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The mechanism and scenarios of how mean annual runoff varies with climate change in Asian monsoon areas

Junxu Chen [a,b,c,*], Jun Xia [d,a], Changsen Zhao [e,f], Shifeng Zhang [a], Guobin Fu [g], Like Ning [a]

[a] Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China
[b] School of Resource Environment and Earth Science, Yunnan University, Kunming 650091, PR China
[c] University of Chinese Academy of Sciences, Beijing 100049, PR China
[d] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, PR China
[e] State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and the Institute of Remote Sensing Applications of Chinese Academy of Sciences, Beijing 100875, PR China
[f] School of Geography, Beijing Normal University, Beijing 100875, PR China
[g] CSIRO Land and Water, Wembley, WA, Australia

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SUMMARY

Understanding the effects of climate change on runoff is important for the sustainable management of water resources. However, the mechanism of such effects in the Asian monsoon region remains unclear. This study revisits Fu's two-parameter climate elasticity index and enhances it by using the Gardner function to strengthen the former's prediction reliability when the future climate condition is beyond the historical range. Then the improved method was applied to study the elasticity change with temperature and precipitation in the eastern monsoon basins of China, whereas to explore the mechanism of climate change on runoff. Furthermore, the runoff change and the elasticity of the study area from 2020 to 2050 under representative concentration pathways (RCPs) were predicted. Results show that the trend of elasticity change assumes a centrosymmetric picture with the symmetric point (0,0). Different catchments respond differently to the same climate change scenario: the sensitivity of the Haihe Basin is the highest; those of Yellow, Huaihe, Liaohe, Songhua, Pearl, Yangtze, and Southeast Rivers are lower, in descending order. The changing mode of precipitation and temperature differs greatly to keep the runoff unchanged. For semi-humid regions in which the mean annual temperature ranges from 0.71 °C to 9.0 °C, such as the basins of Songhua, Liaohe, Haihe, and Yellow, a 1 °C increase in temperature requires a corresponding 3.2–4.0% increase in precipitation to keep the runoff unchanged. However, in wet regions, such as the basins of Yangtze, Southeast Rivers, and Pearl, the same change in temperature requires a less than 2.8% increase in precipitation to keep the runoff unchanged. In the future, the runoff in most basins may decrease in different degrees. The decreasing velocity of the runoff is the fastest in the RCP8.5 scenario and the decreasing trend of the runoff slows down under the RCP4.5 and RCP2.6 scenarios. The proposed method can be applied to other basins to assess potential climate change effects on annual runoff. The results of the basins studies can inform planning of long-term basin water management strategies taking into account global change scenarios.

1. Introduction

The IPCC Special Report on Emissions Scenarios (2007) shows that by the 2020s the global average surface temperature will increase by 0.5 °C compared with that of the pre-industrial period and that by the end of 2100 the average annual temperature in most regions of the world is expected to increase more significantly compared with that of the 2020s. Under such scenarios, the water-holding capacity of the atmosphere and the evaporation in the atmosphere will both increase with the rising temperature (Trenberth et al., 2003) and therefore accelerate the global water cycle (Huntington, 2006). As such, the question that emerges is: how will the runoff change with temperature and precipitation changes? The answer depends on the study area and the climate variability. Accordingly, much research related to the assessment of the effects of climate change on the regional runoff has been conducted around the world in the last 30 years.

* Corresponding author at: Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China. Tel.: +86 10 64889010.
E-mail address: chenjunxu07@163.com (J. Chen).

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Revelle and Waggoner (1983) pioneered the topic in the early 1980s. After 1990, Schaake and Waggoner (1990) developed a simple monthly water balance model to estimate the precipitation elasticity of streamflow. Nash and Gleick (1991) used a conceptual hydrologic model to study the sensitivity of the surface runoff to changes in regional temperature and precipitation. Vogel et al. (1999) developed a regional method by linking streamflow to geomorphic and climate characteristics to estimate the annual streamflow. Sankarasubramanian et al. (2001) further developed a specific estimation formula using the mean value of the climatic variable. Chiew (2006) separated the precipitation elasticity of streamflow (e_P) and the potential evaporation elasticity of streamflow (e_{PET}) and estimated both the e_P and e_{PET} of Australia. Fu et al. (2007) extended Sankarasubramanian's elasticity formula into a two-parameter index climate elasticity of streamflow as a function of both precipitation and temperature. Recently, Gardner (2009) found that the long-term mean annual runoff (R) can be closely fitted by the Schreiber formula (Schreiber, 1904) and developed a runoff change estimation formula for catchments undergoing precipitation and temperature change. In brief, the various methods of quantifying the effect of climate change on the runoff can be grouped into three categories: (1) multivariate historical record regression (Revelle and Waggoner, 1983; Vogel et al., 1999), (2) the single-parameter climate elasticity of runoff (Schaake and Waggoner, 1990; Nash and Gleick, 1991; Sankarasubramanian et al., 2001), and (3) the two-parameter climate elasticity of streamflow index (Fu et al., 2007; Gardner, 2009).

Multivariate historical record regression is useful in obtaining the main influencing factors and in directly describing the relationship of runoff and related climate factors, such as climate and geomorphology (Vogel et al., 1999). The single-parameter climate elasticity of runoff is an easy and direct method of representing the effect of precipitation, the most important factor of runoff. These methods have the advantage of assessing runoff as climate change. However, they still have their limitations. Fu pointed out that the sensitivity of streamflow calculated using historical record regressions was varied and cannot be correct all the time (Fu et al., 2007). The single-parameter climate elasticity of runoff is only a function of precipitation and not of evapotranspiration (temperature) so that its applicability under global warming scenarios is limited (Fu et al., 2007). The sensitivity of the hydrological model differs with climate variations because of differences in model calibrations (Sankarasubramanian et al., 2001). To solve the paradox, the two-parameter climate elasticity of streamflow index was developed.

Throughout China, the various effects of climate change on runoff have been simulated in multi-scales using different methods, which are shown below. In the Dongjiang Basin, a sub-basin of the Pearl River Basin in the South of China, a 1 °C increase in temperature and a 10% increase in precipitation have led to a 5–10% increase in runoff (Jiang et al., 2007). In a northern basin in the south of China and in the Danjiangkou Basin of the Yangtze River Basin, Chen et al. found that a 1 °C increase in temperature reduces the mean annual runoff by about 3.5%, whereas a 10% increase in precipitation increases the mean annual runoff by about 15% (Chen et al., 2007). In the Yellow River Basin of northern China, the streamflow increased by about 0–10% with a 1 °C change in temperature and a 10% change in precipitation (Fu et al., 2007). Overall, the runoff in semi-dry and/or semi-humid regions is small or even zero during the dry season and is very sensitive to temperature increase and rainfall decrease during the dry seasons, whereas that in humid basins is less vulnerable to climate change (Guo et al., 2002). Although, these studies have got a lot of meaningful results on the effects of climate change on water resources, the elasticity methods in researches of Jiang's, Chen's and Guo's are not robust estimators as they depend on the forms of the hydrological models, and always treat the elasticity as only a function of precipitation. Fu's method avoid the problem by using a two-parameter (precipitation and temperature) climate elasticity of streamflow index based on observed data. However, the reliability of the elasticity prediction weakens when the future climate condition goes beyond the historical range and incorporates the climate change aggravated by human activities.

The mean annual runoff in the eastern monsoon areas of Songhua, Liaohe, Haihe, Yellow, Huaihe, Yangtze, Southeast Rivers, and Pearl Basins takes part of the 73.8% of China's total. Most of the socioeconomic production and population are concentrated in these areas. A strong warming of China over the past decades is firmly supported by continuous measurements from 412 meteorological stations. The temperature has increased by 1.2 °C since 1960 (Piao et al., 2010). As such, incorporating the effects of climate change on the runoff in these basins to accurately predict future water supply is increasingly necessary for water resource management. However, for such an important and typical area, the effects of climate change on runoff haven't been assessed in the whole area in above studies. More important, the mechanism of such effects in the Asian monsoon region remains unclear.

Although many researchers have devoted themselves to the study of the effects of climate change on runoff across the world, some questions remain unclear, especially in the Asian monsoon regions: How does the elasticity of runoff change with precipitation and temperature? How do the precipitation and temperature interact with each other when the runoff changes slightly? To deal with the problems, this study enhances a two-parameter (precipitation and temperature) climate elasticity of streamflow index with quantitative runoff forecasting equation firstly. Then, based on the improved method, this study assesses the effects of climate change on the runoff of the main basins of the eastern monsoon areas of China with the newest GCM simulations dataset, predicts the elasticity of various basins from 2020 to 2050, discusses the characteristics of the elasticity change alongside temperature and precipitation, and thereby explores the mechanism of runoff variation under climate change.

2. Methods

The climate elasticity of runoff is defined as the proportional change in runoff to the change in a climatic variable, such as precipitation (Schaake and Waggoner, 1990; Sankarasubramanian et al., 2001). In actual terms, the climate elasticity of runoff represents the sensitivity of a water system to climate change, inclusive of all the changes in temperature, precipitation, and so on (Dooge, 1992). In this study, we choose Fu's method of elasticity assessment, which represents the effects of both temperature and precipitation on runoff. According to Fu's two-parameter climate elasticity of streamflow index ($e_{P,\triangle T}$), the streamflow-precipitation-temperature relationship can be expressed as follows (Fu et al., 2007):

$$e_{P,\Delta T} = \frac{dR_{P,\Delta T}/\overline{R}}{dP_{P,\Delta T}/\overline{P}} = \frac{R_{P,\Delta T} - \overline{R}}{P_{P,\Delta T} - \overline{P}}\frac{\overline{P}}{\overline{R}} \tag{1}$$

where ΔT is change in temperature, $R_{P,\Delta T}$ and $P_{P,\Delta T}$ are the runoff and precipitation influenced by precipitation and temperature, and $\overline{P}, \overline{T}$, and $\overline{R}$ are the average precipitation, temperature, and the modeling runoff, respectively.

In Fu's study, $dR_{P,\Delta T}$ was obtained from the streamflow-precipitation-temperature interpolated surface. On the basis of historical records, the prediction is reliable when future climate falls in the climate range condition of the historical data. However, the reliability of the prediction weakens when the future climate condition goes beyond the historical range and incorporates the