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Contribution of multiple climatic variables and human activities to streamflow changes across China

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Abstract: Using monthly streamflow data from the 1960-2000 period and annual streamflow data from the 2001-2014 period, and also meteorological data from the 1960-2014 period from 815 meteorological stations across China, the Budyko-based hydrothermal balance model was used to quantitatively evaluate the fractional contributions of climate change and human activities to streamflow changes in ten river basins across China. Particular importance was attached to human activities, such as population density and Gross Domestic Product (GDP), and also water reservoirs in terms of their relationship with streamflow changes. Results indicated that: (1) streamflow changes of river basins in northern China were more sensitive to

climate change than those of river basins in southern China. Based on the degree of sensitivity, the influencing factors to which streamflow changes are sensitive included: precipitation > human activities > relative humidity > solar radiation > maximum temperature > wind speed > minimum temperature. Hence, it can be argued that hydrological systems in northern China are more fragile and more sensitive to changing environment than those in southern China and hence water resources management in northern China is more challenging; (2) during 1980-2000, climate change tended to increase streamflow changes across China and have a dominant role in streamflow variation. However, climate change tends to decrease streamflow in river basins of northern China. Generally, human activities cause a decrease of streamflow across China; (3) In recent years such as a period of 2001-2014, human activities tend to have increasing or enhancing impacts on instream flow changes, and fractional contributions of climate change and human activities to streamflow changes are, respectively, 53.5% and 46.5%. Increasing human-induced impacts on streamflow changes have the potential to add more uncertainty in the management of water resources at different spatial and temporal scales.

Key words: Fluvial hydrological processes; Budyko framework; Elasticity coefficients; Climate changes; Human activities

1. Introduction

Streamflow is one of the critical components of the hydrological cycle and is the key to the understanding of influences of climatic change on water resources at regional and global scales (Arnell, 1999). Therefore, understanding of streamflow generation,

variation and underlying causes in a changing environment is critical for the effective management of water resources (Burn, 1994; Arnell, 1999; Zhang et al., 2009, 2016). In general, environmental changes can be classified into two categories: climate-driven and human-driven (Xu, 2011; Wang et al., 2012). Climate change, combined with human activities, triggers remarkable changes in fluvial hydrological processes and these hydrological changes have caused numerous water resource problems across the globe (Barnett et al., 2008; Huang et al., 2013; Tan and Gan, 2015). However, instream flow changes are usually affected by the combination of climatic change, such as precipitation change and evapotranspiration change, and human activities, such as irrigation and building of water reservoirs in many regions of the world (e.g. Wang and Hejazi, 2011; Tan and Gan, 2015; Zhang et al., 2015). Therefore, quantification of the fractional contributions of climatic change and human activities to the instream flow changes is a crucial issue in hydrology. Besides, analysis of fluvial hydrological response to climate variability and human-induced land use and land cover changes is fundamental for understanding watershed hydrology and improving water resources and land management practices (e.g. Xu et al., 2014).

Numerous studies have reported in recent years, quantitatively differentiating the fractional contributions of climatic change and human activities or both to streamflow changes. Taking Minjiang, Fujian province, China, as a case study, Hu et al. (2014) discussed the impact of forest coverage change and its impacts on streamflow changes. Using long-term observational data from 16 meteorological

stations and 2 hydrological stations from the period between the 1950s and 2010, Fan and He (2015) analyzed temperature and precipitation variability and its effects on streamflow in the upstream region of the Lancang-Mekong River (LMR) and Nu-Salween River (NSR). Some studies focused on specific human activities, such as dams or specific component of climatic changes, such as precipitation changes, showing the potential influence of these factors on streamflow changes. Zhao et al. (2012) evaluated the spatiotemporal patterns of dam-induced hydrologic alteration and precipitation variability in the Lancang River basin of southwest China from 1957 to 2000 with the linear regression method, the Mann-Kendall test, and the Range of Variability Approach (RVA). They indicated that the hydrologic regimes of the Lancang River during the 1957-2000 period were affected by damming and precipitation variability, but the hydrologic alteration was relatively low in the upstream areas of the river without a dam (Zhao et al., 2012). Nevertheless, components of climatic change have attracted more concern in the analysis of factors influencing streamflow changes (e.g. Gardner, 2009).

Some investigations addressed the combined influence of climatic change and human activities on streamflow variation. Li et al. (2007) evaluated the impact of climatic change (precipitation and potential evaporation) and human activities (soil conservation) on streamflow changes in the Wuding River basin in China. Bao et al. (2012) used the Variable Infiltration Capacity (VIC) model to model human activities (land use changes) and climatic change on streamflow changes of the Haihe River basin, quantifying the fractional contribution of human activities and climatic change

on streamflow changes within different tributary basins of the Haihe River basin. Analyzing the fractional contribution of damming, precipitation, and evaporation changes on streamflow changes in the East River basin, a tributary of the Pearl River basin, China, Liu et al. (2010) found that climate variability, such as changes in precipitation and evaporation, and human activities, such as reservoir operations, each accounted for about 50% of the streamflow change in the low-flow period. It can be concluded from the above-mentioned researches that most related studies were done at the basin scale (e.g. Zhang et al., 2012). Zhang et al. (2011) analyzed impacts of precipitation changes on streamflow changes across China. However, precipitation only was considered as the major factor influencing streamflow changes. Actually, more than one factor, such as precipitation changes has considerable impacts on streamflow changes (Zhang et al., 2015).

China is wide in territory with various climate types, vegetation coverage and different urbanization intensities, and population densities. Impacts of water reservoirs and withdrawal of water on streamflow changes are also shifting from one river basin to another (e.g. Zhang et al., 2015). Therefore, it is necessary to evaluate the fractional contributions of human activities and climate changes to streamflow changes across China considering different climate types, different intensities of human activities and different LUCCs (Land Use and Cover Changes). Besides, due to the differences in the time intervals the hydrological and meteorological data cover, different impacts of human activities on streamflow changes, and different methods used, conclusions or viewpoints can be sometimes different, which may lead to misunderstanding of

hydrological processes and related underlying causes. This study therefore attempts to analyze monthly streamflow data from more than 300 hydrological stations and daily meteorological data from more than 800 meteorological stations from 10 river basins across China, evaluate the combined impacts of LUCC and climate change on streamflow changes with consideration of as many driving factors as possible with the aim to present a relatively complete picture of hydrological processes across China and related potential driving factors. In fact, attribution analysis of the streamflow change across China has been done. Yang et al. (2014) evaluated the contribution of climate change (precipitation and evaporation) to streamflow changes for 210 catchments across China. Huang et al. (2016) quantified impacts of five climatic variables, i.e., precipitation, net radiation, temperature, wind, and relative humidity, on annual streamflow changes for 207 catchments in China. In very recent study, Wang et al. (2016) quantified contribution of climatic changes such as five evaporation-related elasticities and also catchment alteration elasticity based on Budyko framework at seven large river basins across China. However, previous studies did not consider more influencing factors such as population density, GDP and also water storage capacity of water reservoirs, and these factors are also critical in alteration of hydrological processes besides land use and land cover (e.g. Wang et al, 2016). Meanwhile, due to pretty complicated spatial patterns of influencing factors for streamflow changes, hydrological data from more stations can further enhance human understanding of streamflow responses to external influencing factors when compared to previous studies with hydrological data from fewer stations (e.g. Yang et al., 2014;

Huang et al., 2016; Wang et al., 2016). In this sense, this study can help to present a more complete picture showing impacts of more influencing factors than previous studies considered on streamflow changes at finer spatial scale. What's more, this study includes hydrological changes in very recent years, i.e. 2001-2014, and this point further highlights impacts of intensifying human activities and changing climate on streamflow changes since that climate is changing and human activities are intensifying. Analyses focused on time interval before 2000 only does not fully reflect impacts of climate changes and human activities on streamflow changes in recent years. In this sense, this study can greatly benefit update of human knowledge of streamflow changes and related influencing factors in recent years. Therefore, fractional contributions of six climatic variables, i.e., maximum temperature, minimum temperature, precipitation, relative humidity, solar radiation and wind speed, and also human activities, i.e., Gross Domestic Product (GDP), population intensity and land use and cover changes (LUCC), to streamflow changes across ten large river basins of China.

Instead of using deterministic rainfall-runoff models, the Budyko-based hydrothermal balance model was used in this current study to quantify the fractional contributions of various climatic variables and human activities to streamflow changes within ten large river basins across China based on hydrological data from 372 stations. Moreover, hydrological changes and related influencing factors in recent 2001-2014 were also analyzed and this point clearly differentiate this study from previous studies. The Budyko framework (Budyko, 1974), which expresses the

interaction amongst climate, hydrology, and catchment characteristics, has been widely applied to evaluate quantitatively impacts of climatic variables and human activities on streamflow changes (e.g. Yang and Yang 2011; Tang et al., 2013; Xu et al., 2014; Tan and Gan, 2015; Liang et al., 2016; Wang et al., 2016). The trends of the streamflow and climatic variables were also quantified using the modified Mann-Kendall (MMK) statistic, and the change points were also detected using statistical methods.

The scientific issues this study attempts to address are: (1) What are the potential driving factors behind streamflow variations in 10 river basins across China? (2) What are the exact fractional contributions of each individual influencing factor to streamflow changes? (3) What could be the uncertainty in the evaluation results? This study involves the potential driving factors that may not be well considered in the hydrological literature, and has the potential to better simulate streamflow variation (Yang and Yang, 2011). Moreover, this study quantifies the fractional contributions of various driving factors to streamflow changes in 10 river basins emphasizing different behaviors of driving factors considered in modifying streamflow changes for a specific river basin. Hence, this study can help provide a basis for management of water resources and agricultural irrigation in China under impacts of changing environment in terms of climate change and human activities.

2. Data

Hydrological data analyzed in this study are monthly streamflow data from 372

hydrological stations covering the 1960-2000 period. Locations of these stations can be found in Fig. 1. Besides, annual streamflow data covering the 2001-2014 period were also collected from 41 stations. The hydrological data were collected from the Ministry of Water Resources, China, and the quality of the hydrological data was firmly controlled before its release. The missing data accounted for less than 1% of the total data and were processed using the 7-year moving average method. Daily meteorological data, such as precipitation, maximum and minimum temperature, wind speed and relative humidity, were collected from 815 stations covering the 1960-2014 period. The meteorological data were obtained from the Climatic Data Center, National Meteorological Information Center, China Meteorological Administration, and the quality of the hydrological data was firmly controlled before its release. The missing meteorological data were processed based on the method by Zhang et al. (2011). The 10 large river basins considered in this study were: The Pearl River basin (PR), the Yangtze River basin (YZR), the Huai River basin (HuR), the Hai River basin (HR), the Yellow River basin (YR), the Liao River basin (LR), the Songhua River basin (SHR), the Southeast River basins (SER), the Southwest River basins (SWR) and the Northwest River basins (NWR) (Fig. 1). The basic information of ten large river basins has been displayed in Table 1.

The elevation dataset was the 30-arc-second (1-km) gridded, quality-controlled global Digital Elevation Model (DEM) obtained from <http://www.ngdc.noaa.gov/mgg/topo/globe.html>. The drainage basin area was extracted from this elevation dataset (Fig. 1). Spatial interpolation of meteorological data was based on the inverse

distance weighted method, considering the impact of altitude on the spatial distribution of meteorological factors, and the spatial resolution was 100×100 m. The areal average data of meteorological variables of each sub-catchment was obtained, based on the Zonal Histogram tool of ArcGIS software package. Furthermore, information on 475 water reservoirs was collected, such as building time, water storage capacity and locations (Fig. 2). The GDP, population density data with spatial resolution of 1 km×1 km and land use/land cover data during 2000 were also collected from the Data Center of Resources and Environment, Chinese Academy of Sciences (Fig. 2). And the quality of this dataset was also firmly controlled by Chinese Academy of Sciences, China.

3. Methodology

3.1 Elasticity of each potential driving factors to streamflow changes

Quantitative identification of factors driving streamflow variations has attracted considerable concern. In general, two types of methods have been used in related studies, i.e. hydrological modelling techniques and Budyko hypothesis (Budyko, 1974; Wang, 2014). Hydrological models can well describe changes of hydrological variables. However, the uncertainty related to model structure and parameters and also independence of model parameters violates the interactions between climatic and geographical variables within a river basin, which limit the performance of hydrological models (e.g. Sivapalan, 2003). At shorter time scales, such as daily or monthly time scales, hydrological modelling is in an unshakable position for the

analysis of hydrological processes; at longer time scales, however, the Budyko framework is a recommended alternative method (Dooge et al., 1992; Zheng et al., 2009; Xu et al., 2014).

Budyko (1974) summarized that the primary factors controlling evapotranspiration rate for a long-term mean were the available energy and water and the annual water balance can be expressed in a function of available water and energy. The potential evapotranspiration (E_0) can be used to measure the available energy, while precipitation (P) can be used to measure the availability of water. Therefore, the Budyko hypothesis can be expressed as:

$$\frac{E}{P} = F(E_0/P) \quad (1)$$

in which the function F was supposed to have a common form.

Yang and Yang (2011) deduced the fluvial hydro-thermal balance equation based on Budyko hypothesis as:

$$E = \frac{PE_0}{(P^n + E_0^n)^{1/n}} \quad (2)$$

where E denotes the long-term annual average actual evaporation, P is the long-term annual average precipitation, E_0 is the long-term annual average potential evaporation, and n is the underlying surface parameter. For the long-term catchment water balance (e.g., more than 10 years), soil water storage can be neglected. Based on the water balance equation, $R = P - E$, we can have $R = f(P, E_0, n)$. Streamflow changes can be computed by the following differential equation:

$$dR = \frac{\partial f}{\partial P} dP + \frac{\partial f}{\partial E_0} dE_0 + \frac{\partial f}{\partial n} dn \quad (3)$$

$$\frac{dR}{R} = \left(\frac{\partial f}{\partial P} \frac{P}{R} \right) \frac{dP}{P} + \left(\frac{\partial f}{\partial E_0} \frac{E_0}{R} \right) \frac{dE_0}{E_0} + \left(\frac{\partial f}{\partial n} \frac{n}{R} \right) \frac{dn}{n} \quad (4)$$

$$\frac{dR}{R} = \varepsilon_P \frac{dP}{P} + \varepsilon_{E_0} \frac{dE_0}{E_0} + \varepsilon_n \frac{dn}{n} \quad (5)$$

where $\varepsilon_P = \frac{\partial f}{\partial P} \frac{P}{R}$, $\varepsilon_{E_0} = \frac{\partial f}{\partial E_0} \frac{E_0}{R}$, $\varepsilon_n = \frac{\partial f}{\partial n} \frac{n}{R}$, ε_P , ε_{E_0} , ε_n denotes the elasticity of precipitation, potential evaporation and parameter n of LUCC to streamflow.

The Penman-Monteith equation by FAO is (Allen and Ingram, 1998):

$$E_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} U_2 (vp_s - vp)}{\Delta + \gamma(1 + 0.34U_2)} \quad (6)$$

where E_0 is the reference evapotranspiration (mm day⁻¹), R_n the net radiation at the crop surface (MJ m⁻² day⁻¹), G is the soil heat flux density (MJ m⁻² day⁻¹), T is the mean daily air temperature at 2 m height (°C), U_2 the wind speed at 2 m height (m s⁻¹), vp_s the saturation vapor pressure (kPa), vp the actual vapor pressure (kPa), $vp_s - vp$ the saturation vapor pressure deficit (kPa), Δ the slope of the vapor pressure (kPa °C⁻¹), and γ the psychrometric constant (kPa °C⁻¹). The unit conversion between MJ and Watt is: 1000 Watts•h = 3.6 MJ. It should be noted here that in the above-mentioned equation, the maximum and minimum temperatures are independent and their fractional contribution to streamflow changes should be computed independently.

The net radiation, R_n , is the difference between incoming net shortwave radiation (R_{ns}) and the outgoing net long-wave radiation (R_{nl}):

$$R_n = (1 - \alpha) \left(a_s + b_s \frac{n}{N} \right) R_a - \delta \left(\frac{T_{max}^4 + T_{min}^4}{2} \right) (0.56 - 0.08\sqrt{e_a}) \left(0.1 + 0.9 \frac{n}{N} \right) \quad (7)$$

where n is the actual duration of sunshine (hour), N is the maximum possible duration of daylight hours (hour), a_s is the regression constant, $a_s + b_s$ is the fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$), R_a is the

extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), δ is the Stefan-Boltzmann constant, e_a is the actual vapor pressure that can be calculated from the relative humidity, and the computation procedure can be found in Chapter 3 of the FAO paper 56 (Allen et al., 1998).

Roderick et al. (2007) formulated the following partial differential equation based on pan evaporation equation to quantify the fractional contribution of meteorological factors to pan evaporation changes, i.e.:

$$dE_0 \approx \frac{\partial E_0}{\partial Rn} dRn + \frac{\partial E_0}{\partial U_2} dU_2 + \frac{\partial E_0}{\partial D} dD + \frac{\partial E_0}{\partial T} dT \quad (8)$$

Yang and Yang (2011) deduced the general differential equation quantifying the fractional contribution of solar radiation, temperature, relative humidity and wind speed to potential evapotranspiration, i.e.:

$$dE_0 \approx \frac{\partial E_0}{\partial Rn} dRn + \frac{\partial E_0}{\partial T} dT + \frac{\partial E_0}{\partial U_2} dU_2 + \frac{\partial E_0}{\partial RH} dRH \quad (9)$$

Similarly, based on Equation (6), the following differential equation can be obtained as:

$$dE_0 \approx \frac{\partial E_p}{\partial Rn} dRn + \frac{\partial E_0}{\partial T} dT_{max} + \frac{\partial E_0}{\partial T} dT_{min} + \frac{\partial E_0}{\partial U_2} dU_2 + \frac{\partial E_0}{\partial RH} dRH \quad (10)$$

$$\begin{aligned} \frac{dE_0}{E_0} &\approx \left(\frac{Rn}{E_0} \frac{\partial E_0}{\partial Rn} \right) \frac{dRn}{Rn} + \left(\frac{T_{max}}{E_0} \frac{\partial E_0}{\partial T_{max}} \right) dT_{max} + \left(\frac{T_{min}}{E_0} \frac{\partial E_0}{\partial T_{min}} \right) dT_{min} \\ &+ \left(\frac{U_2}{E_0} \frac{\partial E_0}{\partial U_2} \right) \frac{dU_2}{U_2} + \left(\frac{RH}{E_0} \frac{\partial E_0}{\partial RH} \right) \frac{dRH}{RH} \end{aligned} \quad (11)$$

With the combination of Equation (5), the following equation can be obtained as:

$$\frac{dR}{R} = \varepsilon_P \frac{dP}{P} + \varepsilon_n \frac{dn}{n} + \varepsilon_{Rn} \frac{dRn}{Rn} + \varepsilon_{T_{max}} \frac{dT_{max}}{T_{max}} + \varepsilon_{T_{min}} \frac{dT_{min}}{T_{min}} + \varepsilon_{U_2} \frac{dU_2}{U_2} + \varepsilon_{RH} \frac{dRH}{RH} \quad (12)$$

Where $\varepsilon_{Rn} = \varepsilon_{E_0} \frac{Rn}{E_0} \frac{\partial E_0}{\partial Rn}$, $\varepsilon_{T_{max}} = \varepsilon_{E_0} \frac{T_{max}}{E_0} \frac{\partial E_0}{\partial T_{max}}$, $\varepsilon_{T_{min}} = \varepsilon_{E_0} \frac{T_{min}}{E_0} \frac{\partial E_0}{\partial T_{min}}$, $\varepsilon_{U_2} =$

$\varepsilon_{E_0} \frac{U_2}{E_0} \frac{\partial E_0}{\partial U_2}$, $\varepsilon_{RH} = \varepsilon_{E_0} \frac{RH}{E_0} \frac{\partial E_0}{\partial RH}$, ε_{Rn} , $\varepsilon_{T_{max}}$, $\varepsilon_{T_{min}}$, ε_{U_2} and ε_{RH} denote the elasticity

of solar radiation, maximum temperature, minimum temperature, wind speed and

relative humidity to streamflow changes.

3.2 Fractional contribution of influencing factors to streamflow variations

Based on Equation (10), the fractional contribution of each individual influencing factor to streamflow variations can be obtained by the following equation:

$$\Delta R_x = \varepsilon_x \frac{R}{x} \Delta x \quad (13)$$

where R is the long-term annual average streamflow, x denotes the long-term annual average of each influencing factor, such as precipitation, LUCC, solar radiation, maximum air temperature, minimum air temperature, wind speed and relative humidity. ΔR_x denote the streamflow changes due to each influencing factor. Δx denotes the change of long-term annual average of each factor. Tan et al. (2015) made an attribution analysis of streamflow changes in Canada using Equation (5), showing that the underlying parameter, n , can be used in mirroring the impacts of human activities on streamflow changes, such as building of water reservoirs, land use and land cover changes. Climate change tends to exert impacts on streamflow changes via variations of precipitation, temperature, relative humidity and so on. The total streamflow changes as a result of influences of the above-mentioned meteorological variables can be evaluated as:

$$\delta R_{clim} = \frac{\Delta R_{clim}}{\Delta} \times 100\%, \quad \delta R_{hum} = \frac{\Delta R_{hum}}{\Delta} \times 100\% \quad (14)$$

where δR_{clim} and δR_{hum} are the fractional contributions of climate change and human activities to streamflow changes with unit of %. Δ denotes the total amount of human- and climate-induced streamflow changes.

3.3 Detection of trends and change points

Detection of trends was done, based on the modified Mann-Kendall statistic (MMK) as recommended by Hamed and Rao (1998). This method was with amended variance when the lag- i autocorrelation coefficients were significantly different from zero at the 95% confidence level. Hamed and Rao (1998) have shown MMK with consideration of lag- i autocorrelation and related robustness to autocorrelation. In this study, the significance level for MMK was set at 0.05.

Detection of change points was done, based on a variety of appropriate methods, including a kind of fully-integrated “changepoint” method Killick and Eckley (2014) developed the R package, changepoint, which is free of the normality assumption and can be used in detection of multiple change points. Villarini et al. (2009) suggested Pettitt test to analyze the change point. Compared the performances of 8 change-point test methods, Liu et al. (2015) found that the Ordered Clustering test was more effective in detection of detect change points. Hence, in this study, AMOC, Ordered Clustering Test method, and Pettitt test method were used for the detection of change points. To avoid possible uncertainty and misleading results based on the individual method, the assembled change points were obtained, based on more than one method. If the results are all different, the median change point would be selected.

4. Results

4.1 Timing of change points of streamflow series

The fractional contributions of human activities and climate change to

streamflow changes were evaluated, based on coincident change points with the aim to compare the impacts of human activities and climate change on instream flow changes in different river basins considered in this study. The length of streamflow time series was mostly 41 years, i.e. during 1960-2000, being comparatively short. Besides, the building time of water reservoirs in different river basins and even in one river basin was different. It was therefore almost impossible and infeasible to subdivide streamflow series with different building times of numerous water reservoirs. Poff et al. (2007) suggested the mean building time of one river basin as the time point for subdivision of streamflow series. Tan and Gan (2015) argued that the mean time of the change points can be taken as time point for subdivision of streamflow series of the study region. Fig. 3a illustrates the building times of 475 water reservoirs considered in this study, showing that the 50% and 75% percentile values of the building times of almost all river basins, except SWR, was 1980 or just before 1980 respectively. The mean building time of all water reservoirs across China is 1972. Furthermore, Fig. 3b illustrates the detection results of change points of streamflow series from 372 stations across China, showing distinct differences in change points of streamflow series. However, it can be seen from Fig. 3b that the 50% percentile value of streamflow changes is mostly before 1980, and the mean time of the change points of streamflow series is around 1980. It should be noted here that 1980 is the time when Reform and Open policy in China started, and the building of hydraulic engineering facilities and water reservoirs being pursued vigorously to satisfy the development of agriculture and industry and this point well justify the

time point of abrupt changes of streamflow series. In this case, the time point of 1980 was accepted as the change point for streamflow series across China and the entire streamflow series were subdivided into two time intervals, i.e. period 1 (1960-1979) and period 2 (1980-2000).

4.2 Changing properties of hydrometeorological variables

Fig. 4 demonstrates the MMK trends of annual precipitation, maximum/minimum air temperature, relative humidity, solar radiation, and wind speed during 1960-2000 and streamflow changes during period 2 relative to those during period 1. The MMK statistic value of greater (smaller) than 1.96 (-1.96) shows significant increasing (decreasing) trend at 95% confidence level. Trends of annual precipitation were subject to distinct spatial distribution pattern. Significant decreasing annual precipitation can be observed in the YR, HR, LR, central parts of YZR and also central and western parts of the PR. The decreasing magnitude of areal average annual precipitation during period 2 reached 10% when compared to that during period 1. Other regions were dominated by increasing annual precipitation, specifically annual precipitation in the SHR and Poyang basin during the period 2 was 10% more than that during period 1. The areal average annual precipitation variability ranged between -22%-20% (Fig. 4a). The maximum air temperature changes were subject to different patterns in northern and southern China (Fig. 4b): increasing maximum air temperature was found in northern China and decreasing (even significant decreasing) maximum air temperature in southern China. However,

different spatial patterns were identified for minimum air temperature when compared to those of maximum air temperature (Figs. 4c, 4b). Generally increasing minimum air temperature was observed except for parts of central China. Increasing and significant increasing minimum air temperature were detected mainly in northern China. The relative humidity (Fig. 4d) was generally increasing, particularly in southern China. Specifically, a more evident increase of relative humidity was observed in most parts of the YZR, SWR. The relative humidity tended to decrease in northeastern China. Increasing minimum temperature and increasing annual precipitation should be one of the causes for increasing relative humidity in southern China. Solar radiation changes (Fig. 4e) were in adverse spatial patterns when compared to maximum air temperature: decreasing solar radiation in northeastern and northern China but increasing solar radiation in southern China, which should be attributed to increased aerosol in northern China. Decreasing wind speed was dominant across China except some specific parts of river basins which should be due to the underlying surface properties, such as land use and land cover changes such as urbanization (Li et al., 2008).

When it comes to underlying parameters, n (Fig. 4g), decreased n was identified in the western parts of SHR, middle and lower YZR and parts of the PR. Other regions were dominated by increased n values, and it was particularly true for the n values in the YR and HR, being about 0.21-0.98 as the increasing magnitude, implying intensifying human activities in these regions and these intensifying human activities had the potential to decrease streamflow amount.

Fig. 5 demonstrates that the MMK trends of monthly minimum/maximum streamflow, streamflow coefficient and annual streamflow during 1960-2000 and annual streamflow changes during period 2 relative to those during period 1. Increasing monthly minimum streamflow can be observed mainly in the PR, YZR, SER, SWR and NWR, and particularly significant increasing trends were detected mainly in the SER, YZR and SWR. The monthly maximum streamflow (Fig.5b) have partly different spatial patterns when compared to monthly minimum streamflow (Fig. 5a). Significant increasing trends were detected mainly in few watersheds in YZR. Specifically, significant decreasing trends with larger decreasing magnitude were observed in the YR and HR. The MMK trends of streamflow coefficient (Fig. 5c) were in adverse spatial patterns when compared to the relative changes of n (Fig. 4g): the positive n values resulted in the decreasing trends of streamflow coefficient and were observed mainly in northern China, and negative n values resulted in the increasing trends of streamflow coefficient and were observed mainly in southern China. As shown in Fig. 6, the MMK trends of streamflow coefficient were in linear relations with those of underlying surface parameters, i.e., n , with R^2 of 0.491 and $P < 0.0001$. The changes of underlying surface can be one of the most important influencing factor behind runoff coefficient changes.

The annual streamflow depth (Fig. 5d) was subject to similar spatial patterns when compared to those of annual precipitation (Fig. 4a), which clearly indicated that precipitation changes still occupied the unshakable position for streamflow changes. Increasing trends of annual streamflow depth were found mainly in the

lower SHR, LR, HR and YR, and particularly significant decreasing trends of annual streamflow depth were detected mainly in the YR and HR. The decrease of annual streamflow depth reached as much as 31 mm. Increased annual streamflow depth was observed mainly in the YZR, PR, SER, SWR and NWR, and particularly significant increasing annual streamflow depth was detected in the middle and lower YZR basin and also in the NWR. In general, decreasing annual streamflow depth was detected mainly in northern China and increasing annual streamflow depth in southern China. However, it should be clarified here that spatial patterns of annual precipitation and annual streamflow depth matched considerably well, but not perfectly good. For example, the lower SHR basin was mainly characterized by increasing annual precipitation but decreasing annual streamflow depth. Similarly, the headwater regions of the YR were mainly dominated by increased annual precipitation but decreased annual streamflow depth. However, the underlying parameter, n , has an increasing tendency, showing the enhancing influence of human activities on streamflow changes in these two regions. Therefore, it can be said that streamflow changes were impacted by both climate change and human activities and the influencing degrees were different from one river basin to another across China (Zhang et al., 2015).

4.3 Elasticity of streamflow to meteorological variables and LUCC

The elasticity of streamflow denotes the variation of streamflow depth according to the 1% increase of each climatic variable. An absolute value of elasticity can

reflect the sensitivity of streamflow changes to influencing factors (Xu et al., 2014). It can be seen from Fig. 7 that the sensitivity of streamflow changes to various influencing factors was distinctly different from one river basin to another. Generally, the elasticity of streamflow changes to influencing factors was larger in river basins in northern China than that of those in southern China. The elasticity coefficients of streamflow changes to precipitation ranged between 1.62-4.84 with a mean value of 2.24 in the SHR, LR, HR, YR and HuR, indicating that an increase of 10% in precipitation caused an increase of 22.4% in streamflow. However, the elasticity coefficients of streamflow changes to precipitation ranged between 1.05-1.61 with a mean value of 1.57 in the YZR, PR, SWR and SER, showing that an increase of 10% in precipitation would cause a 15.7 % increase of streamflow. LUCC had negative effects on streamflow changes with elasticity coefficients between -1.46--5.07 in most basins of northern China, and with a mean elasticity coefficient of -10.85 across china, implying that a 10% increase of LUCC parameter, n , would cause a 14.6%-50.7% decrease of streamflow.

Generally, increasing precipitation and relative humidity increased streamflow but increasing maximum/minimum temperature, solar radiation, wind speed and LUCC tended to decrease streamflow because maximum/minimum temperature, solar radiation, wind speed tended to increase evapotranspiration. It can be found from Fig. 7 that streamflow changes were more sensitive to precipitation changes and LUCC than other influencing factors considered in this study. Specifically, streamflow variations in the LR were highly sensitive to precipitation changes and

streamflow variations in the NWR were highly sensitive to LUCC. Generally, streamflow processes in river basins of northern China were more sensitive to various influencing factors than southern China, being reflected by larger elasticity coefficients of streamflow variations to climate changes and LUCC in river basins of northern China than in river basins of southern China. Specifically, based on elasticity coefficients the streamflow changes to influencing factors, the order of the influencing factors was, respectively: precipitation > LUCC > relative humidity > solar radiation > maximum air temperature > wind speed > minimum air temperature. These results were in good agreement with those by Yang and Yang (2011) in YR and HR.

4.4 Impacts of influencing factors on streamflow changes

Fig. 8 compares simulated streamflow, i.e. $\Delta R_P + \Delta R_n + \Delta R_{RH} + \Delta R_{Tmax} + \Delta R_{Tmin} + \Delta R_{U2} + \Delta R_{RH}$, and observed streamflow. It can be seen that simulated and observed streamflow matched statistically well with a correlation coefficient of 0.996 and the mean absolute error (MEA) between simulated and observed streamflow depths was 2.41 mm. The relative error was 4.89%. Hence, the Budyko-based hydrothermal coupled balance model was used in this study to differentiate influencing factors for streamflow changes across China. Fig. 9 shows different influences of various influencing factors on streamflow changes in space. It can be seen that precipitation increased the streamflow amount in the most hydrological stations among the SHR, middle and lower YZR, lower PR, SER, SWR

and NWR. Particularly, precipitation changes caused 81 mm in streamflow depth in the lower YZR, which should be due to a significant increase of precipitation amount and also precipitation intensity in the lower YZR (e.g. Zhang et al., 2008). The river basins with a decrease in annual precipitation (Fig. 9a) were mostly characterized by decreased streamflow, such as south parts of the LR, HR, YR, HuR and middle and lower PR. Specifically, a decrease by 40 mm in streamflow depth was found in the YR, HR, middle YZR and also in the middle PR (Fig. 9a). Impacts of temperature changes on streamflow were relatively spatially complicated. The maximum air temperature generally increased streamflow in river basins of southern China (Fig. 9b) but decreased streamflow of river basins in northern China. However, the minimum air temperature increased slightly streamflow in the central China, but decreased streamflow in other river basins (Fig. 9c). Spatial patterns of impacts of relative humidity on streamflow were relatively complex (Fig. 9d). The relative humidity tended to increase streamflow in the middle and lower YZR, contributing to 2.0-7.1 mm increase in streamflow depth. The impacts by solar radiation and wind speed were relatively minor (Figs. 9e and 9f). However, LUCC had a considerable effect on streamflow changes with evident spatial variability. LUCC tended to decrease streamflow at most river basins considered in this study, and it was particularly the case for streamflow amount in the lower SHR, HR, YR, HuR, northwest parts of YZR, NWR and SWR.

Fig. 10 shows influences of various influencing factors on streamflow changes during 2001-2014 relative to streamflow changes during the period of 1960-1979.

Visual comparison between Figs. 9 and 10 indicate similar spatial patterns of streamflow changes due to influencing factors considered in this study. However, the difference lies in the higher sensitivity of streamflow changes to human activities, i.e. underlying parameters. In other words, human activities exerted intensifying impacts on streamflow changes. Besides, air temperature, relative humidity and wind speed also tended to have enhancing impacts on streamflow changes. Comparatively, impacts of precipitation changes on streamflow changes were decreasing. Particularly significant impacts of intensifying human activities on streamflow processes should arouse considerable concerns in modelling of hydrological processes and in the management of agricultural irrigation and water resources with consideration of human interferences.

Fig. 11 illustrates the impacts of various influencing factors on streamflow changes during 1980-2000 relative to the period of 1960-1979 for each river basin. Precipitation had an evident influence on streamflow changes. Precipitation change tended to increase streamflow in the YZR, SER, SWR, SHR and NWR, especially in the SER and SHR, Precipitation change increased streamflow in all of the watersheds. Table 2 indicates that precipitation changes had the most evident impacts on streamflow changes in the SER and YZR, causing 67.1mm and 34.5 mm of streamflow depth in these two river basins. However, decreased precipitation caused 22.7 mm, 19.4 mm and 9.7 mm of streamflow depth in the HuR, HR and YR.

As for impacts of other influencing factors except for the above-mentioned ones, wind speed generally contributed to the increase of streamflow amount and

minimum temperature tended to decrease streamflow of the river basins considered in this study. However, the maximum air temperature and relative humidity tended to decrease streamflow in river basins of northern China and increase streamflow in river basins of southern China. Solar radiation had a limited impact on streamflow changes. LUCC generally decreased streamflow and it was particularly true for the HuR, HR and SWR with 62.1 mm, 32.8 mm and 23.3 mm of decrease of streamflow depth (Table 2). These river basins were dominated by intensifying human activities, such as increasing agricultural irrigation and increasing withdrawal of water resources due to booming socioeconomic development. However, a slight increase of streamflow was found in the PR, YR and SER with an increase in streamflow of 0.7 mm, 10.5 mm and 13.7 mm. It should be attributed to decreased crop land areas in these river basins which is particularly true for the lower PR.

4.4 Climate- and human-induced impacts on streamflow changes

To further differentiate the dominant influencing factors for streamflow variations, Fig. 12 compares climate-induced streamflow changes, i.e. $\Delta R_P + \Delta R_{Rn} + \Delta R_{Tmax} + \Delta R_{Tmin} + \Delta R_{U2} + \Delta R_{RH}$, with human-induced streamflow changes, i.e. ΔR_n . It can be seen that climate change plays a key role in modifying streamflow processes at hydrological stations in southern China and northwestern China. For streamflow changes in river basins in northern China, human activities have more impacts on streamflow variations than does climate change, such as the lower SHR, HR, middle LR and most parts of YR. Table 3 shows that climate change tends to increase the

streamflow amount in river basins of southern China, such as PR, YZR, SHR, SER, and SWR; and decreases streamflow in river basins of southern China, such as HR, HuR, YR, and LR during 1980-2000 period. Generally, human activities play a dominant role in the reduction of streamflow and it is particularly true for streamflow changes in YR. Human activities cause a 19.4 mm decrease in streamflow depth, which should be attributed to massive ecological conservation in the YR (Liang et al., 2015). In general, the fractional contribution from climate changes and human activities to streamflow changes is, respectively, 71.0% and 29.0% across China.

Fig. 12b shows potentially dominant influencing factors for streamflow changes during 2001-2014 as compared to those during 1960-1979. The hydrological data collected at 41 stations can well represent hydrological processes of major river basins considered in this study. It can be seen that climate change still played a key role in modifying hydrological processes, and streamflow changes at 27 out of 41 stations were mainly due to climate changes during 1960-2000 period. During 2001-2014, however, streamflow changes at 26 out of 41 stations were attributed to human activities (Table 3). The dominant influencing factors for streamflow changed at 22 out of 41 stations shifted from climate change to human activities, implying human activities gradually played the main role in streamflow changes in recent years, and this result should arouse considerable concern in terms of water resources management and river basin management. In recent years, precipitation changes tended to reduce streamflow, e.g. climate change caused 62.3 mm and 11.6 mm in

streamflow depth in the PR and YZR. For streamflow changes across China in recent years, the fractional contribution of climate change and human activities to streamflow changes was 53.5% and 46.5%, respectively. Therefore, the fractional contribution of human activities to streamflow changes during 2001-2014 period was significantly greater than that during 1980-2000 period, implying that the human activities tended to enhance the impacts on streamflow changes.

5. Discussions

5.1 Human-induced impacts on streamflow change

The availability of data concerning human activities is usually not ideal and it is often done, based on certain human activity index during a certain year or certain time interval. Long-term dataset is often not available (e.g. Wang and Hejazi 2014; Tan and Gan, 2015). Particularly, water reservoirs, cropland, population density and GDP are subject to huge spatial diversity and/or spatial heterogeneity within ten river basins across China (Fig. 2). Therefore, it is necessary to differentiate influences of these diverse human activities on streamflow changes at finer spatial scales. In this study, 372 tributaries controlled by hydrological stations considered in this study were categorized into ten groups, based on degrees of influences of human activities on streamflow changes. Then, comparison was done between mean human contribution to streamflow changes and related human activities (Fig. 13). It can be seen from Fig. 13 that human-induced streamflow change was negatively related to cropland changes. Increasing cropland can be expected to increase agricultural

irrigation, increase evapotranspiration and hence decrease streamflow. The storage of water reservoirs was also negatively related to human-induced streamflow variations (Fig. 13b). The storage of reservoirs was directly related to the impoundment effects. Besides, reservoirs with larger storage capacity increase water evaporation. These factors all decrease the streamflow amount of a river basin. Besides, the population and GDP are also important influencing factors for streamflow. Figs. 13c and 11d indicate that these two factors had significant negative relations with human-induced streamflow changes, implying that the higher the population density and socioeconomic development, the more the decrease of streamflow. Higher population density implies more human demand of water resources and vice versa. Specifically, the relationship was uncertain between human-induced streamflow changes, population density and GDP density in the watersheds where human activity can increase streamflow depth. Generally, higher population and GDP tended to increase the human use of fresh water and hence decreased streamflow. The human-induced increased streamflow could be attributed to other factors, e.g., deforest, urbanization and so forth, rather than the population and GDP. For example, in Poyang Lake basin, economic development and population growth caused increasing human use of water resources and reduced the streamflow; however, deforestation and lakes landfill significantly increased the streamflow (e.g. Zhang et al., 2016). Therefore, increasing streamflow cannot be attributed to population and GDP themselves.

5.2 Uncertainty in attribution analysis

Tang et al. (2013) evaluated the impacts of various meteorological variables on streamflow changes at the Huayuankou station, the middle YR, indicating that relative to streamflow changes during 1960-1990, the fractional contribution of precipitation, solar radiation, air temperature, wind speed and relative humidity to streamflow changes during 1991-2002 was, respectively, -27.3%, 1.7%, -3.5%, 6.7%, -1.7%. In this study, the fractional contribution of solar radiation, maximum temperature, minimum temperature, wind speed and relative humidity to streamflow changes was, respectively, -43.3%, 1.0%, -3.7%, -3.2%, 7.1%, -1.8%. These results were largely in good line with differences due to the computation of elasticity coefficient based on different potential evapotranspiration models and comparison of different time intervals.

Furthermore comparison was also done between results of this study (Table 3) and of other published ones (Table 4), showing that the dominant influencing factors obtained by this study for each individual river basin were similar, but were still slightly different from those by other researchers. For example, based on the results of this study, the fractional contribution of climate change to streamflow changes in the YR and HuR during 1980-2000 was, respectively, 78.7% and 22.7% and this fractional contribution obtained by published researches was, respectively, 72% (Zhao et al., 2015) and 33% (Zhang et al., 2016). These differences were attributed to choices of different methods and also the time intervals considered in each study. When compared to results by hydrological models (Table 4), the results by this study

for climate-induced streamflow changes seemed to be underestimated for river basins in northwestern China and southwestern China. The streamflow changes of the river basins in these regions were partly from melting snow or glaciers. Impacts of air temperature on streamflow changes were realized via evapotranspiration but not via impacts of temperature on the melting processes of snow or glacier, this point should be the cause behind the underestimation of fractional contribution of climate change to streamflow changes.

The Budyko-based model also had limited performance in differentiating the influencing factors for streamflow changes. When meteorological variables, such as precipitation, are subject to moderate variability, the fractional contribution of each meteorological variable to streamflow changes is statistically acceptable with an acceptable error. The larger the changing variability of meteorological variables the larger the error in the fractional contribution evaluated by Budyko-based model (e.g. Yang et al., 2014). Yang et al. (2014) pointed out that a 10 mm increase of long-term annual average precipitation can cause a 0.5-5% in error in the precipitation-induced contribution to streamflow changes, and when the increase of long-term annual average precipitation reached 50 mm, the error increased to 2.5-25%. Besides, more rainstorms or more intensifying precipitation events, the fractional contribution of underlying parameter, n , to streamflow changes decreased (Donohue et al., 2012). Though the Budyko-based model had a certain uncertainty in modelling the influencing factors for streamflow changes, the Budyko-based model effectively avoided negative impacts of complicated parameterization and model structure of

hydrological models on modelling results, and hence can be an ideal model for differentiating influencing factors for streamflow changes for multiple river basins across a relative large territory.

6. Conclusions

This study evaluated quantitatively the fractional contribution of climate change, i.e. precipitation, air temperature, relative humidity and so on, and human activities, i.e. building of water reservoirs, cropland, GDP and population density, to streamflow changes within ten river basins. The elasticity of meteorological variables to streamflow changes was obtained, based on the Penman-Monteith evapotranspiration model for maximum/minimum temperature, relative humidity, precipitation and solar radiation. Besides, comparison was done between research results of this current study and those of published researches. This investigation led to the following conclusions:

- (1) Elasticity coefficients of climate change and human activities to streamflow changes in river basins of northern China are significantly larger than those in southern China, implying higher sensitivity of streamflow changes to changing environments in northern China than those in southern China. Thus, more importance should be attached to water resources management in northern China. Generally, increasing precipitation and relative humidity tend to increase streamflow and the maximum/minimum air temperature, solar radiation, wind speed and LUCC have negative influences on streamflow changes. For streamflow changes across China, the influencing factors with larger to smaller sensitivity of

streamflow changes are: Precipitation > LUCC > relative humidity > solar radiation > maximum air temperature > wind speed > minimum air temperature.

(2) Climate change impacts streamflow variations via precipitation, temperature and relative humidity. Meteorological variables have different influences on streamflow changes. During 1980-2000, precipitation tended to increase streamflow across China with a 12.1 mm increase in streamflow depth. Wind speed generally contributed to the increase of streamflow amount and minimum temperature tended to decrease streamflow of the river basins. Maximum air temperature and relative humidity tend to decrease streamflow in river basins of northern China and tend to increase streamflow in river basins of southern China. Solar radiation has a limited impact on streamflow changes. Generally, precipitation is one of the meteorological variables which has the largest effect on streamflow variations. During 1980-2000, climate change increases streamflow in river basins of southern China and decreases streamflow in river basins of northern China, having a fractional contribution to 29.0% of streamflow changes. During 2001-2014, however, human activities tend to have an increasingly important role in modifying streamflow variations. The fractional contribution of climate change and human activities to streamflow changes is, respectively, 53.5% and 46.5%. Recent years have witness increasing human-induced influences on hydrological processes of river basins, which pose a serious challenge in water resources management.

(3) The Budyko based model has limited performance in differentiating influencing

factors for streamflow changes, because the results are somewhat impacted by changing variability of meteorological variables. However, comparison indicates that fractional contributions of climate change and human activities differentiated by the Budyko based model and hydrological models are similar in terms of magnitude with slight differences. The differences lie in the selection of different evapotranspiration models and time intervals considered in different studies. Even so, the Budyko based model effectively avoids limitations the hydrological models have in complicated parameterization and rigorous requirements of dataset. Hence, the Budyko based model can be ideal in quantitative evaluation of the influencing factors for hydrological processes at a longer time scale.

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Fig. 1 Locations of meteorological and hydrological stations in China. Ten river basins considered in this study are: Songhua River basin (SHR), Liao River basin (LR), Hai River basin (HR), Huai River basin (HuR), Yangtze River basin (YZR), Yellow River basin (YR), Pearl River basin (PR), Southeast Rivers (SER), Southwest Rivers (SWR) and Northwest Rivers (NWR).

Fig. 2 Spatial distribution of GDP population, reservoir storage and land use changes across China, which are used in this study for validation of direct human impacts on mean annual streamflow changes.

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882 Fig. 3 Construction time of large reservoirs (Fig.3a) and change-points of annual
883 streamflow series (Fig.3b) in 10 river basins in China
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Fig. 4 Spatial distribution of trends (shaded areas) in (a) annual precipitation amount, (b) maximum temperature, (c) minimum temperature, (d) relative humidity, (e) solar radiation, and (f) wind speed. Triangles denote changing rate of above-mentioned meteor-hydrological variables during 1980-2000 relative to those during 1960-1979 at 372 hydrological stations. Fig. 4(g) shows relative changes of n during 1980-2000 relative to those during 1960-1979.

Fig. 5 Spatial distribution of trends (shaded areas) in (a) monthly minimum streamflow, (b) monthly maximum streamflow, (c) streamflow coefficient, (d) annual streamflow. Triangles in Fig. 5(d) denote changing rate of streamflow during 1980-2000 relative to those during 1960-1979 at 372 hydrological stations.

Fig. 6 Relationships between relative changes of n during 1980-2000 relative to those during 1960-1979 and the trends of runoff coefficient in 372 watersheds during 1960-2000.

Fig. 7 Spatial distribution of elasticity coefficients of streamflow changes relative to changes in meteor-hydrological variables such as (a) annual precipitation, (b) maximum temperature, (c) minimum temperature, (d) relative humidity, (e) solar radiation, (f) wind speed, and (g) landscape changes. Elasticity in this study is the measurement of how responsive streamflow changes are to a change in a specific meteor-hydrological variable (%).

Fig. 8 Comparison between modeled streamflow change as a result of impacts of meteor-hydrological variables considered in this study, i.e. $\Delta R_P + \Delta R_n + \Delta R_{Rn} + \Delta R_{Tmax} + \Delta R_{Tmin} + \Delta R_{U2} + \Delta R_{RH}$, and the observed changes in streamflow. The straight line is a 1:1 straight line.

Fig. 9 Spatial distribution of absolute changes in streamflow changes during 1980-2000 relative to those during 1960-1979 due to impacts of specific meteor-hydrological variables (unit: mm) at 372 hydrological stations, i.e. (a) annual precipitation, (b) maximum temperature, (c) minimum temperature, (d) relative humidity, (e) solar radiation, (f) wind speed, and (g) landscape parameter n .

Fig. 10 Spatial distribution of absolute changes in streamflow changes during 2001-2014 relative to those during 1960-1979 due to impacts of specific meteor-hydrological variables (unit: mm) at 41 hydrological stations, i.e. (a) annual precipitation, (b) maximum temperature, (c) minimum temperature, (d) relative humidity, (e) solar radiation, (f) wind speed, and (g) landscape parameter n .

Fig. 11 Changes in streamflow in 10 river basins across China due to impacts of meteor-hydrological variables such as (a) annual precipitation, (b) maximum temperature, (c) minimum temperature, (d) wind speed, (e) relative humidity, (f) solar radiation, and (g) landscape parameter n .

Fig. 12 Spatial distribution of relative fractional contribution of human activities and climate changes to streamflow changes across China. Filled circles denote that climate changes act as the dominant factor influencing streamflow changes, and filled triangles denote that human activities play the key role in influencing streamflow changes. Fig. 12(a) shows spatial distribution of the key influencing factors for streamflow changes during 1980-2000 relative to those during 1960-1979 at 372 hydrological stations; Fig. 12(b) illustrates spatial distribution of the key influencing factors for streamflow changes during 2000-2014 relative to those during 1960-1979 at 41 hydrological stations. For the sake of comparison, the key influencing factors contributing streamflow changes during 1980-2000 relative to those during 1960-1979 are also in Fig. 12(b).

Fig. 13 Relationships between human-induced streamflow changes and streamflow changes due to specific human activity. Light blue shadow represents the data field for the regression analysis. 372 river sub-basins are classified into ten groups of river basins based on relative fractional contribution of human activities to streamflow changes. Comparison is done on mean human contribution to streamflow changes in each individual river sub-basin and mean human activity parameter of each river sub-basin. Four human activity variables are considered in this study, i.e. (a) cropland, (b) reservoir storage, (c) population density, and (d) GDP density. Reservoir capacity ratio is the ratio of total capacity in the whole watershed and annual streamflow.

976 Table 1 The average of Hydroclimatic variables in 10 river basins across China.

Basin	Area (10 ⁴ km ³)	P (mm)	E ₀ (mm)	T _{max} (°C)	T _{mi} n (°C)	RH (%)	Rn (MJ/(m ² ·day)	WS (m/s)	Runoff depth (mm)
HR	30.0	507	1020	14.4	1.9	58. 1	7.9	2.8	136
HuR	31.8	889	1098	19.3	9.8	71. 4	8.9	2.8	277
LR	29.3	581	991	13.3	1.2	59. 8	7.5	2.8	140
NWR	316.8	198	1036	13.1	-1.2	51. 7	8.0	2.2	81
PR	57.8	1512	1205	24.1	15. 6	78. 7	10.4	1.8	838
SER	20.1	1597	1105	22.6	13. 7	79. 5	10.0	2.0	902
SHR	85.3	523	811	8.7	-4.1	66. 0	6.9	2.9	145
SWR	86.1	913	1152	18.9	6.6	66. 7	10.0	2.0	453
YR	75.7	490	997	13.3	0.5	60. 4	8.6	2.4	111
YZR	178.3	1236	1071	19.9	10. 9	76. 4	9.7	1.9	644

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Table 2 The average contributions of different factors to streamflow changes in 10 river basins across China. The factors are: precipitation (P), parameter n of LUCC (LUCC), maximum temperatures ($T_{\max}$); minimum temperatures ($T_{\min}$); wind speed (WS); relative humidity (RH) and solar radiation (R_n).

River basins	P	LUCC	Tmax	Tmin	WS	RH	Rn
PR	-0.9	0.7	0.1	-1.1	2.4	-0.7	0.06
YZR	34.5	10.5	0.7	-0.8	2.7	1.1	-0.05
SER	67.1	13.7	0.8	-1.2	4.2	2.1	-0.08
SWR	9.7	-23.3	-0.3	-1.0	0.9	-0.4	0.13
HuR	-22.7	-62.1	0.3	-0.9	3.7	0.9	-0.08
HR	-19.4	-32.8	-1.0	-0.9	4.0	-0.4	0.06
YR	-9.6	-19.4	-0.4	-0.5	1.4	-0.1	-0.01
LR	-5.4	-11.8	-1.2	-1.7	4.1	-1.2	0.15
SHR	19.3	-6.0	-1.6	-2.8	2.7	-0.7	0.20
NWR	5.8	-3.5	-0.2	-0.2	0.5	0.0	0.01
China	12.1	-6.0	-0.17	-1.2	2.55	0.1	0.04

984 Table 3 Fractional contribution of climate changes and human activities to
985 streamflow changes during the period 2 (1980-2000) and period 3 (2001-2014) related to the
986 period 1 (1960-1979) within 10 large river basins considered in this study.

Basin	Periods	ΔR (mm)	Climate-induce		Human-induce		No. of stations dominated by Climate/Human
			d mm	%	d mm	%	
PR	period-2	1.2	0.5	40.6	0.7	59.4	36/26
	period-3	-65.9	-62.3	92.0	-5.4	8.0	5/2
YZR	period-2	49.5	38.6	78.7	10.5	21.3	65/40
	period-3	-29.4	-11.6	39.1	-18.0	60.9	5/8
SER	period-2	87.7	73.3	84.2	13.7	15.8	11/2
	period-3	65.7	10.0	15.2	55.8	84.8	1/5
SWR	period-2	-13.3	9.8	29.6	-23.3	70.4	8/14
	period-3	—	—	—	—	—	—
HuR	period-2	-73.7	-18.3	22.7	-62.1	77.3	6/9
	period-3	-16.0	-10.9	67.8	-5.2	32.2	2/1
HR	period-2	-47.4	-16.8	33.8	-32.8	66.2	3/19
	period-3	—	—	—	—	—	—
YR	period-2	-27.3	-8.4	30.3	-19.4	69.7	10/28
	period-3	-27.5	-4.8	16.9	-23.5	83.1	0/9
LR	period-2	-15.3	-3.9	24.7	-11.8	75.3	8/17
	period-3	2.9	-6.3	41.1	9.0	58.9	0/1
SHR	period-2	14.1	20.0	76.9	-6.0	23.1	33/19
	period-3	3.8	7.3	68.4	-3.4	31.6	1/0
NWR	period-2	3.2	6.6	65.7	-3.5	34.3	12/6
	period-3	9.2	14.8	72.2	-5.7	27.8	1/0
China	period-2	8.9	14.4	71.0	-6.0	29.0	192/180
	period-3	-23.4	-12.9	53.5	-11.2	46.5	15/26

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989 Table 4 Comparative studies of fractional contribution of climatic changes and human activities to streamflow changes.

Basin	Catchment	Number of stations	Study period	Method/model	$\delta R_{\text{clim.}}$	$\delta R_{\text{hum.}}$	Sources
PR	East River	3	1956-2000	Back-propagation artificial neural network (BP-ANN)	46.8%	53.2%	Liu et al., 2010
YZR	Yangtze River	4	1953-2010	Linear regression	72%	28%	Zhao et al., 2015
	Poyang Lake basin	5	1955-2009	Australia Water Balance Model; Sensitivity analysis	72.1%	27.9%	Zhang et al., 2016
SWR	Yarlung Zangbo River	4	1974-2000	Modified double mass curve	70%-77%		Liu et al., 2014
	Lanchang and Nu Rivers	2	1950s-2010	Random forest regression	about 65%	/	Fan et al., 2015
HuR	Huaihe River Basin	14	1960-2011	Based on Budyko hypothesis model	33%	67%	Zhang et al., 2012
HR	Haihe River Basin	33	1956-2005	Based on Budyko hypothesis model	26.90%	73.10%	Xu et al., 2014
	Luan, Chaobai and Zhang River	3	1957-2000	Hydrological model and Sensitivity analysis	32.7%-41.7%	58.3%-67.3%	Wang et al., 2013
YR	Yellow River	7	1950-2009	Slope change ratio of cumulative quantity	7.93%	92.07%	Wang et al., 2012
	Yellow River	14	1961-2009	Based on Budyko hypothesis model	38.0%	62.0%	Liang et al., 2015
	Yellow River	7	1960s-2008	Linear regression	17.0%	23.0%	Miao et al., 2011
LR	West Liaohe River Basin	1	1964-2009	VIC model	36%	64%	Yang et al., 2014
SHR	Songhua River Basin	3	1960-2009	Double cumulative curve	62%-82%	63%-65%	Li F et al., 2014
NWR	Tarim River Basin	5	1957-2008	Periodicity-trend superposition model	85.2%	14.8%	Ling et al., 2014