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Hydrological effects of cropland and climatic changes in arid and semi-arid river basins: A case study from the Yellow River basin, China

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ABSTRACT

The Yellow River basin is a typical semi-arid river basin in northern China. Serious water shortages have negative impacts on regional socioeconomic development. Recent years have witnessed changes in streamflow processes due to increasing human activities, such as agricultural activities and construction of dams and water reservoirs, and climatic changes, e.g. precipitation and temperature. This study attempts to investigate factors potentially driving changes in different streamflow components defined by different quantiles. The data used were daily streamflow data for the 1959–2005 period from 5 hydrological stations, daily precipitation and temperature data from 77 meteorological stations and data pertaining to cropland and large reservoirs. Results indicate a general decrease in streamflow across the Yellow River basin. Moreover significant decreasing streamflow has been observed in the middle and lower Yellow River basin with change points during the mid-1980s till the mid-1990s. The changes of cropland affect the streamflow components and also the cumulative effects on streamflow variations. Recent years have witnessed moderate cropland variations which result in moderate streamflow changes. Further, precipitation also plays a critical role in changes of streamflow components and human activities, i.e. cropland changes, temperature changes and building of water reservoirs, tend to have increasing impacts on hydrological processes across the Yellow River basin. This study provides a theoretical framework for the study of the hydrological effects of human activities and climatic changes on basins over the globe.

1. Introduction

Variability and availability of instream flow are critical for the conservation of ecological conditions and for the management of water resources at the river basin scale. Investigation of hydrological processes and related underlying causes is needed to assess the influences of climatic changes and human activities on the hydrological cycle at regional and global scales (Zhang et al., 2009a; Xia et al., 2012; Zhou et al., 2014). Precipitation was widely accepted as a key factor that drives changes in streamflow (e.g. Novotny and Stefan, 2007; Zhang et al., 2013a,b). Ryberg et al. (2013) and Frans et al. (2013) also indicated that climate change is the major factor in explaining streamflow changes over the U.S. Midwest. However, streamflow changes are also the result of diverse other factors, such as temperature, and basin attributes (Tran and O'Neill, 2013; Gosling, 2014). In addition, impacts of human activities on streamflow changes have focused attention on population growth and increasing human activities, such as irrigation, dam/reservoir construction, land use and land cover changes (Barnett et al., 2008; Zhan et al., 2013; Ahn and Merwade, 2014). When analyzing the relationship between precipitation and streamflow across China, Zhang et al. (2015) indicated that the influence of human activities coupled with changes in precipitation on streamflow were different for different river basins. Zhang and Schilling (2006) indicated that most of the increases in streamflow in the Mississippi River Basin since the 1940s are largely related to changes in land use and land cover. These results are similar to the findings by Raymond et al. (2008) and Schilling et al. (2010). Damming-induced fragmentation of river basins is a major driver

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for homogenization of flow regimes. Thus, through the construction of dams and reservoirs, the disturbance of human to the hydrological process has greatly changed the rainfall-runoff transformation.

The differentiation between climate change and other human influences on streamflow has attracted increasing attention in recent years. Using a macroscale hydrology model, Frans et al. (2013) assessed the hydrologic implications of climate and LUCC (Land Use and Cover Changes) changes between 1918 and 2007 in the Upper Mississippi River Basin and showed that at local scales, modelled annual runoff decreased (increased) by up to 9% (5%) where grasslands (forests) were replaced by croplands. Artificial field drainage amplified annual runoff by as much as 13%. Wang and Hejazi (2011) used the Budyko hypothesis to quantify the climate impact and direct human impact on mean annual streamflow (MAS) for 413 watersheds in the contiguous United States. They found that climate changes caused increasing MAS in most watersheds, while the direct human-induced change was spatially heterogeneous in the contiguous United States with strong regional patterns. Also, Wang and Hejazi (2011) showed that the climate- and human-induced changes were found to be more severe in arid regions. Related research has been carried out for river basins or regions in the USA (Barnett et al., 2008; Wang and Hejazi, 2011), Australia (Potter and Zhang, 2009), Canada (Tan and Gan, 2015) and other countries. Rivers in China are heavily regulated and fragmented by reservoirs and other hydraulic structures (Zhang et al., 2015). There are 98,002 reservoirs or hydraulic structures each having a 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 total streamflow of the rivers in China (Sun et al., 2013). There have been numerous studies on individual impacts of climatic change (mainly changes in precipitation and temperature) and human activities (mainly building of dams or water reservoirs) to streamflow. These have included studies done in the Poyang Lake basin (S. Zhang et al., 2016; Q. Zhang et al., 2016), and Haihe basin (Xu et al., 2014), Huaihe basin (S. Zhang et al., 2016; Q. Zhang et al., 2016) and in the Yellow River basins (e.g. Wang et al., 2012; Tang et al., 2013), to name but a few.

The Yellow River is the second largest river in China and is the paramount water source in northwestern and northern China. However, it is also an area of water shortages (Zhang et al., 2009b). Due to climatic changes and intensifying human activities, particularly increasing human withdrawal of water for agriculture irrigation, streamflow in the lower Yellow River has significantly decreased since 1986 (Zhang et al., 2009b). Although there are many researches addressing individual contributions of climatic changes and human activities to streamflow changes (e.g. Wang et al., 2012; Tang et al., 2013), most researches have focused on either the influence of human activities, such as building of water reservoirs (e.g. Yang et al., 2008), or the influence of climatic changes, e.g. precipitation and temperature, on streamflow variation (Tang et al., 2013). However, no reports are available so far that concern impacts of cropland changes on streamflow changes.

This study therefore attempts to address: (1) the quantification of fractional contributions from climatic changes, e.g. precipitation and temperature, on streamflow changes; (2) impacts of cropland changes, such as maize, soybean and corns, on streamflow variations; and (3) impacts of changes in precipitation, temperature and cropland on spatial and temporal measurements of specific streamflow components. Results of this study can shed light on the impacts of agricultural activities on instream flow changes and hence would be important for management of agricultural irrigation in a changing environment.

The paper is organised as follows: Section 2 describes the study area and the data analyzed in this study; methods are introduced with considerable details in Section 3; the results are presented and discussed in Section 4; and the conclusions are obtained and summarized in Section 5.

2. Study area and data

The Yellow River has a drainage area of 7.95×10^5 km^2 (Fig. 1), and its topography is highest in the west and the lowest in the eastern parts of the Yellow River basin. The basin is located at mid-latitudes with a different climate prevailing in the southeastern part (higher precipitation) as compared to the northwestern part (lower precipitation). In addition, 91.93% of the total land has been utilized for vegetative cover in the basin, and the unused land being mainly sandy land, bare rock gravel land and saline alkali land. Agricultural land accounted for 90.58% of land use. Grassland, cultivated land, and forest land accounted for 48.48% and 28.84%, and 13.26% respectively of that total (Yan et al., 2006). This shows that agricultural land use is dominant in the basin and thus it is necessary to quantify the contribution of cropland changes to streamflow changes across the basin.

The data used in this study were daily precipitation and temperature data for 1960–2013 from 77 meteorological stations, information pertaining to water storage for 24 large water reservoirs for the 1950–2013 period, cropland area (mainly maize, corn and soybean) for the 1950–2013 period, and daily streamflow data from 5 hydrological stations along the mainstream of the Yellow River for the period of 1960–2005. The data were obtained from the Climatic Data Center, National Meteorological Information Center, China Meteorological Administration, and Hydrological Bureau of Yellow River Conservancy Commission of Ministry of Water Resources.

3. Methodology

3.1. Detection of trends and change points

Trends in streamflow were explored using non-parametric Mann-Kendall (MK) trend test (Mitchell et al., 1966; Alan et al., 2003; Chebana et al., 2013). Hamed and Rao (1998) proposed a modified MK (MMK) test, based on effective or Equivalent Sample Size (ESS), to eliminate the effect of autocorrelation, where they used the modified variance of the MK statistic to replace the original one if the lag-i autocorrelation coefficients were significantly different from zero at the 5% level. Threshold values were defined as follows: when the value is less than 0, indicating that the streamflow components are in a decreasing tendency; when the value is less than -1.96, showing that the streamflow components are in a significant decreasing trend.

Detection of change-point (CP) was done, based on the method by Killick and Eckley (2014) which proposed a kind of fully-integrated test method, i.e. "changpoint" R package. The package includes more than one algorithm, such as binary segmentation algorithm, segment neighborhood algorithm, and Pruned Exact Linear Time (PELT) method. It can be used to detect CPs in mean and variance. In this paper, the single change point detection method, AMOC, was used. This method is the likelihood function framework with large flexibility without assuming that the series follows the Gaussian distribution and timing of change point before test analysis. For single CP detection for a time series, $y_{1:n} = (y_1, \cdots, y_n)$, there are two hypotheses: null hypothesis H_0 is that there is no CP; and alternative hypothesis H_1 is that there is CP in the series. In the alternative hypothesis, assume that the CP occurs in $\tau_1 (\tau_1 \in \{1, 2, \ldots, n-1\})$, then the likelihood function for τ_1 is (Killick and Eckley, 2014):