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RESEARCH ARTICLE

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Effect of climatic change and afforestation on water yield in the Rocky Mountain Area of North China

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Abstract

Aim of study: We studied effects of climatic variability and afforestation on water yield to make a quantitative assessment of the hydrological effects of afforestation on basin water yield in the Rocky Mountain Area of North China.

Area of study: Seven typical forest sub-watersheds in Chaobai River watershed, located near Beijing's Miyun Reservoir, were selected as our study object.

Material and methods: Annual water yield model and Separate evaluation method were applied to quantify the respective contributions of changes in climate and different vegetation types on variations in runoff.

Main results: Statistical analysis indicated precipitation did not vary significantly whereas the annual runoff decreased significantly in the past decades. Although forest increased significantly in the late 20th century, climatic variations have the strongest contribution to the reductions in runoff, with the average contribution reaching 63.24%, while the remainder caused by human activities. Afforestation has a more positive impact on the reduction in runoff, with a contribution of 65.5%, which was more than the grassland of 17.6% and the farmland of 16.9%.

Research highlights: Compared to the impact of climatic change, we believe the large-scale afforestation may not be the main reason for the reductions in basin water yield.

Keywords: Annual water yield model; Separate evaluation method; North China.

Abbreviations: AWY-Annual water yield model; *AET*-actual evapotranspiration; *Y*-annual water yield; *P*-precipitation; *R*-runoff; *T*-temperature.

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Introduction

North China, covering an area of more than 1.5 million km^2, is one of China's six administration regions, and has a very important political, economic and cultural position in China. Since the latter half of the 20th Century, this region has suffered from severe water shortages and soil erosion as a result of several natural and anthropogenic causes (Xia *et al*., 2007). To control severe soil and water losses, several large-scale forestation programs, such as the Returning farmland to forest project, Desertification control program and the wind breaker belt project in the north, have been implemented in the past few decades (Li, 2004). Over the past 20 years in particular, comprehensive control of soil erosion has brought noticeable improvements, and soil erosion in North China has been effectively controlled by afforestation and construction of water conservancy projects (Wei *et al*., 2005).While the natural eco-environment of North China improves effectively, the water yield from the mountain areas, which are essential sources of freshwater supply for urban people, showed a significant decreasing trend (Xia *et al.*, 2004). Taking the Miyun reservoir as an example, the average annual inflow to the reservoir during the period of 1980–1997 had decreased by 0.4 billion m^3, compared with the period of 1960–1979 (Wang *et al.*, 2000). Reductions in runoff from the mountains have put tremendous pressure on the ecological environment (Liu & Wei, 1989). Water resources issues in North China have received considerable attention from the Chinese government. At this time, some researchers believe that afforestation was primarily responsible for reducing basin water yield, and was also responsible for accelerating the shortage of water resources (Wang & Zang., 2001; Sun *et al.*, 2006; Wei *et al.*, 2008), which have directly affected the development of the local forestry, and also had a indirectly negative impact on the social and economic development in this region. Hence, it is urgent to understand forest and water relations in the Rocky Mountain area of North China, especially in the water source protection areas, for providing a theoretical reference for basin water resources management and forestry planning in future.

In general, climatic variation and land use change were usually considered as key factors controlling the hydrological behavior of forest watershed by affecting the generation of runoff and soil moisture (Wang *et al.*, 2011a). Climatic variables, especially rainfall, largely determine the runoff volume of a catchment (Wang *et al.*, 2009). Moreover, land use change caused by forestation practices result in significant impacts on hydrology by affecting the characteristics of watershed evapotranspiration, soil moisture, infiltration and groundwater recharge over a range of temporal and spatial scales (Gabris *et al.*, 2003; Farley *et al.*, 2005). During the past few decades, land-use changes vary dramatically in North China, mainly due to the influence of implementation of afforestation project. Increase in forest area will inevitably have an important impact on the local water balance. Furthermore, it will increase ET and reduce the annual water yield at the watershed-scale, which will also exacerbate water shortages in this region.

During the past century, much progress has been made in understanding forests and associated water relations around the world (*e.g.* Bosch & Hewlett, 1982; Sahin & Hall, 1996; Robinson *et al.*, 2003; Andreassian, 2004). Although there is a large variability due to differences in climate, vegetation, terrain and soils conditions, these studies all suggest that deforestation generally increases water yield, and afforestation reduces the annual runoff for most watersheds. Simultaneously, much progress has also been made in Chinese forest hydrology research (*e.g.* Yu 1991; Wang & Zhang, 2001; Sun *et al.*, 2006; Wei *et al.*, 2008; Wang *et al.*, 2011b). Liu and Zhong (1978) reported that forest watersheds have a lower water yield (25 mm/yr) than adjacent basins with lower forest coverage in northwestern China. Sun *et al.* (2006) suggests that the average water yield reduction may vary from about 50 mm/yr (50%) in the semi-arid Loess Plateau region in northern China to about 300 mm/yr (30%) in the tropical southern region. Wang *et al*. (2011a) using a variety of published data showed there is a positive relationship between forest cover and the runoff coefficient (r = 0.77, $p < 0.05$) in Northeast China. However, contradictory reports on the impact of forest on water yield also exist. For example, Ma (1993) suggested that basins with higher forest coverage generally had higher runoff/rainfall ratios through comparing stream flow from 10 large basins (>100 km^2) in the Yangze River basins. Similar positive correlations between forests and water yield for large basins were reported for northern China (Wei *et al.*, 2003). Why are there different conclusions about the relation between forest and runoff? Wei *et al*. (2008) argued that the effects of afforestation on runoff are not consistent, for there have been only a limited number of paired catchment studies undertaken in China.

The above studies have shown there is uncertainty and variability with the relationship between forestation on potential hydrologic responses across China due to the large differences in climate and watershed characteristics (Sun *et al.*, 2006). Although numerous studies have been conducted in some regions and significant progress has been made in understanding forest-water relations, it is often difficult to reach a consensus on the issue of the relationship between forest and water yield, especially at the large spatial scales, and a comparative multi-basin synthesis on forest–water relationships is still needed. This is especially critical in the Rocky Mountain of northern China that has been experiencing chronic water shortages (Wang *et al.*, 2011a). More importantly, a key issue is that current knowledge about the impacts of forestation on annual runoff at different scale within the Rocky Mountain Area of North China remains too limited to support the regional forestry development and associated water resources management. Therefore, we examined seven case study basins in this region to determine the reason for the reduction of water yield from the mountain areas and provide an objective assessment of the effects of afforestation on catchment runoff.

Hydrologic models and the classic paired-catchments approach have been widely applied for determining changes in water yield caused by land use change through excluding the effects of other environmental variables (Brown *et al.*, 2005; Wagener 2007; Franczyk & Changk, 2009). However, the lack of standard paired watershed experiments has impeded to the development of forest hydrology research in China (Wei *et al.*, 2008). Hydrological models also require a lot of data which may be unavailable, particularly spatial data representing the landscape structure and its catchment properties. There is little solid, long-term (>40 years) scientific data available from studies in China (Wei *et al.*, 2008). Due to these limitations, a method which has a sound scientific base and is of great practical use is highly desirable. Therefore, the annual water yield model (AWY) developed by Sun *et al*. (2005) and separate evaluation methods, which have been proved to be applicable in North China (Zhao *et al.*, 2012), were applied to explore the main reason for the reduction of water yield in the typical forested watershed of North China. Moreover, a further objective is to provide sound scientific, quantitative information on the potential hydrologic consequences of forestry management in different regions, and offer guidance for policy making in forestation programs in North China.

Materials and Methods

Study area

The study region is the earth-rocky mountain area which is located in North China. This area is the source of most of northern cities' water supply. Miyun Reservoir, located in this region, is one of the major water supplies for Beijing. In recent years, this region has experienced a severe water resource shortage (Xia *et al.*, 2007). Reductions in water yield from the mountains have exacerbated the water shortage problem. To explore the impact of afforestation on basin water yield, seven forested subwatersheds located in the Chaohe and Baihe watershed, the most important water source for Miyun Reservoir, were selected as our study area. No water conservation measures exist in these basins which are located upstream of the Miyun Reservoir. With the implementation of the afforestation project, the watershed forest coverage has changed greatly, and the average forest coverage reached about 60% in the late 20th century. The locations and descriptions of the basins selected for this study are shown in Figure 1 and Table 1, respectively. All of them possess a semi-arid climate. In addition, the field research did not involve endangered or protected species and no specific permits were required for the associated field research.

Data collection

Four satellite images of the study watersheds were obtained from the Institute of Geographic Sciences and

Table 1. Characteristics of watersheds.

No	Watershed	Sub-watershed	Area/km^2	Forestry cover/%	Mean precip. (mm/year)	Mean PET mm/year	Mean water yield mm/year
1	CHAOHE	HONGMENCHUAN	110.54	81	446	1082	122
2		BANGCHENGZI	66.10	96	657	1043	89
3		DAGE	1659.93	57	520	995	50
4		DAIYING	4633.48	65	568	1002	53
5		XIAHUI	1536.18	63	591	1006	51
6	BAIHE	XIABU	1193.23	38	441	1004	29
7		SANDAOYING	5890.50	69	534	1003	52

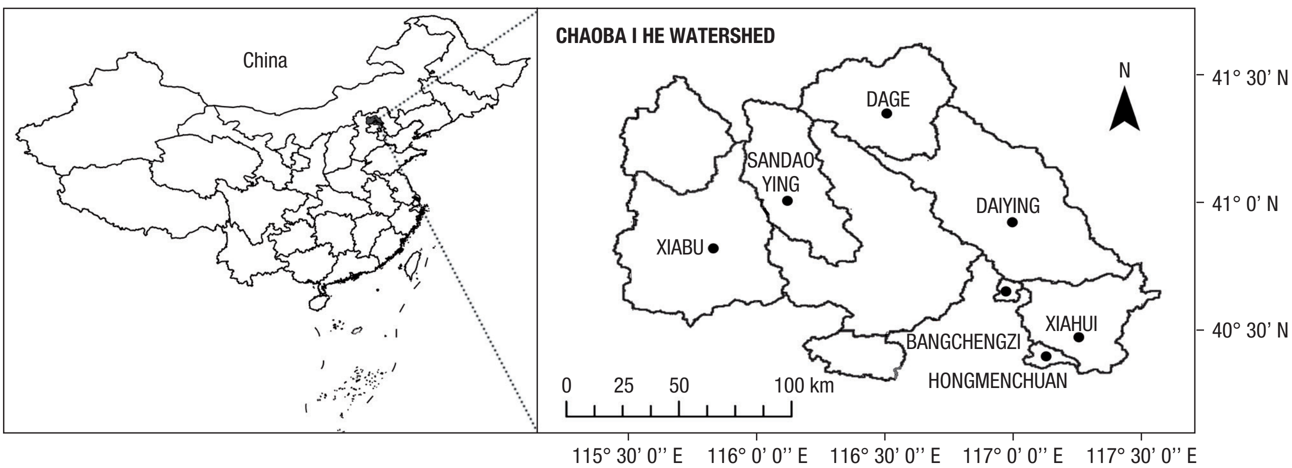

Figure 1. Location of the study region.

Natural Resources Research, Chinese Academy of Science (CAS). Using ArcGIS9.3, land use structure and land cover change of the watersheds were obtained through overlay analysis. According to the national land-use classification system (2001), six land uses such as forest, farmland, grassland, settlements, water body and unused land were identified.

Daily precipitation data from 38 rain gauging stations in the Chaobai River watershed were collected for the period 1975 to 2008. Air temperature and other meteorological factors including relative humidity, solar radiation and wind speed were derived from seven national weather stations. Daily runoff data for each watershed were collected from the Hydrological Yearbook of Chaobai River.

Annual water yield model

The AWY model was developed by Sun *et al.* (2005) in southeastern United States. This model is based on actual evapotranspiration (*AET*) changed by land use.

Regional annual water yield (*Y*) at a meso-scale can be estimated as the difference between precipitation (*P*) input and actual evapotranspiration (*AET*) output:

$$Y = P - AET \tag{1}$$

The *AET* can be described and estimated by the following formula:

$$AET = \frac{1 + w\dfrac{PET}{P}}{1 + w\dfrac{PET}{P} + \dfrac{P}{PET}} \times P \tag{2}$$

where, *PET* is potential evapotranspiration (mm); *w* is the plant-available water coefficient and represents the relative differences of water use for transpiration. Our previous studies (Zhao *et al.*, 2012) calibrated the *w* parameter, and found that *w* coefficients were 1.5 for grass and farmland, 2.8 for forests and 0 for a water body, and settlements provided the best predictions of *AET* in the Chaobai River. To clarify the effects of afforestation on runoff, the deforestation effects on water yield were simulated by a reduction of the *w* parameter from 2.8 to 0.0. The runoff restored was simulated after deforestation, and then the percentage of decreased runoff from forests was calculated. The same method was used to estimate the effects of farmland and grass on runoff.

For a watershed with mixed land uses,

$$AET = \sum\left(AET \times F_i\right) \tag{3}$$

Where, F_i is the percentage of land use; *i* including forest, farmland, grass and water bodies.

Separate evaluation method

Separation evaluation was used to examine the impacts of climatic variability and land use change on runoff. It is critical to determine the inflection point in the runoff records. According to the inflection point of runoff, the study period is divided into two periods, the ‘‘base period’’ influenced slightly by human activities and the ‘‘compared period’’ marking significant changes in land use by human activities and takes the inflection point as the cut-off to reflect the effect of land use change on runoff. The method after Wang *et al.* (2008a) is:

$$W_T = W_{HR} - W_B \tag{4}$$

$$W_H = W_{HR} - W_{HN} \tag{5}$$

$$W_C = W_{HN} - W_B \tag{6}$$

$$\eta_H = \frac{W_H}{W_T} \times 100\% \tag{7}$$

$$\eta_C = \frac{W_C}{W_T} \times 100\% \tag{8}$$

where ΔW_T is the total change of annual runoff; ΔW_H and ΔW_C are the amount of annual runoff affected by human activities and climate change, respectively; W_{HR} and W_{HN} are respectively the measured runoff and natural runoff in human activities over the affected period. W_B is the runoff in the base period. η_H and η_C are the percentages of hydrological variables affected respectively by human activities and climate change.

Results and Discussion

The regional characteristics of land use changes

Based on ArcGIS 9.3, land uses in different periods in the selected watersheds were obtained (Table 2) and shows that the watersheds selected in our study were all dominated by forest land, and the average forest cover generally reached 60% in the late 20th century. In addition, forest areas in the watersheds all exhibited an increasing trend to different degrees, especially around 1998, showing that vegetation restoration pro-

Table 2. Area of land use types in each of four periods in the Chaobai River watershed hm^2.

Watershed	Sub-watershed	Year	Grassland	Water body	Forest land	Farmland	Settlements	Un-used land
CHAOHE	HONGMENCHUAN	1990	1502.08	588.08	9799.76	570.85	243.35	95.88
		1995	1539.75	323.83	9947.04	643.98	264.36	81.04
		2000	1731.89	309.86	9771.62	595.94	289.89	100.80
		2005	1480.01	268.8	9789.43	816.5	350.79	94.47
	BANCHENGZI	1990	102.71	82.19	6357	6.47	20.54	41.09
		1995	86.38	66.57	6399.46	3.81	18.56	35.28
		2000	66.48	69.35	6414.35	13.58	22.15	24.09
		2005	108.97	45.78	6358.38	9.70	25.84	61.35
	DAGE	1978	33200.96	5382.692	85207.70	40408.96	825.25	967.57
		1988	35206.76	4707.66	86910.96	37649.52	832.54	685.68
		1998	18054.61	3275.42	104821.70	38656.03	996.16	188.89
		2008	18751.21	753.28	100679.64	42234.45	2980.49	593.68
	DAIYING	1978	87001.19	12840.99	268158.1	92436.3	1703.46	1208.74
		1988	89934.07	10708.47	275289.4	84814.68	1738.99	863.09
		1998	42912.31	8542.285	326267.6	80758.47	4132.3	735.27
		2008	28493.44	1577.32	337371.51	88075.66	7219.57	609.93
	XIAHUI	1978	101121.8	16201.01	362068.9	106240.1	2131.64	1286.93
		1988	104057.6	14060.67	373710.7	94111.45	2168.43	941.47
		1998	50520.22	11819.61	433696.4	87583.94	4605.56	824.06
		2008	30044.37	2048.17	452005.45	95448.41	8851.82	650.84
BAIHE	XIABU	1978	106557.2	11694.17	128381.2	146222.6	2132.643	1030.279
		1988	117789.4	10635.11	139941.1	124384.1	2158.842	1109.107
		1998	63597.44	7355.91	238021.6	85073.05	1662.437	307.8775
		2008	90094.96	2297.73	195131.22	102678.12	5777.95	37.09
	SANDAOYING	1978	23934.1	4050.42	81904.93	43202.78	493.14	33.0012
		1988	31283.50	2602.08	93169.95	26002.89	538.58	21.3758
		1998	22529.61	1997.994	112066.3	16317.28	554.64	152.3172
		2008	32885.71	610.51	98888.30	19890.51	1343.47	0

ceeded well in North China. At the same time, the reduction of water body area and increase of residential land was another distinctive feature of the land use change in this region.

Dynamics of precipitation, temperature and runoff

Average annual precipitation (P) and air temperature (T) from 1978 to 2008 in the Chaobai River was calculated by using the Kriging interpolation method, and trend analysis was also carried out for the P, T and runoff (R) in this region (Figure 2). This indicates that the long-term average annual precipitation was 437.4mm, ranging from 313 mm to 563 mm. General linear regression analysis found that the average annual precipitation showed a slightly decrease during the research period (p = 0.415) while the mean temperature markedly increased ($p < 0.001$), with a much lower coefficient of variation ($C_V = 0.08$). Due to the warmer and drier climate, annual runoff showed a statistical significant decreasing trend with a much higher annual variation of C_V (0.59, 0.65) in the Chaohe and Baihe watersheds, respectively.

To remove the noise of large variability on trend detection, Nonparametric Kendall's trend test was used to detect the inflection point of data record of P, T and R as it has the capability of handling unusual data records (Wang *et al.*, 2008b). Nonparametric Kendall's trend test indicated that P did not show a significant trend at the 0.05 significance level. The results were consistent with that of the linear regression tests. Compared to the Nonparametric Kendall's test for P, the annual runoff in Chaohe and Baihe watershed both showed a remarkable decreasing trend at the 0.01significance level. One inflection point in 1998 was identified. With this result, the study period may be divided into two parts: a base period (1975-1998) and a compared period (1999-2008). The results were consistent with the variation trend of R/P (Figure 3). Figure 3 shows that the significant decline in R amounts to a change from a runoff ratio (R/P) of approximately 0.11 in the first 24 years of the record to a ratio of approximately 0.04 in the last few years of the record at the 0.05 significance level.

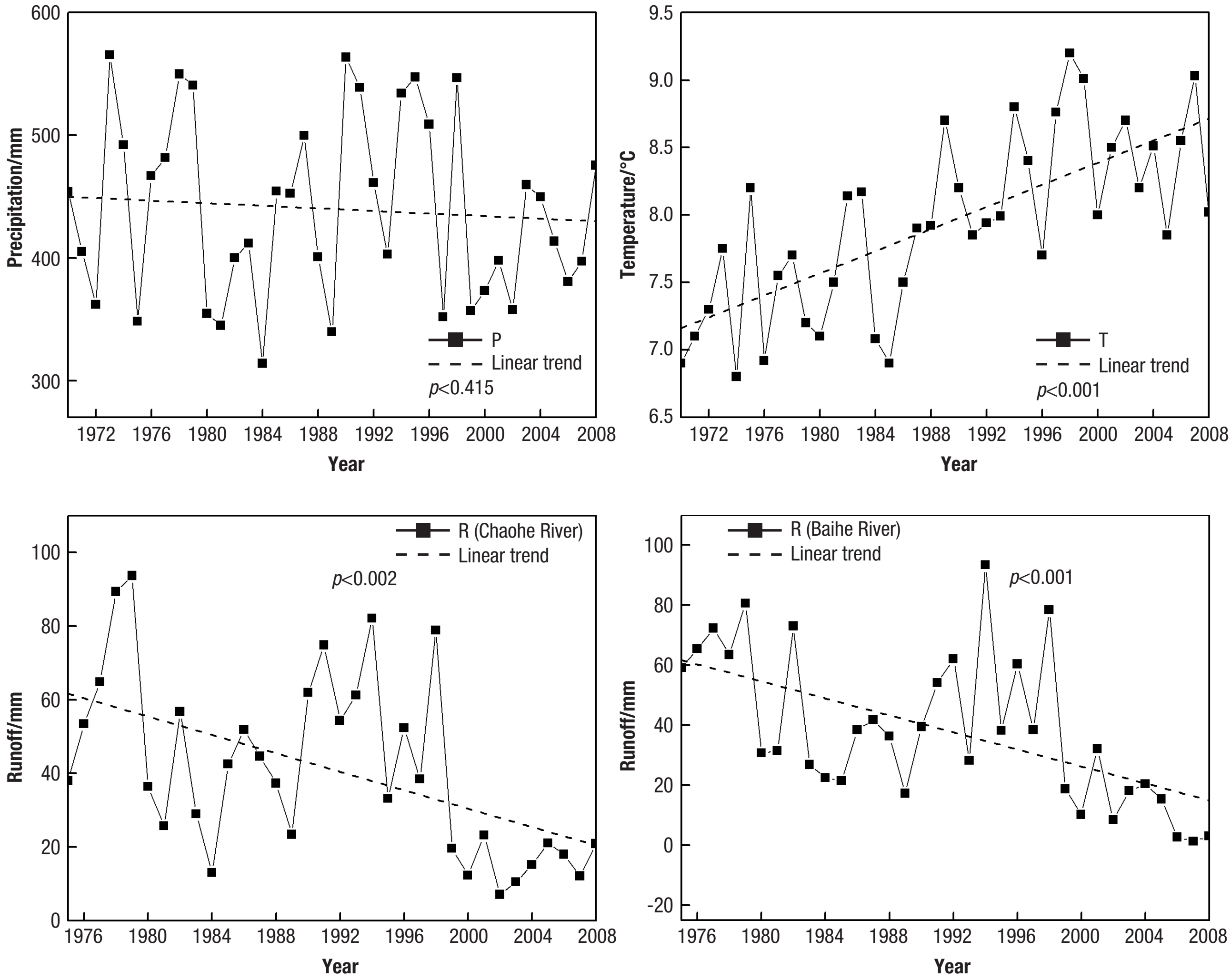

Figure 2. Annual Variation of *P*, *T*, and *R* with their respective linear regression line.

Effects of climate variations and human activities on runoff

Climate variation and land use change caused by human activities were usually responsible for the hydrological change. As mentioned in the above section, the study period was divided into two phases: base period (1975-1998) and effect of human activities period (1999-2008). Our previous studies (Zhao *et al.*, 2012) concluded that the AWY model performed well in estimating the contribution of changes in climate and land use on runoff after calibrating the *w* parameter in North China. So, combing the previous studies, the calibrated *w* values for grassland, farmland, forest and settlements were 1.5, 1.5, 2.8, and 0, respectively.

Model parameters in the calibration and the land use in 1998 were kept constant, whereas the meteorological data during the effect of human activities phase were inputted to the model. The results of the measured and simulated annual runoff during the evaluation period are shown in Table 3. The separate evaluation method was used to determine the quantitative effect of climatic variation and land use change on annual runoff. Table 4 indicates that climatic variation was the strongest contributor to the reduction in mean annual runoff of the Chaohe and Baihe watersheds, and the contribution reached 57.33% and 69.16%, respectively, while the remaining was caused by human activities. There are many reasons for the differences. Referring to Zheng *et al*. (2013), we find that precipitation and other climate factors such as temperature, wind, and solar radiation in the Chao River Basin are not very different from those in the Bai River Basin because the two basins are contiguous and their shapes are similar. Therefore, under the condition that the total annual amount of precipitation and other climate factors differed slightly, changes in the precipitation pattern are mostly assumed to be responsible for the differences inthe effect of climate change on water yield, for runoff is usually caused by a few erosive rainfall events that are short and intense (Angulo-Martinez & Begueria, 2009).

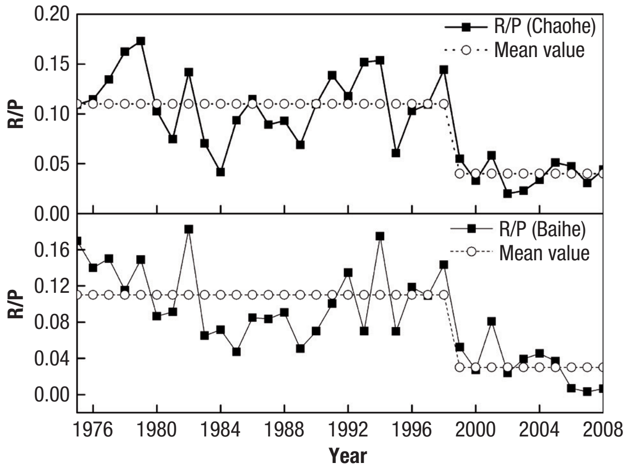

Figure 3. Annual variation of rainfall/precipitation ratio(R/P) in the Chaohe and Baihe watersheds.

Combined with the evaluation results of the two watersheds, we assumed that the decreases in runoff between the two periods can be attributed to 63.24% from climate variations in the ChaoBai River watershed. Still, almost 36.76% of human influence is an important anthropic effect. Hence, climate change was considered to the main reason for the reduction of water yield. This conclusion is consistent with the result by Zhan *et al.* (2011).

Effects of different vegetation types on runoff

As mentioned above, the major causes of annual runoff reduction associated with climatic variation can be greatly accelerated by human activities such as afforestation and farming, etc. Based on the AWY model, the effects of different vegetation types on runoff were evaluated (see Table 5). Table 5 indicates that the effects of different types of vegetation on the reduction in annual runoff were quite dissimilar. The results for the seven basins indicated that the average contribution of forest land was about 65.5%, which was more than the grassland at 17.6 and the farmland at 16.9%. On one hand, there was a larger proportion of forestland in the selected basins, which were generally > 60% in the later periods. On the other hand, the forest cover increased the surface roughness and so intercepted more precipitation, leading to a reduction of surface runoff. Combined with field surveys, the farmland is usually located in a relatively flat terrain where it is easy to conserve soil and water. However, the grassland was present as hillside meadow where it is more conducive to the generation of runoff. Therefore, we predict that runoff generation is much more sensitive to grassland than farmland. Zhao *et al.* (2012) reported that forest has the biggest impact on runoff in all the vegetation types in Chaobai River Watershed by intercepting precipitation and affecting the characteristics of watershed evapotranspiration and infiltration. This conclusion is also consistent with the result by Zheng *et al*. (2013). Zheng *et al.* (2013) augured that the influence of forests on annual runoff depth was significant and increased gradually from 1978 to 2008 in Chaobai River Watershed.

Conclusions

Climatic variability and land-use change in North China can ‘tip’ the water balance, resulting in serious social and ecological consequences. North China has experienced severe water shortages due to the combined impacts of climate change and human activities during the past decades (Li & Li, 2008). Widespread

Table 3. Annual water yield of the observation and simulation over a decade evaluation period.

Watershed	Evaluation period	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
CHAOHE	W_{HR}	19.6	12.3	23.2	7.1	10.5	15.2	21.1	18	12.1	20.9
	W_{HN}	33.5	34.2	45.8	22	22.8	37.5	14.2	33.6	32.1	35.9
BAIHE	W_{HR}	18.7	10.2	32.1	8.5	18.1	20.4	15.3	2.651	1.235	3.055
	W_{HN}	31.3	24.1	50.8	21.1	31.2	18.5	30.2	10.5	10.2	12.9

Table 4. Contributions of climate change and land-use changes to runoff.

Watershed	Period	ΔW_T/mm	ΔW_H/mm	ΔW_C/mm	η_H/%	η_C/%
CHAOHE	1975-1998 1999-2008	–35.53	–15.16	–20.37	42.67	57.33
BAIHE	1975-1998 1999-2008	–35.85	–11.06	–24.79	30.84	69.16
AVERAGE					36.76	63.24

Table 5. Effects of vegetation type changes on runoff in each basin.

Watershed	Sub-watershed	Year	Observed runoff/mm	Runoff after separation of land use types/mm		
				Grassland	Forest land	Farmland
CHAOHE	HONGMENCHUAN	1990	146.09	162.8	204.8	150.1
		1995	183.47	202.5	255.1	190.2
		2000	24	44	90.1	28
		2005	67.9	70.2	155.24	81.2
	BANCHENGZI	1990	205.36	225.1	324.6	210.8
		1995	76.77	93.4	188.2	80.1
		2000	43.6	68.9	113.5	45.8
		2005	4.8	15.5	46.2	10.7
	DAGE	1978	53.9	72.1	119	77
		1988	51.1	48	83.1	49.3
		1998	74	152.4	279.3	174.7
		2008	19.3	26.9	67.9	37.1
	DAIYING	1978	79.5	100.4	173.3	102
		1988	39.9	51.3	99.4	50.2
		1998	79.2	150.1	299.3	165.1
		2008	13.6	30.1	97.2	41.2
	XIAHUI	1978	81.1	110.2	198.2	111.5
		1988	33.6	55.4	114.5	53.6
		1998	77.7	144.4	301.4	155.8
		2008	10.1	33.5	112.8	44.1
BAIHE	XIABU	1978	30.9	67.3	78.4	77.3
		1988	24.9	39.8	46.8	40.9
		1998	40.5	91.6	171.5	99.2
		2008	18.1	31.9	53.5	34
	SANDAOYING	1978	66.3	80.9	143.2	96.8
		1988	66.1	50.5	98.1	47.3
		2008	22.6	45	91.6	37.5
Average				65.5	17.6	16.9

afforestation has been proposed as one means of addressing the increasing dry land and stream salinity problem in North China. However, watershed hydrologic effects of forestation have not been well studied in this region. There is an urgent need to study the effects of afforestation on watershed hydrologic processes to fully understand the magnitude of water quantity responses at multiple spatial and temporal scales across China. Such eco-hydrological studies are essential to guide the recent massive afforestation and ecological restoration campaigns.

Our study suggested that climate change should be responsible for the reduction of water yield from the mountains in the past 30 years, with a contribution of 63.24%. Although afforestation plays an important role in the reduction of runoff, it was not the major reason for the reduction of water yield from mountain areas. The quantification of annual runoff response to afforestation in our study is just a first step towards a better understanding of the impacts of land cover change on water resources in North China. Further research should focus on the effect of change in climate and land use on baseflow and stormflow components at the regional to continental scale.

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