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Potential Threats from Variations of Hydrological Parameters to the Yellow River and Pearl River Basins in China over the Next 30 Years

Lüliu Liu [1,*], Tong Jiang [1,2], Hongmei Xu [1] and Yong Wang [3]

[1] National Climate Center, China Meteorological Administration, Beijing 100081, China; jiangtong@cma.gov.cn (T.J.); xuhm@cma.gov.cn (H.X.)
[2] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, School of Geography and Remote Sensing, Nanjing University of Information Science & Technology, Nanjing 210044, China
[3] Chongqing Climate Center, Chongqing 401147, China; wngyng023@126.com
* Correspondence: liull@cma.gov.cn; Tel.: +86-10-58995906

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Abstract: An assessment of the impact of climate change on regional hydrological processes is vital for effective water resources management and planning. This study investigated the potential effects of climate change on water availability, seasonal runoff, flooding, and water stress in the Yellow River and Pearl River basins in China over the next 30 years, using a semi-distributed hydrological model based on a combination of five general circulation models with four Representative Concentration Pathway scenarios and five Shared Socioeconomic Pathways. The results indicated annual mean temperature could rise higher in the Yellow River Basin than the Xijiang River Basin during 2021–2050. Higher risks of small floods and some big floods, but lower risks of rare big floods are projected for both basins. Water scarcity will continually threaten the Yellow River Basin, especially during the dry season and around 2025. In comparison with the effects of climate change, population variation was expected to have a greater impact on water scarcity. A longer and drier dry season is projected for the Pearl River Basin, which could aggravate water stress and saltwater intrusion into the Pearl River delta. Although the present findings have implications for water resource management planning, caution should be observed because of the neglect of reservoir/dam operations and inherent projection uncertainty.

Keywords: water stress; floods; Yellow River; Xijiang River

1. Introduction

Warming of the lower atmosphere increases its capacity to hold water vapor, which consequently strengthens the hydrological cycle on a global scale [1]. Changes in the hydrological cycle can lead to diverse impacts and risks [2]. Alterations of annual water availability, seasonal discharge, and extreme flows, with variations among river basins, have been detected and projected by many previous studies. For example, significant trends of increase or decrease in river discharge during 1948–2004 were detected for about one third of the main rivers in a global analysis [3]. In China, trends of decrease in annual runoff have been observed in most rivers in the northern areas since the 1950s [4]. Another recent study projected an increase in runoff in a catchment within the Yellow River Basin, but slight decreases were projected in the Yangtze River and Pearl River Basins under 1.5 and 2 °C global warming [5,6]. In addition, alterations of seasonal discharge have also been projected [2,6,7]. In some basins, wet seasons are expected to become wetter and dry seasons drier in a world changing from 2 °C warming to 4 °C warming [8]. River basins dominated by a monsoonal regime are particularly vulnerable to changes in the seasonality of runoff [9]. For example, runoff in the dry season is projected to decrease both in the Pearl River Basin under the Representative Concentration Pathway (RCP) 4.5 [7] and in the Yellow River Basin under the Special Report on Emission Scenarios A2 and B2 [10]. As for extremes, severe risks of flooding and drought could increase [9]. The estimated risk associated with 4 °C warming is considered much higher than that associated with 2 °C warming, and it is projected to have substantial catchment-scale variability [1,9]. For example, more severe floods with long return periods (25 and 50 years) are expected for certain catchments within the Yellow River and Pearl River basins [6].

In addition to climate change, non-climatic drivers such as population increase, economic development, urbanization, and land use, or natural geomorphic changes also challenge the sustainability of resources by increasing water supply or increasing demand [2,11]. The percentage of the global population living in river basins with new or aggravated water scarcity is projected to increase from 8% under 2 °C warming to 13% under 5 °C warming [12]. In Asia, water scarcity is projected to constitute a considerable challenge in many regions because of increasing water demand from population growth and rising per capita consumption associated with improved standards of living [13].

The Pearl River and the Yellow River are two large rivers that are subjected to the monsoon climate in China. The Yellow River is the second longest river in China, and its basin covers approximately 752,443 km^2. Although the basin holds only 2% of China's water resources, it occupies 15% of the country's cultivated area and it supports 12% of the national population [14]. The per capita water resource of about 579 m^3 includes 485 m^3 of surface water resources [15]. The Yellow River has suffered the effects of severe water scarcity, and the lower reaches of the river have dried up many times since 1972 because of climate change and anthropogenic activities [16,17]. However, although the river flow can be modulated by storing flood water in reservoirs during the wet season and releasing it during the dry season, water scarcity is expected to become increasingly severe in the next decade because of the projected rapid increases in population, urbanization, and industrialization [18], and this situation is anticipated even if annual discharge increases [10]. Thus, it is important to assess the potential effects of climate change and population increase on runoff and water scarcity in the Yellow River Basin, considering that water scarcity is a serious challenge for regional water resource management and conservation of the ecological environment [17,18].

The Pearl River is the third longest river in China but the second most important in terms of runoff. The basin, which covers approximately 453,700 km^2, has an important role in China's economic development. The water resources of the Pearl River Basin account for about 16% of national water resources [19]. They irrigate about 3% of the national cropland [20], support 12% of the national population, and help generate 13% of the national gross domestic product [21]. The basin primarily experiences a subtropical and tropical climate. The climate in combination with topography causes frequent floods and droughts. The frequency of floods has increased since 1980 [22], and increasingly frequent and severe saltwater intrusions have occurred in the delta area during the dry season since 1990 [23], largely because of factors such as reduced runoff during the dry season and increased water demand [24]. These factors, which have caused difficulties in maintaining water supplies and have contributed to losses of life and property [7,24], are expected to become increasingly severe in the future [7,25]. Thus, it is important to assess the variations in both seasonal runoff and hydrological extremes in the Pearl River Basin.

The motivation for this study was to identify potential threats from global warming and population increase to the Yellow River and Pearl River basins over the next 30 years. Changes in annual and seasonal runoff in the Yellow River Basin in the 21st century have been studied based on the Special Report on Emission Scenarios A2 and B2 [10]. However, few studies have investigated such changes in combination with an examination of anticipated flooding and water scarcity under scenarios of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and IPCC Sixth Assessment Report (AR6). In the Pearl River Basin, studies have projected changes in annual runoff, seasonal runoff, and hydrological extremes during different time slices during the 21st century based on the IPCC AR5 [6,7,26]. However, few studies have focused on such changes during the short term (2021–2050), or on the impacts of climate change and population growth on base-scale water management. Thus, the primary objectives of this study were: (1) to estimate the impact of climate change on annual water availability, seasonal runoff, and hydrological extremes; (2) to investigate the changes in water stress due to climate change and population development; and (3) to identify key threats to the two basins. The results will help regional stakeholders and policy makers integrate climate change and population change into long-term plans to strengthen basin-scale water resources management.

Catchment-based hydrological models (CHMs) and non-calibrated global hydrological models with coarse resolution are two types of hydrological model commonly applied to investigate the hydrological impacts of climate change. CHMs are run based on more explicit representations of catchments than are available from global hydrological models; thus, they usually provide information that is more reliable, allowing regional stakeholders to develop appropriate adaptation policies. Among the many CHMs available, semi-distributed hydrological models are more useful than physically-based distributed hydrological models for exploring climate change over long timescales and large geographic areas [27]. Semi-distributed hydrological models preserve the underlying conceptual information of the spatially-distributed parameters, while advoiding an increase in the number of parameters with area increasing [28]. As a semi-distributed model, various versions of the HBV (Hydrologiska Byråns Vattenbalansavdelning, the predecessor of the Swedish Meteorological and Hydrological Institute) model have been applied successfully in many catchments. In comparison with the original HBV, the HBV-D has an improved description of land cover characteristics and has more physically sound evapotranspiration schemes, making it more appropriate for investigations of regional hydrological impacts of global change in large basins [28]. The HBV-D has been used previously in many basins or catchments in China from small catchments to large basins such as the Yellow River and Pearl River basins with various climatic conditions [6,26,29]. In this study, the HBV-D model was used to simulate runoff. Then, the changes of several hydrological parameters were investigated based on hydrological projections under various RCPs and population predictions under Shared Socioeconomic Pathways (SSPs). The IPCC AR5 scenario was used instead of the IPCC AR6 scenario because the dataset of climate projections under the latter cannot be officially accessed.

2. Materials and Methods

2.1. Descriptions of the Study Basins

2.1.1. Yellow River

The division between the middle and lower reaches of the Yellow River in northern China is marked by the Huayuankou (HYK) station. The studied area comprised the watershed upstream of station HYK (length: 4696 km, area: 730,036 km^2), which accounts for 97% of the entire Yellow River Basin (Figure 1). The annual runoff through HYK accounts for about 98% of the Yellow River flow [10]. Annual average temperature in the Yellow River Basin is 8–11 °C, and the annual average precipitation is 340–700 mm. Precipitation during the flood season (June–September) accounts for about 70% of the annual total. Consequently, runoff through station HYK during the flood season accounts for 36% of the annual total.

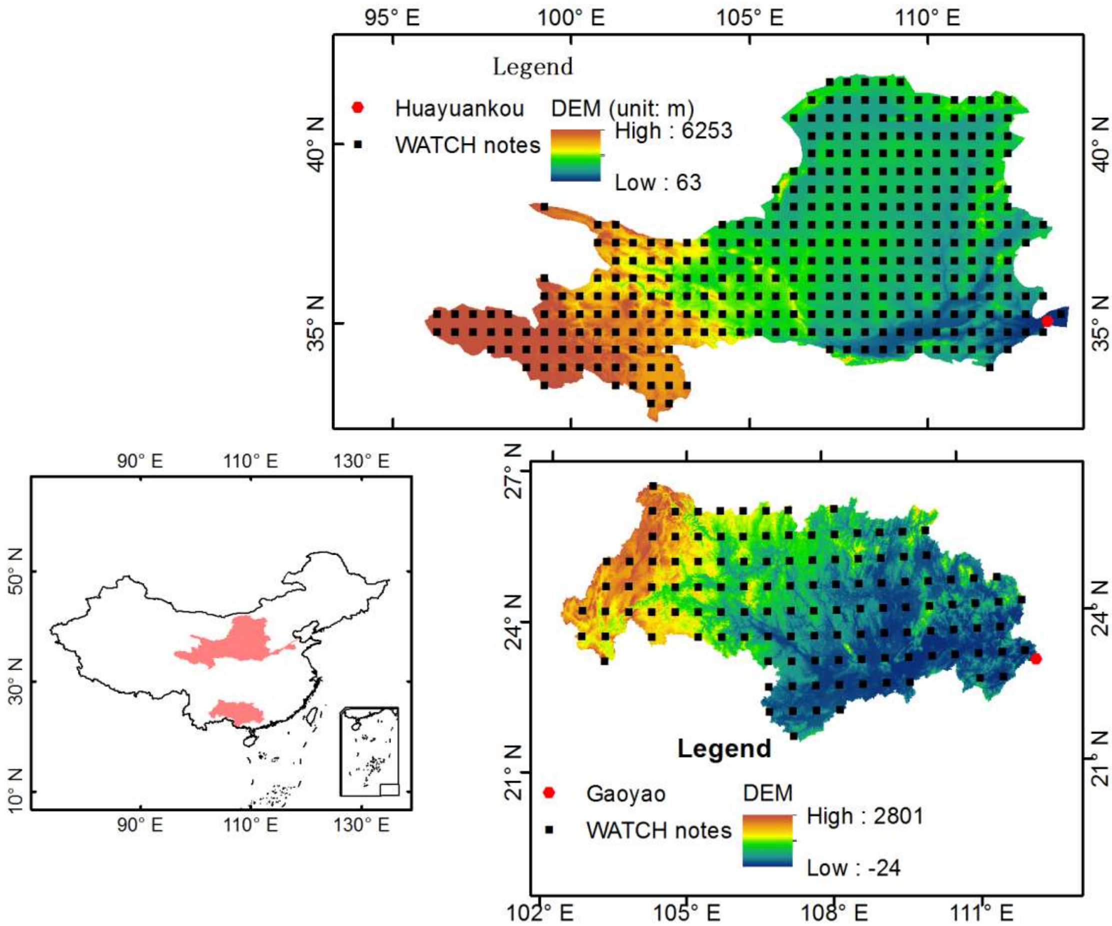

Figure 1. Locations of the studied basins in China (**lower left panel**). Overview maps of the Yellow River Basin (**upper panel**) in northern China and the Xijiang River Basin (**right lower panel**) in southern China. Grid denotes climate forcing, and red hexagons show the positions of the Huayuankou and Gaoyao hydrological stations.

2.1.2. Xijiang River

The Xijiang River drains the entire western and central parts of the Pearl River Basin in southern China. It is the largest tributary of the Pearl River with length of 2214 km and area of 353,100 km^2 [26], and it accounts for 78% of the Pear River Basin. The watershed area upstream of the outlet hydrological station (Gaoyao station) accounts for 99% of the Xijiang River Basin [29]. The locations of the Xijiang River Basin and the Gaoyao hydrological station are shown in Figure 1. The annual average temperature is 18–21 °C, and the annual average precipitation is in 1070–1700 mm. The basin is dominated by the effects of the East Asian summer monsoon and 80% of the annual precipitation falls in the flood season (April–September). Modulated by the seasonal precipitation pattern, runoff during the flood season accounts for 74% of the annual total.

2.2. Data

A digital elevation model (DEM) with scale of 1:250,000 was developed by the National Geomatics Center of China [30]. Soil field capacity was estimated based on soil property data from the Food and Agriculture Organization Soil Map of the World [31]. Catchment land use was extracted from digital national land use maps with scale of 1:500,000 compiled by the Ministry of Land and Resources of China based on national land use surveys conducted during 1984–1995 [32]. Changes in land use were not considered in the modeling of baseline and future river discharge.

Daily temperature and precipitation data at 0.5° × 0.5° resolution during 1958–2001 were derived from the Water and Global Change Program (WATCH) meteorological forcing datasets (http://www.eu-watch.org/data_availability) [33], and they were used to calibrate and validate the hydrological model as climate forcing.

Climate projection data was derived from the Inter-Sectoral Impact Model Intercomparison Project (https://esg-pik-potsdam.de), which corrected the output of five general circulation models (GCMS) of the Coupled Model Intercomparison Project Phase 5 (i.e., GFDL-ESM2M, HaDGem2, IPSL_CM5A_LR, MIROC-ESM-CHEM, and NorESM1-M) (https://esgf-node.llnl.gov/search/cmip5/), using the trend-preserving bias correction approach based on WATCH forcing data [34]. The dataset covers the period 1950–2099, and has 0.5° × 0.5° resolution.

Data on the population of China with 0.5° × 0.5° resolution under five SSPs during 2010–2050 were projected using a population–development–environment model [35] and they are provided by the National Climate Center of the China Meteorological Administration.

Digital observations of monthly runoff during 1961–1990 at Gaoyao station, provided by the Hydrology Bureau of the Pearl River Water Resources Commission, were used to calibrate and validate the HBV model for the Xijiang River. The digital naturalized monthly runoff data during 1961–1990 at station HYK, provided by the Hydrology Bureau of the Yellow River Conservancy Commission, were used to calibrate and validate the HBV model for the Yellow River.

2.3. Methods

2.3.1. Hydrological Modeling

The HBV-D semi-distributed hydrological model was used to simulate future daily runoff in the Yellow River and Xijiang River basins. Among various versions of the HBV, HBV-D has also been used to project changes in runoff or to define rainfall thresholds from small watersheds to large basins under different climatic and physiographic conditions in China [6,36,37]. In this study, the performance of the HBV-D model was evaluated with three widely used criteria: the Nash–Sutcliffe efficiency (*Ens*, range between minus infinity and 1) [38], coefficient of determination (R^2, range between −1 and +1), and percent bias (*PBLAS*, range −100% to infinity). The first two were used primarily for daily and monthly flow calibration–validation [39].

For the Yellow River Basin, monthly naturalized runoff other than that observed at station HYK during 1961–1990 was used to calibrate and validate the HBV-D model. This is because heavy human water consumption has led to the observed streamflow being consistently lower than the naturalized streamflow for the middle and lower reaches of the Yellow River Basin [10,14]. It is difficult to handle the physical processes of irrigation and interbasin water diversion in most hydrological models because of the scarcity of management data and the deficiency regarding the human component in such models [14]. The projection and analysis of natural runoff change are useful for water balance research and water resources management [10]. Good agreement was found between the naturalized and simulated monthly runoff curves for the Yellow River Basin (Figure 2), with bias (*PBIAS*) of 5.2%, and 2.2% for the calibration (1961–1975) and validation (1976–1990) periods, respectively. Furthermore, for the calibration and validation periods, *Ens* was found equal to 0.75 and 0.70, and R^2 was found equal to 0.87 and 0.84, respectively. In addition, it was established that the HBV-D model was capable of reproducing the seasonal dynamics of streamflow reasonably well for the upper reaches of the Yellow River [40].

For the Xijiang River Basin, the HBV-D model was verified to simulate monthly runoff well and to simulate daily runoff acceptably using observed in situ precipitation and temperature as climate forcing [26,29]. Here, WATCH climate forcing was used, and the monthly and seasonal patterns of observed monthly runoff were reproduced acceptably (Figure 3), with bias of 10.5% and 10.8%, *Ens* of 0.89 and 0.85, and R^2 of 0.96, and 0.95 for the calibration and validation periods, respectively. Furthermore, the daily runoff was reproduced acceptably with *Ens* of 0.80 and 0.78, and R^2 of 0.90

and 0.90 for the calibration and validation periods, respectively, and good agreement was achieved between observed and simulated flow duration curves, as shown in Figure 4.

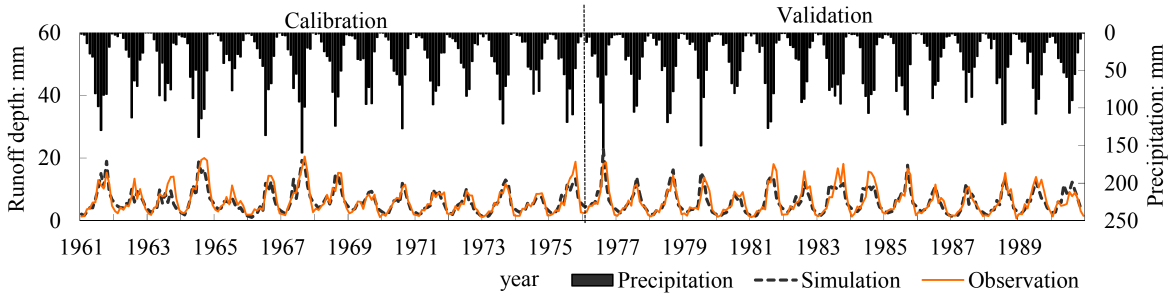

Figure 2. Monthly precipitation and observed/simulated runoff through the Huayuankou hydrological station on the Yellow River (1961–1990).

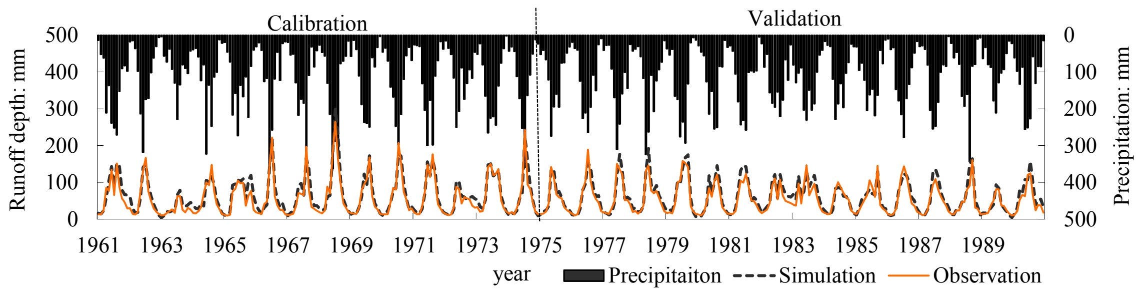

Figure 3. Monthly precipitation and observed/simulated runoff through the Gaoyao hydrological station on the Xijiang River (1961–1990).

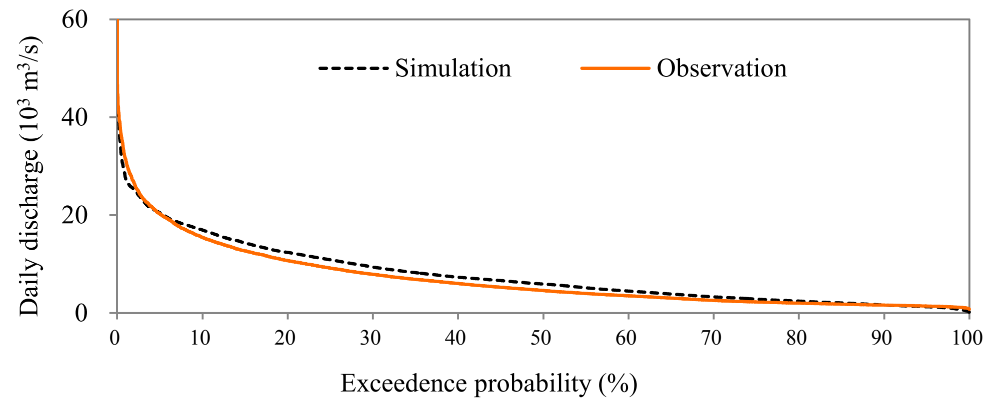

Figure 4. Flow duration curves of daily observed/simulated runoff through the Gaoyao hydrological station on the Xijiang River (1961–1990).

These results verify the model capable of sufficiently accurate long-term simulation of monthly runoff for the two basins. And the simulated daily runoff was satisfactory for the Xijiang River Basin.

2.3.2. Climate and Population Projection

Climate projection information for 2010–2050 was derived from 20 combinations of four RCPs (RCP2.6, RCP4.5, RC6.0, and RCP8.5) and five GCMs, as mentioned in Section 2.2.

The population information during 2010–2050 under five SSPs (SSP1, SSP2, SSP3, SSP4, and SSP5) in China was projected using a multi-dimensional population–development–environment model [41,42] involving fertility, mortality, migration, and education. The population in a specified year can be derived as follows [35]:

$$P_{t+1} = P'_t \times (1 - D_{t+1}) + M_{t+1} \quad (1)$$

where, P_{t+1} is the population at the age t + 1 in a specified year, P'_t is the population at the age t in the former year, D_{t+1} is the mortality rate at the age t + 1 in a specified year, and M_{t+1} is the migration rate at the age t + 1 in a specified year.

$$P_n = \sum_{t=15}^{49} P_t \times R_t \times F_t \quad (2)$$

where P_n is the newborn population in year n, P_t is the population at the age t in year n, R_t is the female ratio at age t in year n, F_t is the fertility rate at the age t in year n.

Fertility, mortality, and migration were classified into low, middle, and high levels, while education was classified into four categories: illiterate, primary, secondary (junior and senior high school) and tertiary (graduate and above), in accordance with the assumptions of Samir and Lutze [43] and then revised according to regional characteristics including the population policy of China [35]. Thus, their projections were different under each SSP using initial demographic data based on the Sixth National Population Census of 2010.

2.3.3. Hydrological Variables and Water Scarcity Projection

Based on the projected daily runoff, the mean annual runoff and floods were calculated to investigate the various hydrological responses of the two basins over the next 30 years. Floods were derived using the peak-over-threshold (POT) model, which is more informative than annual maximum model [44]. Here, floods were extracted at an average rate of three per year (POT3 floods), following the application of standard independence criteria [45]. To facilitate a comparison, the percentage changes in annual runoff and POT3 during 2021–2050 were compared with the baseline period (1976–2005).

Water stress or scarcity can be defined as the balance between water supply and water demand. Hydrologists generally treat 1700 m^3 of water per capita as the threshold for meeting the water requirements for agriculture, industrial production, and energy generation. Per capita water availability below the threshold of 1000 m^3 is considered to represent a state of water scarcity, while anything below 500 m^3 represents a state of absolute scarcity [46]. Here, annual river runoff per capita was used to measure the water stress of the two river basins. Similarly, per capita annual runoff in a given basin was applied as a measure of water resources per capita with which to investigate water stress [8]. Considering the bias of the projection, a simple method was used to correct the values. The corrected water scarcity was considered equal to the annual runoff per capita in 2010 plus the projected anomaly relative to the 2010s as follows:

$$WSI_{cor} = WSI_{obs}^{2010} + \left(WSI_{ori} - WSI_{ori}^{2010}\right) \quad (3)$$

where WSI_{cor} is the corrected water stress index, WSI_{ori} is the water stress index estimated based on runoff and population predictions, and WI_{ori}^{2010} is the water stress index estimated in 2010.

WSI_{obs}^{2010} for the Xijiang River was obtained from the Pearl River Water Resources Bulletin 2010 [18]. WSI_{obs}^{2010} for the Yellow River was estimated based on the naturalized annual runoff through the HYK hydrological station in 2010 [15], and the population derived using the gridded population dataset for China at 1° resolution [47] (http://www.geodoi.ac.cn/doi.aspx?doi=10.3974/geodb. 2014.01.06.v1).

3. Results and Discussion

3.1. Changes in Annual Mean Temperature, Annual Precipitation, and Runoff

In the Yellow River Basin, rising trends are projected for the annual mean temperature under the four RCPs over the next 30 years (2021–2050), with a 90% confidence bound of 0.3–4.2 °C (Figure 5a). The anomaly mean relative to the baseline for the 20-year loop and the five GCMs will rise from about 1 °C in 2021 to 1.8, 2.1, 1.9, and 2.9 °C in 2050 under RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. As shown in Figure 5b,c, annual precipitation and runoff will change with large uncertainty during the 30-year period. The 90% confidence bounds of the anomaly percent are between −15% and 28% for annual precipitation and between −53% and 41% for annual runoff. The 20-year loop and five GCM means of annual precipitation under the four RCPs, and of annual runoff under RCP2.6 and RCP4.5, are projected to have upward trends over the next 30 years. The annual precipitation anomaly percent will increase from about 2% in 2021 to 8%, 7%, and 10% by 2050 under RCP2.6, RCP4.5, and RCP8.5, respectively. The annual runoff anomaly percent will change from about −10% in 2021 to −6%, −9%, and −6% under RCP2.6, RCP4.5, and RCP8.5, respectively.

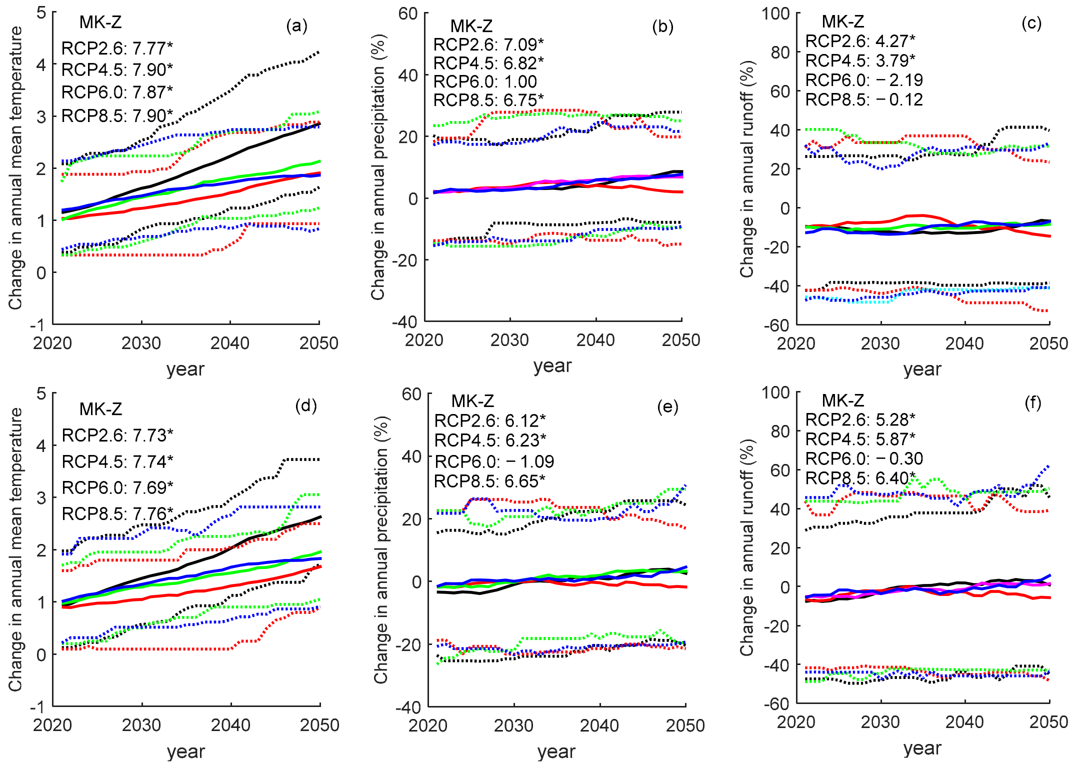

Figure 5. Changes in 20-year loop mean and 90% confidence bounds of the annual mean temperature, annual precipitation, and annual runoff relative to the baseline (1976–2005) in (**a**–**c**) the Yellow River Basin and (**d**–**f**) in the Xijiang River Basin. Blue, green, red, and black lines represent RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. Solid lines indicate RCP mean and dashed lines represent the 90% confidence bounds under each RCP scenario. The values of the Mann–Kendall statistic (MK-Z) were estimated based on RCP means during 2021–2050. * indicate trends significant at the 5% level.

In the Xijiang River Basin, rising trends are projected for the annual mean temperature over the next 30 years (2021–2050) under the four RCPs, with a 90% confidence bound of 0.1–3.7 °C (Figure 5d). The 20-year loop and five GCMs mean of anomaly will rise from about 1.0 °C in 2021 to 1.8, 2.0, 1.7, and 2.6 °C in 2050 under RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. Annual precipitation and runoff will change with large uncertainty over the next 30 years, with the 90% confidence bounds of the anomaly percent between −26% and 31% and −50% and 62%, respectively (Figure 5e,f). Multi-GCM means of both annual precipitation and annual runoff are projected to have increasing trends under RCP2.6, RCP4.5, and RCP8.5. The annual precipitation anomaly percent will change from about −2% or −3% in 2021 to 3% or 5% in 2050 under RCP2.6, RCP4.5, and RCP8.5. The annual runoff anomaly percent will change from −8% or −6% in 2021 to 1% or 6% under RCP2.6, RCP4.5, and RCP8.5. Under RCP6.0, the anomaly percent of annual precipitation is around −2% during the entire period, and annual runoff is around −6%.

These results indicate that rise of annual mean temperature is projected to be larger in the Yellow River Basin than in the Xijiang River Basin. This finding is similar to that of previous study, which found the expected temperature in northern China was larger than in southern China under 1.5 and 2 °C global warming [6].

3.2. Changes in Seasonal Runoff and Floods

As shown in Figure 6a, the same seasonal distribution is expected under the four RCPs over the next 30 years as that of the baseline in the Yellow River Basin. Both the multi-GCM means and medians will decrease relative to the baseline in each month. However, it should be noted that the possibility of runoff increase in each month could be expected based on the projection uncertainty of some GCMs. Two aspects of the effects of the changes are projected: increasingly severe water shortages due to decreased monthly runoff, especially in the dry season, and lower flood risk because of decreased runoff in the flood season. Relatively smaller-sized floods (<4000 m^3/s) and big floods (8000–9500 m^3/s) are projected to happen more frequently in the future, but current medium-sized floods (4000–7000 m^3/s) and big floods (9500–11,000 m^3/s) will occur less often (Figure 6c). Thus, this could reduce the risk of medium-sized floods. With regard to the likely decrease of monthly runoff, a drier spring was projected for a catchment within the Yellow River Basin in a previous study [6].

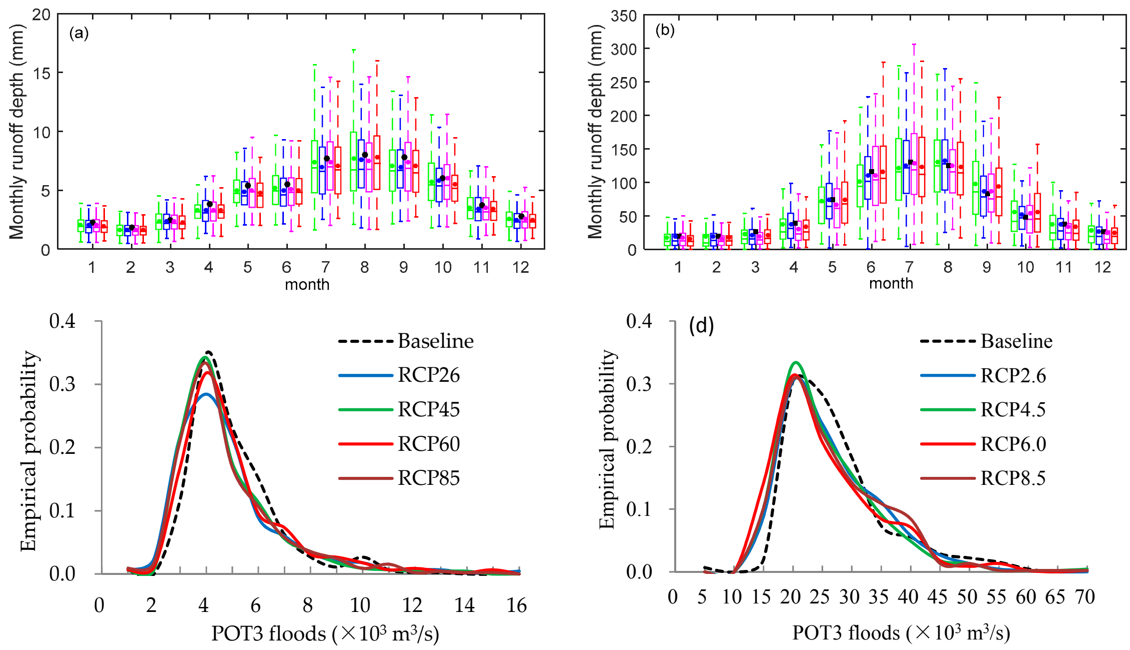

Figure 6. Simulated monthly runoff for 2021–2050 under four RCPs and the baseline in (**a**) the Yellow River Basin and (**b**) the Xijiang River Basin. Green, blue, pink, and red boxes represent RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. Black and colored dots represent baseline and period averages of multi-GCM means under the RCPs. Empirical probability of POT3 floods in (**c**) the Yellow River Basin and (**d**) the Xijiang River Basin for baseline and 2021–2050 under RCP2.6, RCP4.5, RCP6.0, and RCP8.5.

As shown in Figure 6b, a slight change in seasonal distribution is projected for the Xijiang River Basin over the next 30 years. Under the four RCPs, both the multi-GCM means and medians will decrease during the first seven months of the year and then increase in September and October. Contrasting changes in the directions of variation among the various RCPs are projected in the other three months. This could potentially cause the ending time of the dry season to be delayed from March until April and the ending time of the flood season to be delayed from September until October. The longer dry season accompanying reduced flow in March would aggravate drought stress and cause a higher risk of saltwater intrusion in the delta area. Increased runoff in August and September could increase flood risk during the latter stages of the flood season, but decreased runoff in the early flood season could reduce the risk of floods. This confirmed the likely drier and longer dry season in the Pearl River Basin under 1.5 and 2 °C global warming or the last thirty years of the 21st century under RCP4.5 and RCP8.5 [6,7]. As illustrated in Figure 6d, relatively smaller-sized floods (about 10,000–20,000 m^3/s) would become more frequent, but current medium-sized floods (about 20,000–32,000 m^3/s) and rare big flood (>43,000 m^3/s) would become less frequent. These findings suggest a lower risk of medium-sized and rare big floods could be expected over the next 30 years. However, a higher risk of big floods (about 32,000–43,000 m^3/s) is also projected.

3.3. Changes in Population and Water Scarcity

As shown in Figure 7a, the population is projected to first increase and then decrease in the Yellow River Basin over the next 30 years. The population will reach a maximum value at around 2025, 2030, or 2035 under different SSPs, but it will reach a minimum value at around 2050. During the studied period, the population under SSP3 is always the highest and that under SSP4 is always the lowest. The maximum population is projected to be 100, 101, 104, 100, and 100 million and the minimum population is projected to be 94, 96, 102, 91, and 91 million under SSP1, SSP2, SSP3, SSP4, and SSP5, respectively. Affected by variations in both population and annual runoff, *WSI* varies within the range 418–489 m^3 (Figure 7c). Thus, the state of absolute scarcity will continue and the basin will be challenged by the most serious water scarcity at around 2025, when *WSI* will be below 430 m^3. Moreover, there is the probability of even more severe water shortages considering the projection uncertainties, because a value of *WSI* lower than 350 m^3 is projected under some scenarios during 2025–2035 (Figure 7c). Additionally, the results suggest that population change rather than climate change will play the main role in the variation of water scarcity. This is because the ensemble mean of *WSI* fluctuates over the next 30 years with the decrease or increase of population, whereas the ensemble mean of annual runoff does not show such fluctuation. The suggestion is similar to some previous studies that found the changes in water stress will be dominated primarily by population changes rather than climate changes over the next few decades in a 2 °C or <2 °C warming world [2,8].

As shown in Figure 7b, the population will increase gradually in the Xijiang River Basin over the next 30 years under SSP1, SSP2, and SSP3, but it will first increase then decrease under SSP4 and SSP5. The population will reach a maximum value during 2045 and 2040 under SSP4 and SSP5, respectively, whereas the minimum value will occur in 2020 under all five SSPs. Over the 30-year period, the highest population is projected under SSP3, while the lowest population is predicted under SSP5. Under these scenarios, water shortages are expected not to threaten the basin, if annual runoff per capita is used to measure water stress, because even the smallest per capita annual runoff is >3500 m^3 (Figure 7d). However, water shortages are expected to be more serious during the dry season because of the projected decrease in runoff during the dry season. Therefore, caution should be observed when assessing water scarcity using the index of annual runoff per capita in some basins that have distinct dry and wet seasons, because unequal seasonal precipitation and subsequently unequal seasonal runoff will cause seasonal fluctuation of water stress.

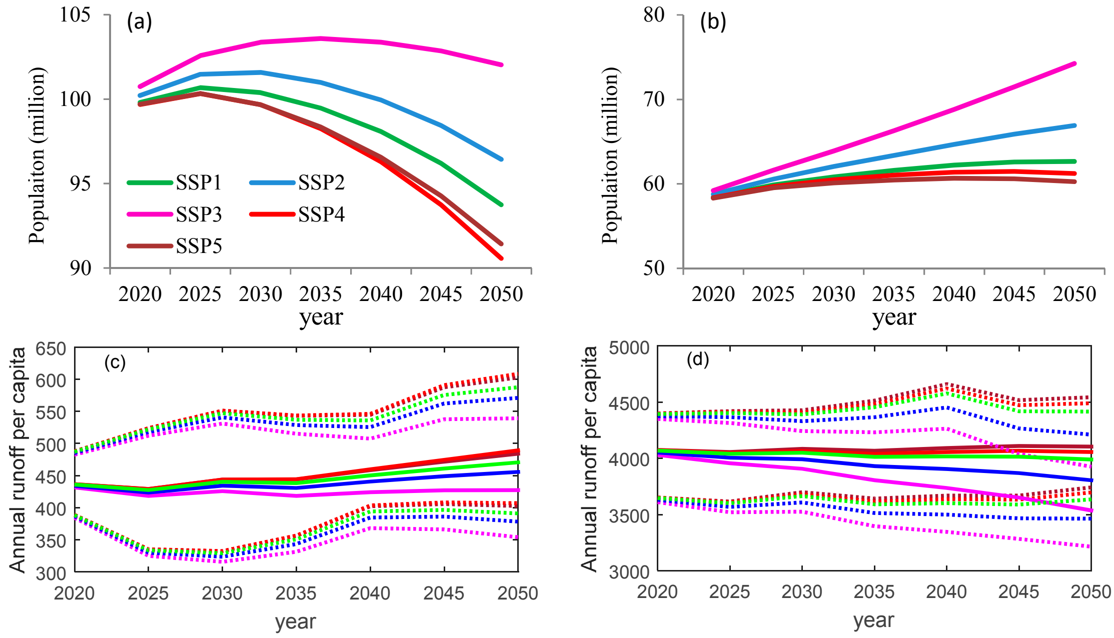

Figure 7. Population in (**a**) the Yellow River Basin and (**b**) the Xijiang River Basin. Mean and 90% confidence bounds of water stress under the five SSPs in (**c**) the Yellow River Basin and (**d**) the Xijiang River Basin. Green, blue, pink, red, and brown lines represent SSP1, SSP2, SSP3, SSP4, and SSP5 respectively. Solid lines indicate SSP mean and dashed lines represent the 90% confidence bounds under each SSP scenario.

3.4. Discussion about Uncertainties

In this study, the uncertainties associated with the GCM structure, RCP scenarios, and SSPs were quantified using five different climate models under the four RCPs for the climate forcing and the predictions of population based on the five SSPs. However, some sources of uncertainty were neglected, such as those associated with the structure and parameterization of the hydrological model, because it is challenging to address the uncertainties from all sources. Although the uncertainty attributable to the hydrological model structure was considered here, the projections based on the HBV-D hydrological model can provide water resources managers and policy makers with important information regarding the two studied basins. Previous studies have investigated the overall performance of the HBV model and that of another seven regional hydrological models, applying them to 12 large-scale river basins worldwide (including the upper Yellow River Basin), and the results indicated that most regional hydrological models were capable of reproducing monthly discharges and seasonal dynamics successfully in all basins except one [40]. The uncertainty from the hydrological parameters is a complex issue. Data with different time series, different parameter optimizing methods, and different objective functions might lead to different parameter sets [39,48]. Although these uncertainties as well as others such as those associated with users were neglected in this study, the derived results still have implications for water resources management and extremes risk management under the context of climate change and regional population development.

4. Conclusions

This study revealed the probability of warming annual temperature and global warming impacts on the climatic and hydrological responses under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 during 2021–2050 in the Yellow River and Xijiang River basins. Furthermore, water scarcity was investigated by considering predicted population changes under SSP1, SSP2, SSP3, SSP4, and SSP5.

The results indicate that global warming could have different or similar climatic and hydrological impacts on the two basins. Specifically, mean annual temperature was projected to have greater increase in the Yellow River Basin than in the Xijiang River Basin under the four RCP scenarios over the next 30 years. Decreases in mean annual runoff were predicted in comparison with the baseline in the Yellow River Basin under RCP2.6, RCP4.5, and RCP8.0, while only slight change in mean annual runoff was projected for the Xijiang River Basin under all four RCPs.

In the Yellow River Basin, aggravated water shortages are expected, especially in the dry season, because runoff on annual and monthly scales is projected to decrease compared with the baseline. Combined with population changes, absolute water scarcity will threaten the basin continually, especially at around 2025 when the risk will be higher than present. Additionally, the results suggest that population change rather than climate change will play the main role in the variation of water scarcity.

In the Xijiang River Basin, a drier and longer dry period and a wetter later flood season were projected in this study. A drier dry season is likely to have negative impact on water security in the Pearl River Basin; e.g., in relation to saltwater intrusion in the Pearl River delta. Additionally, a higher risk of big floods (32,000–43,000 m^3/s) but a lower risk of medium-sized floods (32,000–43,000 m^3/s) and rare big flood (>43,000 m^3/s) could be expected in the future in the Xijiang River Basin.

The present findings have implications for water resources management and extremes risk management. For example, the Yellow River Basin could be challenged by continued but even more serious water scarcity, especially in the dry season, and it might experience more relatively smaller floods. The Xijiang River Basin might be threatened by a drier and longer dry season, more relatively smaller floods, and some big floods. Thus, the results indicate that effective water management measures must be developed, especially in relation to water scarcity in both basins, and that extremes risk management is important regarding the higher risk of some big floods in both basins, although there is the probability of a lower risk of rare big floods. Fortunately, there could be little flood loss in the Yellow River Basin because of intense water management and flood prevention.

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