Naoli River was more uneven and demonstrated a ″bimodal″ distribution. The cycle periods of wet and dry years have changed, wherein the frequency of wet years reduced. The cycle period became longer, and the frequency of dry years increased. Before the 1970s, wet years were predominant. However, dry years accounted for most of the records after the 1970s.

(2) Decreasing precipitation and changes in land use were the two main reasons for runoff reduction in the Naoli River Basin. Rising atmospheric temperature and construction of water conservancy projects also affected the runoff change features in space and time.

Acknowledgements

We would like to thank Chen Zhike and Xue Zhenshan who assisted us with the maping work. We are also grateful to Wang Rongfen who kindly checked the language.

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