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Homogenization of precipitation and flow regimes across China: Changing properties, causes and implications

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SUMMARY

Homogenization and similarities of precipitation and flow regimes across China are thoroughly investigated using Gini coefficient analysis method and the Analysis Of Similarity (ANOSIM) technique, respectively based on daily precipitation data from 554 meteorological stations and monthly streamflow data from 370 hydrological stations covering the period of 1960–2000. The results indicate that: (1) Homogenization of precipitation regimes is increasing from the northwest to the southeast China. However, different spatial patterns of homogenization of flow regions are identified. Spatially, lower homogenization of flow regimes is detected in the northeast China and higher homogenization of flow regimes in the central and southeast China. Temporally, flow regimes during 1961–2000 are characterized mainly by increasing homogenization, and it is particularly true after 1980; (2) precipitation regimes during 1961–2000 are characterized by decreasing dissimilarities. Larger areas of China are characterized by decreasing dissimilarities of precipitation regimes during 1980–2000 when compared to those during 1961–1980, which should be due to increasing precipitation concentration and intensifying precipitation regimes in recent years; (3) distinctly dissimilar precipitation and flow regimes can be identified between geographically separate river basins. Interregional similarities of flow regimes are enhancing after 1980 when compared to those before 1980 though interregional similarities of precipitation regimes are not changed much; and (4) spatial mismatch is evident in terms of spatial range and changing degree of flow and precipitation regimes. Roughly spatial match can be observed between changes of flow and precipitation indicates and it is particularly the case for precipitation and flow changes in dry season such as winter in China. However, influences of human activities and precipitation changes on streamflow are varying as for specific river basins, such as the Yangtze and the Yellow River basins. Damming-induced fragmentation of river basins is the major cause behind higher homogenization of flow regimes. Thus, human interferences in hydrological processes via damming and construction of reservoirs greatly alter streamflow vs. precipitation relations. The results of this study provide theoretical and practical grounds for management and planning of water resources at basin or interbasin scales under the influences of human activities and climate changes.

1. Introduction

Investigation of hydrological processes is crucial for basin-scale water resources management and conservation of fluvial ecosystem, and is also the first step into study of influences of climate changes and human activities on hydrological cycle at regional and global scale (Zhang et al., 2009a, 2014; Dinpashoh et al., 2011; Xia et al., 2012; Zhou et al., 2014). Streamflow is affected by diverse natural factors, such as precipitation, temperature, and fluvial underlying attributes, and by human activities, e.g. irrigation, building of dam/reservoir, and land use and land cover changes (Zhang et al., 2013; Tran and O'Neill, 2013;

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Li et al., 2014; McIntyre et al., 2013; Gosling, 2014). Due to increasing population and intensifying human activities and also the subsequent impact of humans on the hydrologic cycle, growing interest appears concerning how hydrologic variables are affected by external forcing such as the human activities (Zhang et al., 2013; Zhan et al., 2013; Ahn and Merwade, 2014). Human activities such as construction of single and cascade reservoirs and water diversion tunnels/channels have further altered the hydrology and water quality of rivers (Li et al., 2014). Moreover, since natural flow variability is of great importance for maintaining ecological integrity and diversity, any alterations resulting from human impacts might induce complex responses or the potential degradation of riverine ecosystems (Petts, 2009; Yin and Yang, 2011). Therefore, investigation of hydrological alterations in terms of frequency, duration, and timing of flow regimes as results of changing climate and human activities has been arousing increasing human concerns in recent decades (Jiang et al., 2014).

Eco-hydrological effects of reservoirs have been widely investigated due to the fact that hydro-environmental changes due to human alterations of natural flows may significantly influence hydrological regimes and thus the ecology of rivers (Li et al., 2014; Zhang et al., 2014; Iacob et al., 2014). In China, there are a bunch of researches addressing influences of reservoirs on downstream flow regimes and related eco-hydrological effects (Yin and Yang, 2011; Li et al., 2014). Besides, impacts of climate changes, particularly precipitation variations, have been widely investigated (Ma et al., 2010; Liu et al., 2013; Xu et al., 2013). Bao et al. (2012) analyzed the attribution of climate variability and human activities for streamflow decrease in three catchments located in different parts of the Hai River basin, i.e. Taolinkou, Zhangjiafen and Guantai catchments. Tang et al. (2011) presented a geomorphology-based non-point source pollution (GBNP) model that links the processes of rainfall–runoff, soil erosion, sediment routing, and pollutant transport of the Miyun reservoir, Beijing, China. There are also other related studies addressing streamflow regimes and related impacts from human activities and climate changes and these researches will not be enumerated here with details. The above-particularized researches are theoretically and practically significant in the development of human understanding of flow regimes and related impacts on ecological environment under the influences of human activities and climate changes. However, these researches focused on flow regimes of river basin at local scale.

Rivers in China are heavily regulated and fragmented by reservoirs and other hydraulic facilities. There are 98,002 reservoirs or hydraulic infrastructures with storage capacity of >0.1 million m^3, and the total storage capacity of the reservoirs is about 932.3 billion m^3, accounting for 34.5% of the total streamflow of the rivers in China (Sun et al., 2013). Parts of the reservoirs are shown in Fig. 1. Besides, China is characterized by different climate types with different underlying attributes, and different river basins are dominated by diverse intensity of human activities. In this case, it is practically and scientifically important investigate spatiotemporal variations of flow regimes across whole China. However, such reports have not been found so far and this is the major motivation of this study.

This study aims to investigate changes of flow regimes and precipitation changes based on long-term hydro-meteorological records across China by clarifying diverse influences of reservoirs on flow regimes at different river basins over China and also possible impacts on diversity of biota of river basins in China. The results of this study are of significant relevance in terms of development of human knowledge concerning spatiotemporal variations of flow regimes over China under influences of changing climate and human activities and are also crucial in basin-scale water resources management and training of river basins.

2. Data

Adequately considering the climate conditions and geographical features of river basin, 31 provinces of China were divided into ten large river basins based on the Ministry of Water Resources of China at http://www.mwr.gov.cn/zwzc/hygb/szygb/, i.e. Songhua River basin (SHR), Liao River basin (LR), Hai River basin (HR), Huai River basin (HuR), Yangtze River basin (YTR), Yellow River basin (YR), Pearl River basin (PR), Southeast Rivers (SER), Southwest Rivers (SWR) and Northwest Rivers (NWR) (Fig. 1). Table 1 displays detailed information of these ten river basins. It can been seen from Table 1 that precipitation is the main driving factor for streamflow variations in almost all the river basins. However, human activities play an important role in interfering precipitation vs. streamflow relationships, such as surface water withdrawal (Table 1), irrigation, reservoir storage and land use. In this case, other than influences of precipitation on streamflow variations, combined impacts of precipitation changes and human activities and also other natural factors such as fluvial topography (Fig. 1b) surface water withdrawal, agricultural irrigation, reservoir storage and land use. Daily precipitation data covering the period of 1961–2000 from 554 meteorological stations and monthly streamflow covering the period of 1960–2000 from 370 hydrological stations are collected. The hydrological data are from the Ministry of Water Resources of China and the meteorological data are collected from National Meteorological Information Center of the China Meteorological Administration. The quality of precipitation and streamflow data were firmly controlled and were applied in our previous studies (e.g., Zhang et al., 2011b, 2012). Both precipitation and streamflow datasets contain small amount of missing values. There are 38 rain gauge stations containing missing daily precipitation data. However, only one station had 1.09% missing values, and most of others had less than 0.1% of total missing values. The missing values in these series were replaced by the long-term average of the same days or months of other years (Xiao et al., 2014). For example, for streamflow data, if there is a missing value in May in the year 1980, the missing value would be replaced by the average of the streamflow values of May of the study time period (excluding 1980). Besides, information of building time, storage capacity and locations of the large reservoirs whose total capacity is more than 100 million built before 2000 are also collected from Hydrology Bureau of Ministry of Water Resources of China at http://xxfb.hydroinfo.gov.cn/ssIndex.html?type=2. The irrigation data from 1978 to 2000 and surface water withdrawal data of 31 provinces are collected from National Bureau of statistics of China at http://www.stats.gov.cn/ and China Water Resources Bulletin in 2000, respectively. The data of land use and topography are provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) at http://www.resdc.cn. The locations of the hydrological stations, meteorological stations and also reservoirs can be found in Fig. 1a.

3. Methodologies

3.1. Gini coefficient

The Gini coefficient (also known as the Gini index or Gini ratio) is a measure of statistical dispersion with aim to mirror the income distribution of a nation's residents, and is the most commonly-used measure of inequality. In this study, the Gini coefficient is used to analyze the annual and inter-annual distribution of streamflow regimes. For the sake of completeness, the computation of Gini coefficient is introduced as follows.

Assume that Y is a positive random variable and denotes the streamflow in this study. The accumulative probability distribution of Y is $F(x)$, i.e.