Contrasting Influences of Human Activities on Hydrological Drought Regimes Over China Based on High-Resolution Simulations

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Abstract How human activities have altered hydrological droughts (streamflow deficits) in China during the past five decades (1961–2016) is investigated using the latest version (v2.0) of PCR-GLOBWB model at high spatial resolution (~10 km). Although both human activities and climate variability have significant effects on river flows over China, there are large regional north-south contrasts. Over northern China, human activities generally intensify hydrological droughts. We find that human activities exacerbated drought deficit by about 70–200% from 2004 to 2015. In contrast, droughts over southern China are generally alleviated by human activities. For instance, irrigation and water management (such as reservoir operation and water abstraction) increase drought StDef (standardized drought deficit volume) by about 80% in the Yellow River (north) but reduce it by about 20% in the Yangtze River (south). Human activities slightly reduce drought deficit in the Yangtze River due to the combination of large reservoir storage and low ratio of agriculture consumption to abstracted irrigation water. In contrast, hydrological drought is aggravated in the semiarid Yellow River basin because of high water consumption from agricultural sectors. This study suggests that human activities have contrasting influences on hydrological drought characteristics in the northern (intensification) and southern (mitigation) parts of China. Therefore, it is critical to consider the variable roles of human activities on hydrological drought in China when developing mitigation and adaptation strategies.

Plain Language Summary China faces unprecedented challenges for water resources management under a changing climate, which is expected to lead to more frequent and severe droughts in the future. Of particular importance is streamflow drought, which jeopardizes regional water supply and local ecosystem services. On one hand, human activities through reservoir operation can effectively alleviate drought by releasing water during the low flow period. But on the other hand, water abstraction to meet sectoral water demand (such as irrigation) could exacerbate the streamflow deficit. To what extent such human activities differ across regions is not clear. In this study, we use a physically based hydrological and water resources model to investigate how human activities have altered streamflow droughts in China during the past five decades (1961–2016). We find that human activities generally alleviate streamflow droughts in the southern region (e.g., Yangtze River) but intensify them in the northern part of China (e.g., Yellow River). Our research highlights the contrasting geographical differences of human influences on hydrological drought across China, which can be useful for making more effective drought adaptation strategies.

1. Introduction

Drought is one of the most damaging and pressing natural disasters in terms of economic loss (Sheffield & Wood, 2012). Compared to other types of natural hazards, severe drought can extend over large regions and persist for months to years (He et al., 2019; Lin et al., 2019; Luo et al., 2017; Mishra 

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Singh, 2010; Wang et al., 2011). China has suffered long-lasting and severe droughts during past several decades, which caused tremendous economic and societal losses and threatened food and water security (e.g., Wu et al., 2011; Yu et al., 2014). For example, a severe drought struck southwestern China in 2006 (mainly over Sichuan and Chongqing), causing water shortages for over 16 million people and 17 million livestock. It devastated crops over more than 2.5 million hectares of farmland and resulted in US$3.5 billion of direct economic damages (http://www.weather.com.cn/zt/kpzt/28353.shtml). From the summer of 2009 to spring of 2010, a similar drought occurred in Yunnan, Guizhou, Guangxi, Sichuan, and Chongqing, leading to water shortages for 16 million people, 6 million fewer livestock, and 1.5 million more hectares of crop failures than in 2006. The severe drought in 2011 caused a total loss of US$2.3 billion and led to low water stages or complete dry-out of many local lakes, as well as severe water deficit for crops and municipal use (Jin et al., 2013). These selected events exemplify that drought disasters have become a key factor constraining the sustainable socioeconomic development of China. Therefore, drought risk management and adaptation strategies have been a focus for the Chinese government and research institutions during recent decades.

Drought can usually be categorized into meteorological, agricultural, hydrological, and socioeconomic drought, based on its cause and impact. This generally reflects the components of the hydrological cycle or sector of human activities that are affected (Mishra & Singh, 2010). Among the various types of droughts, hydrological drought (deficit of streamflow) directly affects municipal, industrial, and agricultural water supply and hydropower and thermoelectric generation and thus can have significant economic, social, and environmental impacts (Barker et al., 2016; Van Loon & Van Lanen, 2012; Vasiladiades et al., 2011). Increased human water use under rapid economic development will likely further increase the risk of hydrological drought as water is increasingly stored, diverted, and consumed (AghaKouchak et al., 2015; He et al., 2017; Wada et al., 2013). Therefore, it is essential to understand how human activities intensify or mitigate hydrological drought in China, to provide guidance for future adaptation strategies.

However, previous studies have primarily focused on climate change impacts on hydrological droughts (e.g., Huang et al., 2012; Zhang et al., 2011) or focusing on regional drought analysis with limited spatial coverage of China (Jiang et al., 2019; Zhang et al., 2015). Few studies have focused on the long-term impact of human activities on the frequency and intensity of hydrological drought for the entire China, but these were performed at relatively coarse resolutions (typically 0.5° × 0.5°) (Yuan et al., 2017; Zhang et al., 2015), which are unable to resolve local hydrological processes and local drought variability. The PCR-GLOBWB (PCRaster Global Water Balance) (Van Beek et al., 2011; Wada et al., 2011, 2014) model is a grid-based global hydrologic model, which has become an invaluable tool to understand the impacts of climate variability and human activities on water resources (e.g., Bhanja et al., 2017; Zheng et al., 2016). The first version has a relatively coarse resolution (0.5°) and evaluates the water demand and water availability independently. The new PCR-GLOBWB Version 2.0 developed by Sutanudjaja et al. (2018) has higher spatial resolution (5 arcmin) and takes into account the direct feedback between human water use and other terrestrial water fluxes. This new version fully integrates water use, which greatly improves the hydrological simulation of the first version (Liu et al., 2019; Sutanudjaja et al., 2018).

The climate patterns in China vary greatly (from very wet to very dry) in both time and space and so are the available water resources. Coupled with the uneven economic development, water use, and water management, regional vulnerabilities to climate change and natural disasters (such as droughts) vary dramatically across China. Therefore, this study aims to identify the contribution of human water management (exacerbation or mitigation) to hydrological drought in different regions of China, by using the PCR-GLOBWB v2.0 model and variable threshold level method (Van Loon & Van Lanen, 2012; Van Lanen et al., 2013; Van Loon et al., 2014).

This paper is organized as follows: Section 2 provides the details of the hydrological model and methods to calculate drought characteristics (duration, frequency, and deficit). Section 3 briefly introduces the data sets and study domain. The spatiotemporal characteristics of human and climate impacts on hydrological drought in China are investigated in section 4. Section 5 discusses the results with conclusions in section 6.
2. Methods

2.1. PCR-GLOBWB v2.0 Model

The PCR-GLOBWB v2.0 model (Sutanudjaja et al., 2018) is a state-of-the-art grid-based global hydrology and water resources model. In brief, the new version can simulate the water balance at a higher spatial resolution (5 arcmin in this study), which can improve the model performance as it allows for a much better representation of the spatial heterogeneity in surface parameters (e.g., topography, soils, and vegetation) and terrestrial hydrological processes (Bierkens et al., 2015; Pan & Wood, 2010; Wood et al., 2011). Furthermore, the model dynamically calculates water availability, water demand, and water use and solves the interactions between human water use and terrestrial water fluxes at daily time step. The new version resolves the full processes of human water management: water withdrawal, water consumption, and return flow. The parameters of the PCR-GLOBWB v2.0 model mainly fall into 10 categories: upper and lower soil store parameters, land cover fraction, topographical parameters, root fractions per soil layer, Arno scheme defining soil water capacity distribution, ratio of cell-minimum and cell-maximum soil storage to total soil water storage capacities, parameters related to phenology, groundwater parameters, and others including nonirrigation sectorial water demand, desalinated water and lakes, and reservoirs. Parameters used in this study are obtained from Wada et al. (2013, 2014, 2016) and Sutanudjaja et al. (2018).

PCR-GLOBWB v2.0 model simulates irrigation water use bases on daily surface water and soil water balance as well as deficit, taking into account the associated evapotranspiration over irrigated areas and the feedback from irrigation water supply to the soil and groundwater system (Wada et al., 2014). The fractions of paddy and nonpaddy irrigation, monthly crop composition, and the temporal changing total irrigated area are estimated based on the FAOSTAT (http://www.fao.org/faostat/en/#home). The crop-specific calendars and growing season lengths are obtained from the MIRCA2000 data set (Portmann et al., 2010). Different soil types base on the FAO Digital Soil Map of the World (FAO, 2003), and the frequency distribution of groundwater depth bases on the surface elevations of the HYDRO1k Elevation Derivative Database (HYDRO1k, U.S. Geological Survey Center for Earth Resources Observation and Science; http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/HYDRO1K). More details about model parameters can be found in Wada et al. (2013, 2014, 2016) and Sutanudjaja et al. (2018).

PCR-GLOBWB v2.0 model calculates water demands from livestock, households, and industry sectors at a daily time. Livestock water demand is calculated by multiplying the number of livestock in a grid cell with its corresponding daily drinking water requirement, which is a function of daily air temperature (Wada et al., 2011). The gridded global livestock densities (cattle, buffalo, sheep, goats, pigs, and poultry) and their corresponding drinking water requirements are obtained from FAO (2007) and Steinfeld et al. (2006), respectively. The numbers of each livestock type per country were obtained using the distribution of gridded livestock density in 2000 (FAOSTAT, http://faostat.fao.org/). Gridded industrial water demand data in 2000 are estimated from the study of Shiklomanov (1997), WRI (1998), and Vörösmarty et al. (2005). Daily industrial water demand is kept constant over the year similar to the study of Hanasaki et al. (2006, 2008a, 2008b) and Wada, Van Beek, and Bierkens (2011). Household water demand is estimated multiplying the number of persons in a grid cell with the country-specific per capita domestic water withdrawal. The daily course of household water demand is estimated using daily air temperature as a proxy (Wada, van Beek, Viviroli, et al., 2011). The country per capita domestic water withdrawals in 2000 are taken from the FAO AQUASTAT database (http://www.fao.org/nr/water/aquastat/main/index.stm) and Gleick et al. (2009). Available gridded global population maps per decade are used to downscale the yearly country population data (FAOSTAT) to produce gridded population maps for each year (Wada et al., 2014). As for water withdrawal, it is set equal to gross water demand (summed over domestic, industrial, and agricultural sectors), and the groundwater pumping capacity is obtained from the International Groundwater Resources Assessment Centre database (IGRAC; https://www.un-igrac.org) (Wada et al., 2010).

Reservoirs are located on the drainage or river network based on the years of their construction from Global Reservoir and Dams Dataset (GRanD, Lehner et al., 2011). PCR-GLOBWB v2.0 uses a prospective reservoir operation scheme, which is dynamically calculated by evaluation of the downstream water demand (de Graaf et al., 2014) and is extended over multiple cells. The reservoir storage is subdivided by area to ensure that reservoir and lake levels are the same across their extent (Sutanudjaja et al., 2018).
PCR-GLOBWB v2.0 model simulates the water balance of two vertically stacked soil layers and an underlying groundwater layer for each time step and each grid cell. In the PCR-GLOBWB v2.0 model, the local direct runoff, interflow, and baseflow are routed across the river network based on the simulated topological networks. The routing method can be either simple accumulation or simplified dynamic routing (Wada et al., 2014). Streamflow can be reduced by upstream human water consumption from households, industry, and agriculture. The streamflow will be accumulated along the drainage network when the available streamflow more than the local water consumption in a grid cell, or else, no streamflow returns (Wada et al., 2013). The more detailed information of PCR-GLOBWB v2.0 model please reference Wada et al. (2014, 2017) and Sutanudjaja et al. (2018).

This study applies the PCR-GLOBWB v2.0 model for simulating the terrestrial water cycle over China at daily time scale from 1961 to 2016 at 5 arcm ( 10 km) resolution. Two experiments are conducted: A natural scenario is configured without any human water management, and a human scenario is conducted taking into account human activities (e.g., water use, reservoir operations, groundwater pumping, and surface water abstraction). To assess the model performance, the Nash-Sutcliffe coefficient (NSE; Nash & Sutcliffe, 1970), Kling Gupta Efficiency (KGE; Gupta et al., 2009; Kling et al., 2012), and three subcomponents (correlation coefficient [R], relative variability [α], and bias ratio [β]) are used to validate the effectiveness of the discharge simulation (see equations (1)–(5) in the supporting information for details), which have been widely adopted as model performance metrics for hydrological modeling (e.g., Beck et al., 2016; Liu et al., 2019; Veldkamp et al., 2017).

### 2.2. Calculation of Drought Characteristics

Variable threshold level method (Fleig et al., 2006; Hisdal & Tallaksen, 2003) is used to derive drought events from the simulated daily time series of streamflow (discharge, Q, m³/s) in all grid cells (assuming there is one river channel in each cell except over very dry grid cells). The simulated Q90 under the natural scenario is derived from the daily flow duration curve of each grid cell. For each month, simulated daily streamflow of all days in that month from multiple years (1961–2016) are used to calculate the low flow conditions (i.e., 90% of the long-term mean daily flows exceed this value, Q90). The resulting monthly low flow conditions are used as threshold to compare daily streamflow data against. This approach has been used in multiple studies defining drought thresholds (e.g., Fleig et al., 2006; He et al., 2017; Wanders & Wada, 2015). The Q90 derived from the natural scenario is also used as the threshold for identifying droughts in the human scenario. The drought indicator variable S is calculated as

\[
S(t, n) = \begin{cases} 
1 & \text{if } Q(t, n) < Q_{90}(t, n) \\
0 & \text{if } Q(t, n) \geq Q_{90}(t, n) 
\end{cases}
\]

where S(t, n) is the binary time series of the drought state at daily time scale and 1 indicates that drought occurs at location n at a given time t. Q(t, n) is the simulated daily streamflow, and Q90(t, n) is the threshold of every month of the multiple years.

We analyze the spatiotemporal characteristics of hydrological drought characteristics (i.e., drought deficit [Df], standardized drought deficit volume [StDef], duration [D], frequency, and return period) based on the hydrological drought threshold level of Q90. Drought deficit volume (Def) measures how severe the drought, which is compared to the normal streamflow conditions. StDef(t, n) is the standardized deficit volume, which is calculated by dividing the deficit volume with the threshold level (Q90(t, n)), to enable the comparison among different regions with different flow magnitudes (Wada et al., 2013). Drought duration of an event is equal to the number of days between its start (St) and end day (L). The mean drought duration is calculated as the multiyear average of drought duration from 1961 to 2016. Drought frequency is represented by the number of droughts from 1961 to 2016, and annual mean drought frequency is represented by the mean number of droughts over the entire study period. These drought characteristics are calculated as

\[
D_m(n) = \sum_{t=1}^{L} S(t, n),
\]

\[
Def(t, n) = \max(0, Q_{90}(t, n) - Q(t, n)).
\]
\[ \text{StD } ef(t, n) = \frac{\text{Def}(t, n)}{Q_{90}(t, n)}, \]  

(4)

where \( D_m(n) \) is the drought duration of each drought event \( m \) at location \( n \) and \( T_1 \) and \( T_2 \) are the first and the last time step when \( S(t, n) = 1 \).

The total drought deficit volume for each drought event is the sum of the deviations from the threshold times the number of days, which is calculated as

\[ \text{Def}_i = \sum_{t = S_i}^{L_i} \text{Def}(t). \]  

(5)

This study focuses on medium- and long-term droughts, and short-duration droughts less than 5 days are removed, as suggested by Mo and Lettenmaier (2015).

3. Data and Study Area

Daily observed precipitation and temperature over 1961–2016 at 756 meteorological stations are obtained from the National Climate Center of the China Meteorological Administration (CMA). These meteorological variables are interpolated to 5 arcmin (~10 km) spatial resolution and are used to force the PCR-GLOBWB v2.0 over mainland China (excluding Hong Kong, Macao, and Taiwan) (Figure 1). The other input data of PCR-GLOBWB v2.0 model is introduced in section 2.1. We also collect gauge-based daily streamflow data available at 30 hydrological stations from the “Annual Hydrological Report of P.R. China” to evaluate model performance from 2007 to 2015 (Figure 1 and Table S1). The documented water abstraction (groundwater and surface water), abstracted irrigation water, irrigation water consumption, and storage capacity of all reservoirs in the Yellow River and Yangtze River from 2004 to 2015 are obtained from Yellow River Conservancy Commission (YRCC, http://www.yrcc.gov.cn/) and Changjiang Water Resources Commission (CWRC, http://www.cjw.gov.cn/).

China spans many degrees of latitude and has complicated terrain, and therefore, climate varies sharply. The south and the north of China are dominated by different atmospheric circulation systems (Yang et al., 2020; Zhang et al., 2016). North China has typical continental monsoon climate characterized by hot and rainy summers, and cold and dry winters. In contrast, subtropical monsoon climate prevails in the south China, with hot and wet summers, and mild and wet winters. The annual average precipitation gradually decreases in a spatial gradient from more than 2,000 mm at the southeastern coastline to usually less than 200 mm at the northwestern hinterlands. The divergence of climate has different impacts on agricultural production and water use in the north and south parts of China. The north of China planted upland crop, such as wheat and corn, while the south is mainly paddy field (Wang et al., 2014; Yang et al., 2014). The agricultural water use in the north (south) region accounts for about 75% (52%) of total water use, and the domestic and industrial water use in the south is higher than that in the north, as reported by China Water Resources Bulletin from 2000 to 2016. Therefore, this study selects the northern parts of East China (NEC) and the southern parts of East China (SEC) (enclosed by solid black lines) to showcase the contrast of hydrological droughts affected by human activities in north and south regions of China (Figure S1).

In China, dams and reservoirs are mainly located in the southeastern regions, especially in the Yangtze River basin (such as the Three Gorges Dam, TGD), and only a few in the northeast and southwest (Figure S1). Yangtze River (a drainage area of 1,800 × 10^3 km^2) and Yellow River (795 × 10^3 km^2) are the top two largest rivers in China, where human influences are tremendous due to a dense population and an increasing demand for irrigation and economic development (Fu et al., 2004; Wang et al., 2013; Yang et al., 2019). In the past half century, water consumption (surface water and groundwater) of agriculture, industry, and households in the Yellow River basin has increased from 17.8 × 10^9 m^3 in the 1960s (Liu & Zeng, 2002) to 43.2 × 10^9 m^3 in 2015 (YRCC, 2015), due to the booming agriculture and burgeoning population. In the Yangtze River basin, human water use abstracted from surface water accounts for 96% of the total abstraction water, and only 4% is abstracted from groundwater, and the water consumption is 84.9 × 10^9 m^3 in 2015 (CWRC, 2015; Long et al., 2015). As the long-term historical records of water demand and consumption are only available over large river basins (e.g., Yellow River and Yangtze River), we evaluate the contribution of
human activities to hydrological drought in Yellow River Basin in the North China and the Yangtze River Basin in South China (Figure S1).

4. Results
4.1. Model Evaluation

NSE of simulated and observed monthly streamflow at 30 hydrological stations (see Table S1) shows that the simulation under the human scenario of monthly streamflow generally coincides with the observations, though there are only six stations with low NSE values (not shown in Figure 3a). The simulation under the human scenario has better performance in the southern basins with higher NSE, but lower NSE in north-west basins, potentially due to model’s inadequate capability to simulate snow-related hydrological processes. This evaluation indicates that the simulations have relatively poor performance in a limited number of stations, which mainly locate in dry areas or upper reaches.

This study focuses on identifying the contribution of human water management (exacerbation or alleviation) to hydrological drought based on low flow. Therefore, we further calculate KGE and its three subcomponents between observed and simulated low flow ($Q_{90}$) of two scenarios from 2007 to 2015 (Figure 2 and Table S2). In general, most stations have KGE values larger than 0.6 and are mainly located in catchments with larger drainage area (Figure 2a). The KGE subcomponents show a slightly better performance under human scenario than natural scenario (Figures 2b and 2c). In addition, larger catchments have higher $R$ for both scenarios compared to smaller ones. Relative variability ($\alpha$) values are mostly less than 2, and human scenario has slightly higher $\alpha$ than that of natural scenario (Figure 2c).

Results on bias ratio ($\beta$) indicate that model overestimates the low flow climatology at some stations under both scenarios (Figure 2d). In fact, magnitude of low flows is difficult to capture especially for those extreme low values (Giuntoli et al., 2015; Gosling et al., 2017; Wang et al., 2019). These results demonstrate that PCR-GLOBWB v2.0 model can generally well capture the variability and magnitude of low flows over larger basins. However, further efforts are still needed to improve model simulations over smaller river basins.

Furthermore, comparison of deficit volume from model simulations and station observations shows good agreement for all drought events at 30 hydrological stations under the human scenario (Figure 3), which indicates that PCR-GLOBWB v2.0 can adequately reproduce drought events associated with the low flow conditions across China. The model underestimates the drought deficit under the human scenario when the drought deficit is lower than $10^7$ m$^3$ and slightly overestimates the larger drought events with high drought deficit (higher than $10^8$ m$^3$). It should be noted that the overestimation or underestimation of drought deficit at these stations does not necessarily indicate the performance of PCR-GLOBWB v2.0 in reproduce drought events associated with the low flow conditions across China, due to limited stations used in this study.
4.2. Frequency and Duration of Hydrological Drought in China

Drought frequency over 1961–2016 shows a distinct spatial uneven across China (Figure 4). In general, the drought frequency is higher almost over entire China under natural scenario (Figure 4a). Compared to the natural scenario, drought frequency in the human scenario (Figure 4b) is smaller in the southeast. Human activities reduced the drought frequency by up to 100% in parts of the southeast (Provinces/Cities 13, 14, 17–19, 22, and 25) (Figure 4c). In addition, the increases in drought frequency under the human scenario, ranging from 20% to 100%, occur in Hebei, Shanxi, Henan, Gansu, and Xinjiang (Provinces 5, 9, 10, 27, and 30), which are mainly located in the northern part of China. This indicates that the effects of human activities on drought frequency show a spatial inconsistency from north to south regions of China.

Figure 5 compares the percentage of areas in each province with increasing or decreasing trend in drought frequency under two scenarios during 1961–2016. All trend results are evaluated at the 95% significance level ($p < 0.05$), and the analysis is done for each province separately. Significant trends are found mainly in the central and western parts of China. Under the human scenario, parts of the southern region (including Provinces of 14, 16–22, and 31) have fewer percentage areas showing upward trends than those under the natural scenario except for Province 13 (Table S3). In contrast, increasing trends with higher percentage areas than those of decreasing trends mainly occur in the northern parts of China under the human scenario. This clear spatial differences between northern and southern regions of China are also visible for the percentage differences of mean drought duration (Figure 6).

Figure 6 shows that the spatial patterns of average drought duration under human and natural scenarios are distinct different from south to north parts of China, which are similar to the drought frequency distribution patterns (Figure 4c). Under the influence of human activities, drought duration decreases in the southern region, with the largest differences greater than 80% mainly located in Jiangsu, Anhui, Hubei, Jiangxi,
and Hunan (Provinces 13, 14, and 17–19). This is likely due to reservoir operations, which generally increase the release during the low flow period to satisfy the water demands downstream and therefore could alleviate downstream hydrological drought conditions (Wada et al., 2013). However, drought duration increases in parts of Zhejiang, Fujian, and Guangdong (Provinces 16, 20, and 22), which may be caused by the human water use and consumption. In contrast, the drought duration increases in most parts of

![Figure 3](image-url). Comparison of the deficit volume (m³) for each individual drought event over 2007–2016 identified from observations (30 hydrological stations) and model simulations (under natural and human scenarios). Note the logarithmic scale of x and y axis.
the northern region, especially in Liaoning, Hebei, Shandong, and Henan (Provinces 3, 5, 8, and 10). This uneven spatial pattern of drought duration is consistent with the study by Wang et al. (2011). These results demonstrate that human activities (such as human water use and water management, which is included in model simulation) have different impacts on drought duration from south to north parts of China.

4.3. Spatial Heterogeneity of Human Activities Influences on Hydrological Drought Across China

In order to further characterize the spatial heterogeneity of human influences on drought deficit over the NEC and SEC, we compare the histogram of drought deficit and duration for all grid cells in NEC and SEC regions under two scenarios from 1961 to 2016 (Figure 7). Results clearly show that human influence is dramatically different not only in terms of drought frequency but also in terms of drought deficit from northeast to southeast regions of China. In NEC, human activities enhance drought frequency of most drought categories, except for short duration (5–10 days) events. Under human scenario, drought deficit increases substantially for all drought categories, particularly for the 121–180 days duration droughts. The largest difference of drought deficit between natural and human scenarios is found for the 121–150 days duration droughts, where the drought deficit of the human scenario is ~37 times over that of the natural scenario. This indicates that human activities in this region have enhanced drought deficit of all categories droughts, which is similar to previous studies (Fu et al., 2004; Wada et al., 2013; Yuan et al., 2017), which likely due to human water use and management.

For the SEC, there is a large differences in drought deficit between two scenarios for different drought durations, although the drought frequency under human scenario is lower than that of the natural scenario. Under the human scenario, drought events lasting less than 150 days have higher severity than that of the natural scenario. The largest difference of average drought deficit is found over the 181–240 day duration categories between the two scenarios (drought deficit in the natural scenario is about six to eight times bigger than that in the human scenario). This might be explained by reservoir operations and human water

Figure 4. Drought frequency under natural (a) and human (b) scenarios and their percentage difference ((human-natural)/natural × 100%, c) from 1961 to 2016.

Figure 5. Changes in annual drought frequency for each province from 1961 to 2016 under natural and human scenarios. The blue and red color bar summarizes the percentage of each province’s area that shows increasing trend, and the gray and black bar shows decreasing trend under natural and human scenarios, respectively. The filled bar shows areas with statistically significant changing trend at 95% level (tested by a MK test at the 95% confidence level).
consumption, which could reduce local and downstream flow, as suggested by previous studies (Cai et al., 2016; Dai et al., 2008; Wada et al., 2013; Wang et al., 2017). Zhang et al. (2018) found that the average drought duration of these two regions varies from 7.5 to 10.5 months based on different hydrological drought indexes. Zhai et al. (2017) found that the most long-term drought events (>12 months) have been observed in the southeast river basins with three to four drought events during the period of 1960–2013. For extreme drought events with longer duration and higher severity, released water through reservoir operations could alleviate these extreme hydrological droughts (Dai et al., 2008; Shao et al., 2018; Tian et al., 2019; Wang et al., 2017; Yuan et al., 2017). This implies that human activities have direct and heterogeneous effects on hydrological drought in China.

Figure 6. The percentage difference [(human-natural)/natural × 100%] in drought duration between human and natural scenarios over China (1961–2016).

Figure 7. Histograms of mean deficit with different duration for all grids of northern parts of East China (NEC, upper panel) and southern parts of East China (SEC, lower panel) regions under human and natural scenarios from 1961 to 2016.
Furthermore, human and natural scenarios show similar spatial contrast in the trends of StDef between NEC and SEC (Figure 8). StDef under human scenario shows an increasing trend of more than 0.01 per year in NEC (i.e., Hebei and Shandong), which is statistically significant at \( p < 0.05 \) level (Figure S3). This is likely due to increased human water use (i.e., water withdraw or reservoir operation), which enhances the hydrological drought. For SEC region, the slightly decreasing trends of drought StDef generally occur in most parts of SEC region under the human scenario. Particularly in Jiangxi, Fujian, and Guangdong (Provinces 18, 20, and 22), human activities lead to a decreasing trend varying from \(-0.002\) to \(-0.01\) per year. However, the difference in the trend between two scenarios is small in Provinces 13, 17, and 19. Meanwhile, human activities have heterogeneous effects on drought StDef over SEC region. For instance, certain parts of Jiangsu and Anhui (Provinces 13 and 14) show a decreasing trend, whereas Hubei (Province 17) shows an increasing trend. StDef in some parts of Jiangsu and Jiangxi (Provinces 13 and 18) shows an increasing trend of more than 0.01 per year. Relative to the NEC, the effects of human activities on drought StDef are more complex and have higher degree of spatial heterogeneity in SEC. These differences are likely due to human water use mainly abstracted from the surface water, coincident with increased reservoir storage to buffer drought that leads to reduced downstream flow in these regions (Leng & Tang, 2014; Liu et al., 2019).

Human interventions (e.g., irrigation, abstraction, and reservoir operations) have altered the frequency, magnitude, and spatial distribution of hydrological droughts over China (Wada et al., 2013; Yuan et al., 2017). To evaluate the relative contribution of human activities to hydrological drought, we compare simulated river discharge under the natural conditions and under the human influence with \( Q_{90} \) obtained from the selected downstream points (Figure S1) of Yellow River in the north and Yangtze River in the south. Figure 9 shows a clear difference in discharge magnitudes between the two basins. The simulated low flow under the pristine conditions tends to be higher (lower) compared to that of the human scenario in the Yellow River (Yangtze River). Due to the lack of water resources in the Yellow River region, reservoirs are mainly used to supply water during dry seasons, which are coincident with the growing seasons of irrigated crops requiring large amount of water, which reduces the dry season streamflow (Liu et al., 2019). It indicates that human water use for irrigation exacerbates the hydrologic drought in this region.
In contrast, the surface water withdrawal happens when the river discharge higher than 10% of the long-term average yearly discharge under naturalized flow conditions. The net abstraction water in the southern China abstracted from the surface water covers longer period and consists of a small portion of discharge, due to abundant surface water resources. Reservoirs in the Yangtze River are mainly served for flood control and hydropower generation, and water stored in rainy seasons is used to supply water during dry periods. Such operations cut down the surplus in the flood season and store extra water to alleviate droughts in dry seasons. Therefore, the low flow under human scenarios is higher than that of natural scenario in this region. Such findings are consistent with previous studies (e.g., Liu et al., 2019; Shao et al., 2018; Wada et al., 2013; Yang et al., 2010; Yuan et al., 2017; Zhang et al., 2019). For example, in the driest year of 2006 in the Yangtze River, the TGD released about 3.58 × 10^9 m^3 water, and the discharge in the dry season remains the same as the normal year (Dai et al., 2008).

To further investigate the effects of human activities on drought deficit, we compare drought deficit, water abstraction, irrigation water use, ratio of agricultural water consumption to irrigation water (total abstraction water), and storage capacity of all reservoirs in the Yellow River and Yangtze River (Figure 10). Results show that drought deficit is enhanced by about 70–200% ((human-natural)/natural × 100%) under human influence in the Yellow River but this has been reduced about more than 45% in the severe drought years of 2006, 2007, and 2011 in the Yangtze River, which is likely due to different water resources management strategies in these two rivers (see below).

In the Yellow River, 74% of total surface water abstraction and 38% of total groundwater abstraction are used for irrigation. Most of the irrigation water evaporates over this region, and the ratio of irrigation water consumption to total abstraction irrigation water from 2004 to 2015 is more than 59% (YRCC, 2004–2015). This is also reflected by the higher StDef under human scenario than that of natural scenario. Similarly, Wang (1998) found that the irrigation water withdrawal accounts for about 80–90% of the total reduction in discharge of the Yellow River. Another exception by Chen et al. (2003) showed that reductions in discharge of the Yellow River are mainly due to increased irrigation water withdrawal. It demonstrates that high rates of evaporation from the irrigated area create major water losses of surface and groundwater, which decrease the portion of the return flow to total abstracted water. Furthermore, limited water resources amplify the effects of damming on river segments in northern region (Yang & Lu, 2014), despite there are fewer reservoirs compared to southern region (Liu et al., 2019).
In contrast, the Yangtze River has abundant surface water resources and higher annual mean reservoir storage (about $1.368 \times 10^8$ m$^3$ per year in 2006–2015). Seasonal reservoir operation can reduce drought deficits through the release of water during the dry season (Dai et al., 2008; Yang et al., 2010). Human activities reduce the mean drought StDef by 20% compared to the natural scenario. Particularly, StDef of the human scenario in severe drought years of 2006 and 2011 (0.018 and 0.021) is lower than that of the natural scenario (0.026 and 0.033). Ratio of agricultural water consumption to total abstraction water is about 31% from 2004 to 2015 (CWRC, 2004–2015), which is lower than that of the Yellow River. This is supported by previous findings (Dai et al., 2008; Wada et al., 2013; Liu et al., 2017; 2019; Tian et al., 2019) and is consistent with data sets compiled by Changjiang Water Resources Commission from 2006 and 2011. In the severe drought year of 2011, for example, the TGD released about $2.15 \times 10^{10}$ m$^3$ water for mitigating the drought (CWRC, 2011). Water withdrawal for irrigation is less due to the large streamflow and relatively wetter conditions of the Yangtze River region (Liu et al., 2019). Large amounts of paddy rice with specific irrigation practice (requires a certain depth of water in the paddy field during growing seasons) are grown in this region, which may subsequently transfer a tremendous amount of the water withdrawals that are attributed to irrigation to drainage (Leng & Tang, 2014; Liu et al., 2005). Thus, water resources management through reservoir operation (e.g., surface water extraction), together with the local irrigation characteristics, has a particularly strong impact on hydrological drought (Biemans et al., 2011; Liu et al., 2019).

5. Discussion

The PCR-GLOBWB v2.0 model performs reasonable at simulating the hydrological process and especially low flows at 30 hydrological stations, though several issues are worth noting. First, the coverage of
stations used is relatively small (due to data availability), especially in the north, west, and southeast rivers, leading to an evaluation of the performance of the model is not necessarily representative. Second, model simulations largely rely on the accuracy of calculated human water consumption and management. We extract the model parameters from the global database, which are calibrated by Sutanudjaja et al. (2018), and no local calibration is performed. Therefore, uncertainties from human impact parameterizations will lead to biases in the results of this study (Liu et al., 2019; Müller Schmied et al., 2014).

Reservoir regulation scheme is critical in this model, and human impacts on hydrological processes could be much more complex than the simulations in this study for they are associated with many socioeconomic factors (Liu et al., 2017). We compare the correlation of simulated and observed streamflows at Yichange station during the post-TGD period (2007–2015). We find that including human water use and reservoir management (TGD) improves $R^2$ (between the simulated and observed streamflows) from 0.62 to 0.76 during the post-TGD period (Figure S2), albeit with relatively low NSE values (Table S1), which highlights the importance of incorporating more reliable and accurate reservoir regulation rules in the model. Water withdrawal for agricultural irrigation accounts for the largest proportion of human water use in China; the overestimation or underestimation will lead uncertainty to the changes of streamflow in most river segments by model simulation under the human scenario. Human water consumption of this model is subtracted from simulated streamflow that is routed through natural drainage network only, which likely leads overestimation of the reduction of streamflow as the result of human water consumption (Wada et al., 2013).

In addition, obviously large model uncertainties also remain in the meteorological forcing as well as abstraction data. Many studies have analyzed uncertainties in recharge and abstractions, as well as uncertainties in meteorological forcing, using the same model (Sutanudjaja et al., 2018; Wang et al., 2017). Therefore, future work is needed to identify more observational data, including discharge data at more hydrological stations, irrigation and reservoir data, and groundwater data to further calibrate this model. Furthermore, future work might also incorporate future scenarios of climate, cropping, population, and other economic data to assess and predict the severity of hydrological drought, and the vulnerability of drought in the future.

In addition, this study uses a variable threshold of monthly threshold to identify hydrological droughts from daily streamflow time series. As documented by Beyene et al. (2014), this could potentially lead to some errors in drought estimation, especially for shorter (artificial) events. Further analysis should be conducted to examine to what degree such errors will vary across different spatial and temporal scales.

### 6. Conclusions

Complex climatic conditions, land cover/use types, and population density distributions result in different water use and water management scenarios across China and consequently different impacts on hydrological drought. Therefore, it is necessary to evaluate the contribution of human activities to hydrological drought in different regions of China. This study investigates the contribution of human activities (in addition to natural variability) to hydrological droughts in China during 1961–2016 using the PCR-GLOBWB v2.0 model. The model can reproduce the drought climatology across China and adding human activities can slightly improve model skill, although the model results tend to underestimate minor drought events under both natural and human scenarios. We find that human water management can influence the hydrological cycle during drought periods in different ways. Overextraction of surface water for irrigation during dry periods can exacerbate hydrological drought, but human water management can also store wet season water to mitigate drought in later seasons through reservoir operation. As a result, human activities have different impacts in the northern and southern part of East China, which can reduce the severity of hydrological droughts in the southern part but exacerbate hydrological drought in the north.

These results suggest that it is crucial to treat terrestrial water dynamics within an integrated natural-human system and include all kinds of water use and water management practices as well as their interactions, so that effective and efficient water resource management strategies can be developed to coincide with future increased frequency and intensity of droughts. In particular, policymakers need to take into account the heterogeneous impacts of human activities on drought, when planning for large-scale water management and drought risk mitigation/adaption. Nevertheless, although policies on human water consumption and management can be adjusted according to the findings in this study, increasing water demand and the complex regional water resources situation may add the uncertainty and complication of future changes of...
hydrological drought in China. Water infrastructure in China may therefore face increasing challenges even in the near term, and the resilience to drought remains uncertain.

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