Journal of Hydrology 554 (2017) 251–262

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Evaluating the impact of climate and underlying surface change on runoff within the Budyko framework: A study across 224 catchments in China

Qining Shen, Zhentao Cong, Huimin Lei *

State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

A R T I C L E I N F O

Article history:
Received 20 January 2017
Received in revised form 11 September 2017
Accepted 12 September 2017
Available online 14 September 2017
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of Yuting Yang and Shengping Wang, Associate Editors

Keywords:
Attribution
Precipitation depth
Budyko hypothesis
Climate change
Underlying surface change

A B S T R A C T

Climate change and underlying surface change are two main factors affecting the hydrological cycle. In respect of climate change, precipitation alters not only in magnitude, but also in intensity, which can be represented by precipitation depth. To further understand the spatial variation of the impact of precipitation, potential evapotranspiration, precipitation depth and the water storage capacity during 1960–2010, 224 catchments located from arid areas to humid areas across China were analyzed in this paper based on the Choudhury-Porporato equation within the Budyko hypothesis. The results show that underlying surface change is the major driving force of runoff change in the Songhua Basin, the Liaohe Basin and the Haihe Basin, while climate change dominates runoff change in other basins. Climate change causes runoff increase in most catchments, except for some catchments in the Yellow River Basin and the Yangtze River Basin. Specifically, changes in precipitation depth induce runoff increase in almost each catchment and show a considerable contribution rate (14.8% on average, larger than 20% in 32% catchments). The contribution of precipitation depth change has little correlation with the aridity index, while positively correlates to the significance of trend in precipitation depth. This study suggests that precipitation depth is an important aspect that should be taken into consideration in attribution of runoff change. The findings in this study provide a sight for future researches in attribution analysis within the Budyko framework.

1. Introduction

Changes in climate and underlying surface have exerted pronounced influence on regional hydrology during the past decades (Arnell, 1999; Bates et al., 2008; Bronstert et al., 2002; Cheng and Wang, 2002; Foley et al., 2005; Liang et al., 2015; Oki and Kanae, 2006). The effects of climate and underlying surface change on water cycle vary greatly in different geographic locations. Assessing the impacts of each factor can help us to make an incisive understanding of the mechanism of hydrologic cycle. Therefore it is necessary to quantify the effects of both climate and underlying surface for appropriate water resources management strategies.

In the overpopulated areas, the impacts of human activities on underlying surface are dramatic. Therefore, researches on reasons of runoff change are mostly carried out in these areas (Bouwer et al., 2006; Li et al., 2009; Liang et al., 2015; Wilk and Hughes, 2002; Xu et al., 2014; Zhang et al., 2008). In China, large-scale reforestation, land reclamation for agriculture, overgrazing, urbanization and river engineering have greatly altered the characteristics of underlying surface. For example, several forestation programs have been implemented during the past decades, and the woodland in China increased by 10.5% during the period of 2001 to 2013 (Ministry of Land and Resources, P. R. China, 2001, 2014). Specifically, the Grain for Green project has increased vegetation coverage on the Loess Plateau from 31.6% in 1999 to 59.6% in 2013 (Chen et al., 2015). Meanwhile, arable land and built land have also increased by 5.9% and 22.1%, respectively, while grassland decreased significantly with a rate of 16.8% (Ministry of Land and Resources, P. R. China, 2001, 2014). Aside from surface change, climate change also plays an essential role in runoff variation. For individual catchments, runoff depends directly on the precipitation and evapotranspiration (Miller and Russell, 1992). In addition, rainfall intensity will likely have a great impact on runoff by changing the processes of infiltration and generation (Dunne et al., 1991; Nearing et al., 2005). During the past several decades, China has experienced significant climate change, which is dominant in controlling water resources in some regions (Piao et al.,

* Corresponding author.
E-mail address: leihm@tsinghua.edu.cn (H. Lei).

http://dx.doi.org/10.1016/j.jhydrol.2017.09.023

2010). Annual precipitation has decreased over north China, while increased in western China and the southeastern coast (Ding et al., 2007; Zhai et al., 2005). Meanwhile, evapotranspiration showed decline tendencies and rainfall intensity had significant increasing trends throughout most parts of China (Gao et al., 2006; Zhai et al., 2005; Zhang and Cong, 2014). Therefore, the dominant factors associated with runoff changes in China need to be identified in order to provide guidance to water resources management under changing environment.

Budyko (1974) developed a framework, which summarized the relationship between long-term catchment evaporation and runoff to the ratio of potential evaporation to precipitation. Successively, various mathematical equations have been proposed to present the Budyko framework. Some of the widely-used formulas are the Fu (Fu, 1981), Choudhury (Choudhury, 1999; Yang et al., 2008), Zhang (Zhang et al., 2001) and Porporato (Porporato et al., 2004), each of which provides a parameter to describe the catchment characteristics and has an explicit physical mechanism. These well-established conceptual models have been used to identify the impact of climate and underlying surface on runoff change. Ma et al. (2008) used Fu's equation to analyze the Shiyang river basin in the northwest of China and found that climate change accounted for over 64% of the runoff decrease in the past 50 years. Xu et al. (2014) used climate elasticity method to study the runoff decline in the Haihe basin in the north of China and concluded that climate variation and land use change contributed to 26.9% and 73.1% on average, respectively. In general, most of the previous studies were focused on one basin or several small catchments (Cong et al., 2017; Ma et al., 2008; Roderick and Farquhar, 2011; Xu et al., 2014), only a few investigated the effects of climate and underlying surface change over a whole country (Wang and Hejazi, 2011; Yang et al., 2014; Zhang et al., 2015). Based on the Budyko hypothesis, Wang and Hejazi (2011) quantified the climate and human impact on runoff change for 413 watersheds in the United States, indicating that climate change caused increase of runoff in most watersheds and the runoff changes were more severe in arid regions; Zhang et al. (2015) analyzed the main causes of runoff reduction for 107 catchments in the central and northern China and found that runoff was more sensitive to climate and land use changes in relatively arid regions; Yang et al. (2014) researched 207 catchments in China, showing that climate contribution had largest positive values (1.1–3.1%/a) in the Northwest and the largest negative values (−1.0 to −0.5%/a) in the Haihe Basin and the middle reach of the Yellow River basin. However, among these studies, humid areas in China hadn't been researched by Zhang et al. (2015), and only the trend of the impact of climate variation on runoff change was presented in Yang et al. (2014). Therefore, further analysis needed to be carried out to study the impact of climate and underlying surface change on runoff in China. Besides, in terms of climate change, precipitation alters not only in amount, but also in other characteristics such as intensity, duration as well as arrival time. Some studies have investigated the effects of rainfall characteristics on regional water and energy balance within the Budyko framework (Donohue et al., 2012; Gerrits et al., 2009; Li, 2014; Potter et al., 2005). Among these studies, Donohue et al. (2012) incorporated the effect of soil water holding capacity, effective rooting depth and storm depth into the Budyko's curve, and then specifically accessed the impact of changes in storm depth on runoff in the Murray-Darling Basin in Australia; Li (2014) used a stochastic soil moisture model within the Budyko framework to evaluate the impact of interannual variability of precipitation on evapotranspiration; Gerrits et al. (2009) developed an analytical derivation of the Budyko equation on the basis of rainfall characteristics and a evaporation model; Potter et al. (2005) studied the effects of rainfall seasonality and its interaction with soil moisture capacity on regional water balance. However, a little work has been carried out to quantify the impact of precipitation intensity on runoff change. Considering that precipitation intensity can be represented by the precipitation depth, thus, it is valuable to study the effect of change in precipitation depth within the Budyko framework and further quantify the impact of climate and underlying surface change on runoff across China.

Recently, Cong et al. (2015) combined the Budyko hypothesis and the stochastic soil moisture model of Porporato et al. (2004), then proposed an analytical equation to evaluate the impact of precipitation, potential evapotranspiration, precipitation depth as well as the water storage capacity on runoff in five major basins in China. In this research, only the impact of trend for each factor was presented, no more details were presented for percentage contribution. Besides, in this research these five basins were investigated as a whole, actually they are extremely large that different types of climate can be found within a single basin, which will cause large spatial variations in those regions. Therefore, further studies are necessary for a comprehensive knowledge of quantitative assessment on runoff change across China. In this study, we used the method proposed by Cong et al. (2015) to quantify the impacts of climate change and underlying surface change on runoff during 1960–2010 in 224 catchments across China. The objectives of this study were (1) to quantify the impacts of climate change and underlying surface change on runoff as well as further understand its spatial variation from arid areas to humid areas across China; (2) to discuss the effects of changes in mean daily precipitation depth on attribution analysis.

2. Data and methodology

2.1. Study area and materials

In this study, 224 catchments located in 9 major basins in China were investigated (see Fig. 1). Annual runoff data from 1960to 2010 at 224 hydrological stations and the catchment information were collected from Hydrological Year Books, which were published by the Ministry of Water Resources of the People's Republic of China. The catchment boundaries were extracted based on the SRTM 90 m Digital Elevation Data (http://srtm.csi.cgiar.org). Further details of the study catchments are given in Table S1 in the Supplementary material.

Daily hydrometeor data during 1960–2010 at 736 stations including temperature, wind speed, relative humidity, and sunshine hours, were obtained from website of China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do). A high-resolution (0.25°) gridded daily precipitation is used here, which was developed by Shen and Xiong (2016) on the basis of about 2400 stations over Mainland China. In addition, daily solar radiation during 1960–2010 was collected from 118 stations over China.

We used the inverse-distance weighted method to interpolate the hydrometeor data into 0.25° grid data. The method that converted sunshine hours to R_{net} was based on FAO Irrigation and Drainage Paper (No. 56) (Allen et al., 1998. pp. 43–53). According to FAO56, the solar radiation (R_s) can be calculated with the Angstrom formula:

$$R_s = \left(a_s + b_s \frac{n_s}{N}\right) R_a \tag{1}$$

where n_s is the actual duration of sunshine, N is the maximum possible duration of sunshine or daylight hours, R_a is the extraterrestrial radiation, a_s and b_s are the regression constants. In this study, a_s and b_s were calibrated based on the data from the 118 stations where observed solar radiation are available. In each grid the values of a_s and b_s were obtained from the nearest station (Yang et al., 2006). The land use/cover map in 1986 was obtained from the Data