Driving factors for runoff decline in the Upper Hanjiang basin, a major water source for the South-to-North Water Diversion Project in China

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Abstract With dramatic changes in climate and land-cover patterns around the world, it is of great significance to evaluate the corresponding influence on runoff change as water resources have become a strategic resource. We analysed the runoff change driven by landscape change and climate variation in Hanjiang River basin, which is the water source area of the central route of the South-to-North Water Diversion Project in China. Results show that the runoff decreased greatly from 1960 to 2012 in all the six selected sub-catchments. Attribution analysis results show that reduction of precipitation contributed to the catchment runoff decrease by 39.5–64.9% and landscape change, represented by increase of the parameter in the mathematical Budyko function contributed to the runoff decrease by 34.4–63.3%, while potential evapotranspiration change had a slightly negative contribution. In addition, the contribution is spatially variable from downstream to upstream. We conclude with a qualitative description about how water availability changes under changing landscape and climate conditions, and focus on the impact of vegetation cover change.

Key words runoff reduction; climate variation; vegetation change; Budyko hypothesis

INTRODUCTION

Distinguishing the impacts of climate change and human activities on runoff is recognized a necessary for water resources management and land-use planning in changing environments. Variability of precipitation and potential evapotranspiration are considered as direct influencing factors on runoff change. However, runoff variability is also affected by human activities such as afforestation/deforestation, irrigation and regulation from water constructions (Zhang *et al.,* 2001). In addition, regional impacts of climate change and human activities on hydrology vary from place to place and need to be investigated on a local scale. In general, both process-based and elasticity-based methods have been used to quantify the effects of climate and humans on runoff. The elasticity-based method was initially proposed by Schaake (1990), and has been developed by Xu *et al*. (2014) using analytical elasticity based on the Budyko framework. This method uses elasticity coefficients to represent the sensitivity of runoff to meteorological factors and catchment properties. Different from the process-based method, that relies on a large amount of data and is constrained by the difficulties associated with the parameterization of these hydrological models, the Budyko elasticity-based method is simple and also physically-based, and can express the non-linear interaction between climate, hydrology and landscape in a catchment (Xu *et al.,* 2014).

In this study, first we examine the change of annual runoff during the last five decades in Hanjiang River basin. Then we use attribution analysis based on the Budyko hypothesis to assess impacts of changes in landscape and climate on catchment runoff. Eventually, we conclude with a qualitative description of how water availability changes under changing landscape and climate conditions and focus on the impact of vegetation cover change.

STUDY AREA AND DATA

The Hanjiang River, one of the water source areas of the central route of the South-to-North Water Diversion Project in China, is the largest tributary of the Yangtze River. This basin is located in a subtropical monsoon region with a drainage area of 95 200 km^2. The mean annual temperature is approximately 14ºC, and the mean annual precipitation is approximately 877 mm. Figure 1 shows the topography and river network of the Hanjiang River basin. Table 1 shows the hydro-climatic characteristics from 1960–2012 in the six sub-catchments.

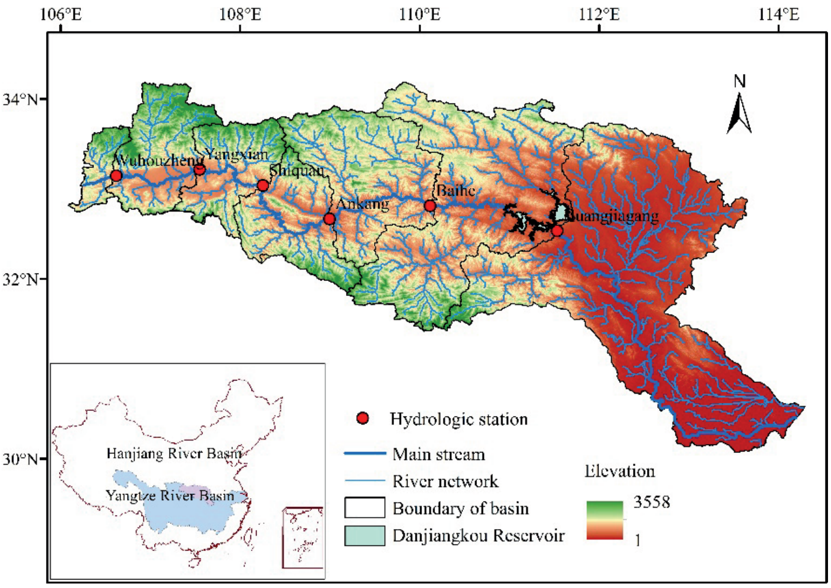

Fig. 1 Location of the sub-catchments and the hydrological stations.

Table 1 Hydroclimatic characteristics from 1960–2012 in the six sub-catchments.

Catchment No.	Hydrological gauge	Drainage area (km^2)	Long-term mean value			
			Annual R (mm)	Annual P (mm)	Annual E_0 (mm)	E_0/P
1	Huangjiagang	95217	215.6	920.4	1065.3	1.16
2	Baihe	59115	234.8	937.5	1063.8	1.13
3	Ankang	38625	296.5	1042.5	1061.7	1.02
4	Shiquan	23805	334.8	1105.2	1063.2	0.96
5	Yangxian	14484	359.7	1116.8	1061.8	0.95
6	Wuhouzheng	3092	352.6	1097	1058.4	0.96

The digital elevation model with a spatial resolution of 90 m was obtained from the global topography database. Annual runoff data in the period of 1960–2012 were obtained from the Hydrological Bureau of the Ministry of Water Resources. Climate data during 1960–2012 were obtained from the China Meteorological Administration (http://cdc.cma.gov.cn/home.do). A land-use/cover map for 1995 was provided by the Data Center for Resources and Environmental Sciences. The 16-day composite data of Normalized Difference Vegetation Index from 1982 to 2010 were obtained from imagery of the Advanced Very High Resolution Radiometer.

METHOD

Trend analysis and abrupt change detection

The Mann-Kendall test (Kendall, 1975; Mann, 1945) is a rank based non-parametric test for assessing the significance of a trend. The null hypothesis is rejected at significance level of 0.05. The nonparametric method developed by Pettitt (1979) is used for detecting the timing of an abrupt change in a time series. The null hypothesis of Pettitt's test is rejected at a significance level of 0.05, which means the absence of abrupt change in this time series.

Attribution analysis based on the Choudhury-Yang equation

Over a long-term time-scale, in a catchment the partitioning of precipitation (P) between evapotranspiration (E) and runoff (R) is treated as a functional balance between the supply of water from the atmosphere and the demand for water by the atmosphere (Budyko, 1974). A couple of mathematical functions were proposed to represent the Budyko hypothesis (Zhang *et al.,* 2001).

In this study, the Choudhury-Yang equation (Yang *et al.,* 2008) was used for simplicity:

$$E = \frac{PE_0}{(P^n + E_0{}^n)^{1/n}} \tag{1}$$

where E is the mean annual actual evapotranspiration, P is the mean annual precipitation, E_0 is the mean annual potential evapotranspiration and the parameter n is the empirical coefficient representing catchment properties (Yang *et al.,* 2009).

The catchment runoff change (ΔR) between period-1 and period-2 could be caused by precipitation change (ΔR_P), potential evapotranspiration change (ΔR_{E_o}) and the catchment landscape change (ΔR_{land}). According to the concept of elasticity coefficients (Schaake, 1990), change in mean annual runoff caused by the change in P, E_0, and n can be expressed as:

$$\Delta R = \Delta R_P + \Delta R_{E_0} + \Delta R_{land} = \varepsilon_P \times \frac{\overline{R}}{\overline{P}} \times \Delta P + \varepsilon_{E_o} \times \frac{\overline{R}}{\overline{E_0}} \times \Delta E_0 + \varepsilon_n \times \frac{\overline{R}}{\overline{n}} \times \Delta n \tag{2}$$

where ε_P, ε_{E_0} and ε_n are the precipitation elasticity, potential evapotranspiration elasticity and landscape elasticity, respectively. Xu *et al.* (2014) derived the climate and landscape elasticity of runoff from the differential form of the Choudhury-Yang equation:

$$\varepsilon_P = \left\{ 1 - \left[\frac{(E_0/P)^n}{1+(E_0/P)^n} \right]^{1/n+1} \right\} \Bigg/ \left\{ 1 - \left[\frac{(E_0/P)^n}{1+(E_0/P)^n} \right]^{1/n} \right\} \tag{3}$$

$$\varepsilon_{Eo} = \frac{1}{1+(E_0/P)^n} \frac{1}{1-(1+(E_0/P)^n)^{1/n}} \tag{4}$$

$$\varepsilon_n = \left\{ \frac{P^n \ln(P) + E_0{}^n \ln(E_0)}{P^n + E_0{}^n} - \frac{\ln(P^n + E_0{}^n)}{n} \right\} \Bigg/ \left\{ \left[1 + (P/E_0)^n \right]^{1/n} - 1 \right\} \tag{5}$$

RESULTS AND DISCUSSION

Trend and breakpoint of hydro-meteorological data and vegetation condition

As shown in Table 2, statistical negative trends in annual runoff were detected for the six study catchments, and the decreasing trends varied from –1.10 mm/year to –2.92 mm/year. Most trends were significant (5% significance level) except in catchment #1. Annual precipitation presented decreasing trends of –0.85 mm/year to –1.78 mm/year, but they were non-significant for all six study catchments. Annual potential evapotranspiration in four of the six catchments had significant decreasing trends, but the change value was not great. The breakpoints of annual runoff for the six study catchments were identified in 1990 significantly, except for catchment #1 where the breakpoint occurred in 1985. In addition, the NDVI series obtained from AVHRR from 1982 to 2010 show a significant increasing trend with the rate of 2–3%.

Table 2 The trend and breakpoint analysis for the six study catchments.

Catchment No.	Breakpoint of R	Trend			
		R (mm/year)	*P* (mm/year)	E_0 (mm/year)	NDVI (/year)
1	1985*	–1.10	–0.85	–1.52*	0.0014*
2	1990*	–2.16*	–1.01	–1.46*	0.0014*
3	1990*	–2.92*	–1.02	–1.17*	0.0014*
4	1990*	–2.50*	–1.14	–1.06*	0.0011*
5	1990*	–2.87*	–1.51	–0.74	0.0010*
6	1990*	–1.83*	–1.78	–0.44	0.0012*

* means *p*-value of the tests less than 0.05.

Attributing results of runoff change and its spatial distribution

The precipitation elasticity ranged from 2.09 to 2.39 (2.22 on average), implying a one percent increase of annual precipitation inducing 2.09–2.39% increase in annual runoff. Potential evapotranspiration elasticity ranged from –1.09 to –1.39 (–2.22 on average), implying a one percent increase of annual potential evapotranspiration inducing 1.09–1.39% decrease in annual runoff. The landscape elasticity ranged from –0.76 to –1.08 (–0.88 on average), implying a one percent increase of annual parameter n inducing 0.76–1.08% decrease in annual runoff. It was found that the high absolute values of elasticity were associated with relatively high values of E_0/P in these catchments, implying that catchment runoff change is more sensitive to climate and landscape change in the relatively dry catchments in this basin.

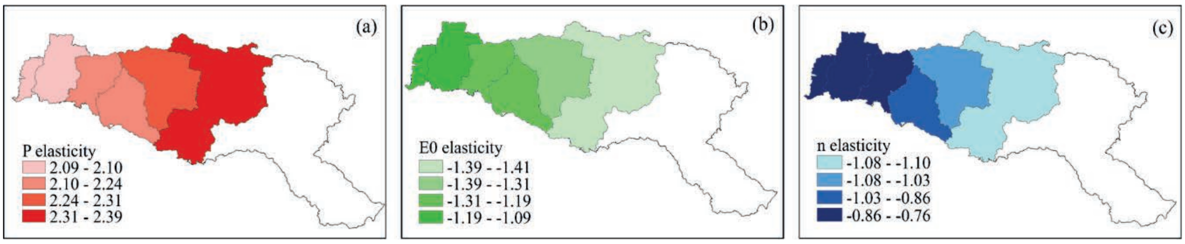

Fig. 2 Elasticity of runoff for the six sub-catchments: (a) the precipitation elasticity; (b) the potential evapotranspiration elasticity; (c) the catchment landscape elasticity.

Decrease in potential evapotranspiration had a slightly negative contribution to the decrease in runoff. While decrease in precipitation had a strongly positive contribution to the decrease in runoff in all the catchments. It contributed to the catchment runoff decrease by 39.5–64.92% (49.07% on average), and was greater than 50% in Catchments #1 and #6). Increase of parameter n contributed to the runoff decrease by 34.38–63.29% (54.02% on average), and was greater than 50% in four catchments (Catchments #1–#4). From downstream to upstream (Catchment #1 to #6), the change in runoff caused by precipitation reduction had an obviously increased trend. And the contributions of parameter n in the downriver sub-catchments (Catchments #1–#3) were greater than in the upriver sub-catchments (catchment #4–#5).

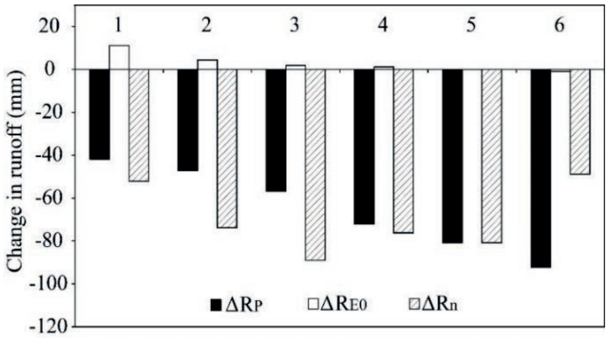

Fig. 3 The quantitative runoff change caused by perturbation in precipitation, potential evapotranspiration, parameter n for the six sub-catchments.

Impact of climate change and landscape change on runoff reduction

Impacts of changes in climate and landscape on catchment hydrology from period-1 to period-2 can be explained by the Budyko curve. As shown in Fig. 4, all catchments became drier (aridity index E_0/P became larger), while the evapotranspiration rate (E/P) increased from period-1 to period-2, which indicated an increase of parameter n. Movement away from the Budyko curve attributes to landscape change and parallel to the Budyko curve attributes to climate change. In some catchments (#5 and #6) the catchment water balance status moved greatly from period-1 to period-2 along the Budyko curve, which means the runoff decrease was primarily controlled by climate change. However in other catchments (#1–#4) the catchment water balance status moved greatly away from the Budyko curve, which indicated that catchment landscape change representing by parameter *n* change, contributed a lot to runoff decrease.

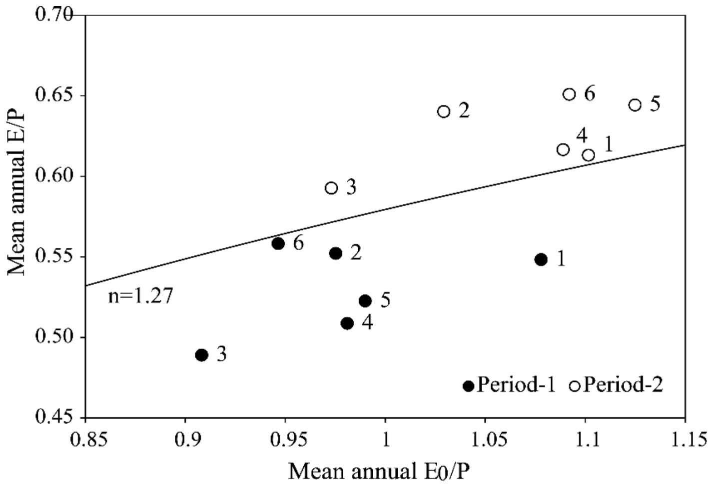

Fig. 4 Distribution of mean annual evapotranspiration ratio (*E/P*) versus mean annual arid index (E_0/P) by using the data in two sub-periods for six sub-catchments.

Assuming the catchment topography, soil and geology were unchanged, the landscape change is mainly due to landscape change induced by human activities and only slightly due to climate variability. The dominant vegetation is grassland (about 46%) and woodland (about 31%). The rest of the land use is croplands (about 20%) and other ecosystems (including urban, barren and water) according to the 1995 landscape data obtained from the Data Centre for Resources and Environmental Sciences. NDVI increased significantly over the whole basin during 1982–2010 (see Fig. 5). But we know that the climate became drier (aridity index increased) in this basin from Fig. 4, therefore the NDVI increasing may be attributed to the national soil-water conservation policy since 1991 and agricultural irrigation. Increase of landscape parameter *n* means increase of vegetation in the same catchment from period-1 to period-2. This landscape change results from the increase of evaporation rate *E/P* (see Fig. 4). This result is consistent with the conclusion given by Zhang *et al*. (2001): under the same climate conditions, landscape changes from grassland to woodland, or if vegetation cover increases, would lead to increased actual evapotranspiration.

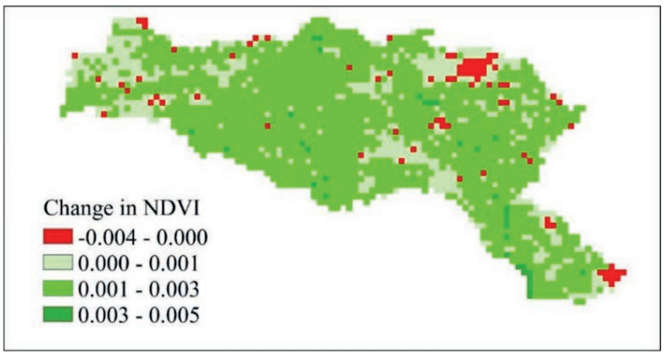

Fig. 5 Change in NDVI from 1982 to 2010.

SUMMARY

This study quantified the impacts of landscape change and climate variation on the runoff change in Hanjiang River basin. Results show that runoff has decreased greatly during the past 60 years.

Precipitation reduction and landscape change (mainly vegetation cover change) caused by the national soil-water conservation policy and agricultural irrigation have contributed a lot to runoff decrease. Future efforts should be made to measure the details of landscape change caused by the climate change and different types of human activities, and identify likely future states of runoff under the changing climate and eco-social-environment conditions.

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