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Attribution analysis based on the Budyko hypothesis for detecting the dominant cause of runoff decline in Haihe basin

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SUMMARY

Catchment hydrological processes have been greatly influenced by the intensive variability in land use/cover, precipitation and air temperature due to climate change and local human activities. It is desired to understand catchment hydrological response to these changes. Observations show that annual runoff had a significant decreasing trend during the past 50 years (1956–2005) in Haihe basin of northern China. In order to detect the major cause for this runoff decline, we first theoretically derived the elasticity of runoff from the Choudhury–Yang equation that is a water-energy balance equation based on the Budyko hypothesis. The elasticity of runoff was calculated in 33 selected mountainous catchments in Haihe basin based on their climate condition (represented by the aridity index, E_0/P) and landscape condition (represented by the parameter, n). We analyzed the breakpoint of the annual runoff of the 33 catchments over the past 50 years and split the whole study period into two sub-periods at the breakpoint (period 1: before the breakpoint; period 2: after the breakpoint). Then we attributed the runoff change between the two sub-periods to the impacts of climate variability and land use/cover change. The change of climate is represented by changes in precipitation (P) and potential evaporation (E_0) and the change of land use/cover is represented by the parameter n in Choudhury–Yang equation. The change of annual runoff from period-1 to period-2 was the catchment hydrological response to the change of precipitation, potential evaporation and land use/cover (represented as ΔP, ΔE_0 and Δn), and we calculated the runoff change based on the elasticities of runoff. For the 33 catchments, the mean annual runoff decreased by 43.0 mm from the period-1 (91.4 mm) to period-2 (48.4 mm). Impacts of climate variation and land use/cover change were accountable for the runoff decrease by 26.9% and 73.1% on average, respectively. Impact of climate variation mainly came from the decrease in precipitation, and impact of land use/cover change mainly came from the vegetation increase. Vegetation increase was mainly due to the reforestation during the soil–water conservation practice during the past 30 years and also partially due to climate variability especially the temperature increase. This methodology can also be used to predict the runoff change in these catchments without direct influence of local human activities under the future climate scenario based on the climate elasticity of runoff estimated from the historical hydroclimatic data.

1. Introduction

1.1. Attribution analysis on runoff change

Analysis of catchment hydrological response to climate variability and land use/cover change induced by human activities is scientifically essential for understanding watershed hydrology and practically significant for improving our water resources and land management. Climate variability includes the changes in precipitation and potential evaporation, which together affect catchment runoff (Budyko, 1974). Human activities can alter river runoff through land use/cover change, reservoir operation, and direct water extraction from surface-water and groundwater. In recent times, hydrologists have paid considerable attention to how much of the observed change in annual runoff can be attributed to climate variability and human activities.

Several recent studies have estimated the contributions of climate and human impacts on change of catchment annual runoff. Two main approaches, process-based and statistic based, have generally been used. The process-based method generally uses a distributed physically-based hydrological model to quantify the contribution of climate variability to runoff change by varying the meteorological inputs for fixed land use/cover conditions, and the contribution of land use/cover variation to runoff change by varying the land use/cover condition for fixed meteorological inputs (Cong et al., 2009; Wang et al., 2009; Ma et al., 2010; Xu et al., 2013). The statistical method estimates the climate elasticity

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of runoff (Schaake, 1990) using nonparametric estimation (Sankarasubramanian et al., 2001) and statistical regression model (Vogel et al., 1999; Ma et al., 2008).

In addition, the Budyko hypothesis (Budyko, 1974) based method has been used to analyze the change of catchment water balance due to climate change (Yang et al., 2006, 2007; Sun, 2007). Yang and Yang (2011) further related the elasticity of runoff to precipitation, net radiation, temperature, wind speed, and relative humidity to separate the contributions of different climatic variables and applied to 89 non-humid catchments in China. Wang and Hejazi (2011) quantified the relationship between climate and direct human impacts on annual runoff in 413 US catchments based on the Budyko hypothesis. In their study, the impact of human activities was simply estimated by subtracting climate impact from the total runoff change. Roderick and Farquhar (2011) derived an analytical expression for the effects on runoff of small perturbations in precipitation, potential evaporation and a parameter representing the catchment properties using the Choudhury–Yang equation (Choudhury, 1999; Yang et al., 2008). Among the above methods, the process-based approaches are more complicated with high uncertainty in their parameters compared with other simple models. Empirical approaches use simple linear relationships derived from long-term historical data, but generally lack physical meanings. Conceptual models built on the principle of catchment water-energy balance are potentially useful for investigating the catchment hydrological response to environmental changes. Previous studies mainly use the Choudhury–Yang equation to analyze changes in runoff related to climate change and did not assess the impacts of land use/cover change.

1.2. Previous studies in Haihe basin

Haihe basin in China is a water-scarce area that has experienced prolonged drought during the 1980s and 1990s. During the recent 30 years, the runoff from the mountain region has decreased sharply (Yang and Tian, 2009; Cong et al., 2010; Bao et al., 2012a) while the groundwater level in the plain area declined severely (Liu et al., 2001; Liu and Xia, 2004; Bluemling et al., 2010; Zhang et al., 2012). Despite the plain area of the basin been an important economic center of China, the water shortage during this period became a bottleneck for economic progress. This has been the main reason for starting the South-to-North Water Diversion Project in 2002, which will transfer water from Yangtze River to Haihe basin in 2014.

The mean annual runoff of Haihe basin during 1980–2000 has been evidently lower than that during 1956–1979 (Ren, 2007). The annual runoff has a decreasing trend in most rivers, such as in Luan River (Wang et al., 2013; Xu et al., 2013), Chaobai River (Wang et al., 2009; Ma et al., 2010; Bao et al., 2012b), Zhang River (Wang et al., 2013), and Hutuo River (Wang et al., 2013). Many previous studies analyzed the reasons for the decrease of runoff in Haihe basin and attributed it to the impacts of climate variability and human activities. For example, Yang and Tian (2009) concluded that increased farmland area was the main and most likely driving factor for the runoff decline; Ren et al. (2002) found that direct water use was the main reason for decreased runoff in the northern area of China; Wang et al. (2009) by using a time-variant gain model estimated the contribution of land use/cover change to be 68% and 70% respectively in Chao River and Bai River and concluded that human impact was the dominant factor for runoff decline in Chaobai River; Ma et al. (2010) by using a physically-based hydrological model and a linear regression model and found that the impact of climate variability and human activities on runoff decline in Chaobai River accounted for 51% and 55% respectively, direct human water extraction accounted for 23% and land use/cover change accounted for 18%; Bao et al. (2012b), using the VIC model, reported that climate variability was the major driving factor in Luan River and human activities were the main driving factor in the northern and southern parts of Haihe basin; Xu et al. (2013), based on statistical data and GBHM model, concluded that the impact of local human activities accounted for 79.5% of the estimated decrease in annual inflow for the Panjiakou Reservoir in Luan River. As can be seen, different conclusions have been drawn from different studies using different models/methods. Therefore, there is a need for a consistent understanding of the dominant cause for runoff decrease in Haihe basin using the same methodology.

1.3. Objectives of this study

The present study focuses on attribution analysis on the change of natural water resources available in Haihe basin. It aims to attribute the natural runoff change to climate variability and land use/cover change using the catchment water-energy balance equation (i.e., Choudhury–Yang equation). In order to avoid infrastructure influence on streamflow and obtain better understanding of change in natural water availability, we selected 33 mountainous catchments in Haihe basin as the study area. The elasticity of runoff was first estimated theoretically from the Choudhury–Yang equation based on climatic and landscape conditions in the study catchments. Secondly, trend of the annual runoff, precipitation and potential evaporation and abrupt change of the annual runoff from 1956 to 2005 was detected. Finally, the runoff decrease in the 33 catchments was quantitatively attributed to the impacts of climate variation and land use/cover change.

2. Methodology

2.1. Elasticity of runoff derived from the Choudhury–Yang equation

Budyko hypothesis (Budyko, 1974) states that the annual water balance can be expressed as a function of available water and energy. Choudhury (1999) introduced an empirical equation of annual evaporation on the basis of the earlier work by Pike (1964). Based on dimensional analysis and mathematical reasoning, Yang et al. (2008) derived the water-energy balance equation analytically at mean annual time scale, which is expressed as:

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

where E is the mean annual actual evaporation, P is the mean annual precipitation, E_0 is the mean annual potential evaporation and the parameter n represents the catchment landscape characteristics, which is mainly related to properties of soil, topography and vegetation (Yang et al., 2008, 2009). Eq. (1) was referred as the Choudhury–Yang equation by Roderick and Farquhar (2011).

From long-term catchment water balance equation,

$$R = P - E \tag{2}$$

where R is mean annual runoff. Substituting Eq. (1) into Eq. (2), we can get:

$$R = P - \frac{PE_0}{(P^n + E_0^n)^{1/n}} \tag{3}$$

Assuming P, E_0 and n in Eq. (3) are independent variables, Eq. (3) can be written as $R = f(P, E_0, n)$. The total differential of R can be written as:

$$dR = \frac{\partial f}{\partial P}dP + \frac{\partial f}{\partial E_0}dE_0 + \frac{\partial f}{\partial n}dn \tag{4}$$