

Earth's Future

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Key Points:

- Societal changes, especially economic growth, are the major contributors to water scarcity problem in northern China (NC) during 2009–2099
- Diverting water from Yangtze River can significantly reduce water scarcity in NC but cannot entirely solve the issue in next few decades
- Water diversion can increase agricultural food (115 Tcal/year) and economic benefit (51 billion RMB/year) in NC under global warming of 1.5°C

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Quantifying Water Scarcity in Northern China Within the Context of Climatic and Societal Changes and South-to-North Water Diversion

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Abstract With the increasing pressure from population growth and economic development, northern China (NC) faces a grand challenge of water scarcity, which can be further exacerbated by climatic and societal changes. The South-to-North Water Diversion (SNWD) project is designed to mitigate the water scarcity in NC. However, few studies have quantified the impact of the SNWD on water scarcity within the context of climatic and societal changes and its potential effects on economic and agricultural food in the region. We used water supply stress index (WaSSI) to quantify water scarcity within the context of environmental change in NC and developed a method to estimate the economic and agricultural impacts of the SNWD. Focuses were put on alleviating the water supply shortage and economic and agricultural benefits for the water-receiving NC. We find that societal changes, especially economic growth, are the major contributors to water scarcity in NC during 2009–2099. To completely mitigate the water scarcity of NC, at least an additional water supply of 13 billion m³/year (comparable to the annual diversion water by SNWD Central Route) will be necessary. Although SNWD alone cannot provide the full solution to NC's water shortage in next few decades, it can significantly alleviate the water supply stress in NC (particularly Beijing), considerably increasing the agricultural production (more than 115 Tcal/year) and bringing economic benefits (more than 51 billion RMB/year) through supplying industrial and domestic water use. Additionally, the transfer project could have impacts on the ecological environment in the exporting regions.

1. Introduction

Water scarcity is a worldwide problem that threatens the stability and sustainable development of human society in many regions (Cosgrove & Loucks, 2015; Hoekstra, 2014; Liu et al., 2017). This problem will be further exacerbated by future climatic and societal changes (Haddeland et al., 2014; Schewe et al., 2014), making the mitigation of water scarcity a critical task in achieving the goal of sustainable development (Gain et al., 2016). In fact, most of the 17 Sustainable Development Goals (SDGs) proposed by the United Nations (UN) are either directly or indirectly associated with solutions for the growing problem of water

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scarcity (Vanham et al., 2018). With decades of rapid social-economic development in China (Lu et al., 2019), the water scarcity of northern China has been further exacerbated by escalating water demands (Haddeland et al., 2014; Schewe et al., 2014; Wang et al., 2017). The South-to-North Water Diversion (SNWD) project, the world's largest water transfer project, was designed to alleviate severe water shortage and promote sustainable development in northern China (including Beijing City). However, it is still unclear whether the SNWD can meet northern China's water needs and how much the SNWD will benefit northern China's economy and agricultural production within the context of rapid climatic and societal changes.

Northern China, defined here by the basins of Yellow (Chinese: Huang), Huai, and Hai River (hereafter called the HHH Region) (Figures 1a and S1), is one of the most water scarce but densely populated regions in the world (Haddeland et al., 2014; Xia, 2012). It comprises one of China's largest industrial centers and intensively irrigated agriculture. With less than 6.5% of China's total water resources (Ministry of Water Resources of China [MWRC], 2011a, 2011b), the HHH Region supports approximately 30%, 29%, and 35% of China's cultivated land, population, and gross domestic product (GDP), respectively. The HHH Plain, located in the east of HHH Region, is a highly productive agricultural area and is often referred to as China's breadbasket (Kong et al., 2014; Shi, 2003). The plain is estimated to have some 1.8×10^4 km² of arable land of which 56% is irrigated (Tian et al., 2008) and produces 35–40% and 60–80% of China's wheat and corn (Liu, Long, et al., 2015), respectively. In past decades, the streamflow in almost every river of the HHH Region displayed a declining trend (Piao et al., 2010; Wang et al., 2017). Reduced water resources in the region are the result of the growing population and industry, the continuous increase in agricultural irrigation, and the higher evaporative demand connected to rising air temperatures (Haddeland et al., 2014; Tang et al., 2007; Wang et al., 2017).

To alleviate the increased water scarcity issues in northern China, the SNWD project was planned to bring water from the water-rich Yangtze River Basin to the HHH Region (Figure 1a) (CAB-SNWD, 2003). The SNWD project is thus far the world's largest interbasin water diversion project with the longest waterway, encompassing three routes. The Eastern Route (ER) moves water from the lower Yangtze River to Jiangsu and Shandong provinces along an existing network of rivers, lakes, reservoirs, and canals. The Middle Route (MR) transports water by gravity from Danjiangkou Reservoir on a tributary of the Yangtze, the Han River, via newly erected canals to Beijing and Tianjin. The ER and MR were completed in November 2013 and December 2014, respectively, and are now in operation. By the end of 2018, the ER has brought accumulated 3.1 billion m³ of water to Shandong (Figure 1b), and the MR has brought accumulated 17.8 billion m³ of water (Figure 1c) (<http://nsbd.mwr.gov.cn>). About 85 million people have benefited from the SNWD project (Figure 1d) (<http://nsbd.mwr.gov.cn>). The Western Route (WR) will link the mountainous headwaters of the Yangtze River and Yellow River (YR). In full capacity, the SNWD project will move approximately 44.8 billion m³ of water northward each year to meet the needs of almost half a billion people by 2050 (CAB-SNWD, 2003). Nonetheless, the impact of the SNWD has been one of the most hotly debated topics for a long time during the planning, design, construction, and operation phases of the project (Liu, 1998; Wang et al., 2019; Zhang et al., 2015). Previous studies of the SNWD project mainly focused on its impact on groundwater resources (Liang et al., 2019; Ye et al., 2014) and energy reductions (Zhao et al., 2017), its effect on phytoplankton (Chen et al., 2018; Zeng et al., 2015), and hydrological nitrogen and phosphorus pollution (Zhao et al., 2019), as well as the pricing system and water allocation schemes and policies (Du et al., 2019; Pohlner, 2016). However, very few studies have discussed the economic impacts of the SNWD within the context of climatic and societal change (Berkoff, 2003; Fang et al., 2015).

In this study, to quantify water scarcity within the context of environmental change in northern China, water supply stress index (WaSSI) was estimated based on the simulated runoff, groundwater recharge and irrigation as well as the downscaled population and GDP. We took the 1.5°C global warming under the Paris Agreement (Intergovernmental Panel on Climate Change [IPCC], 2018), which for the first time brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, as an example to evaluate the potential impacts on economic and agriculture for the water-receiving northern China. The objectives are as follows: (i) to describe the water supply and demand changes in a changing environment, (ii) to examine the future change of water scarcity in northern China and its major contributors, (iii) to quantitatively investigate how much the SNWD will alleviate the water supply stress in northern China, and (iv) to quantitatively assess the potential impacts of water scarcity

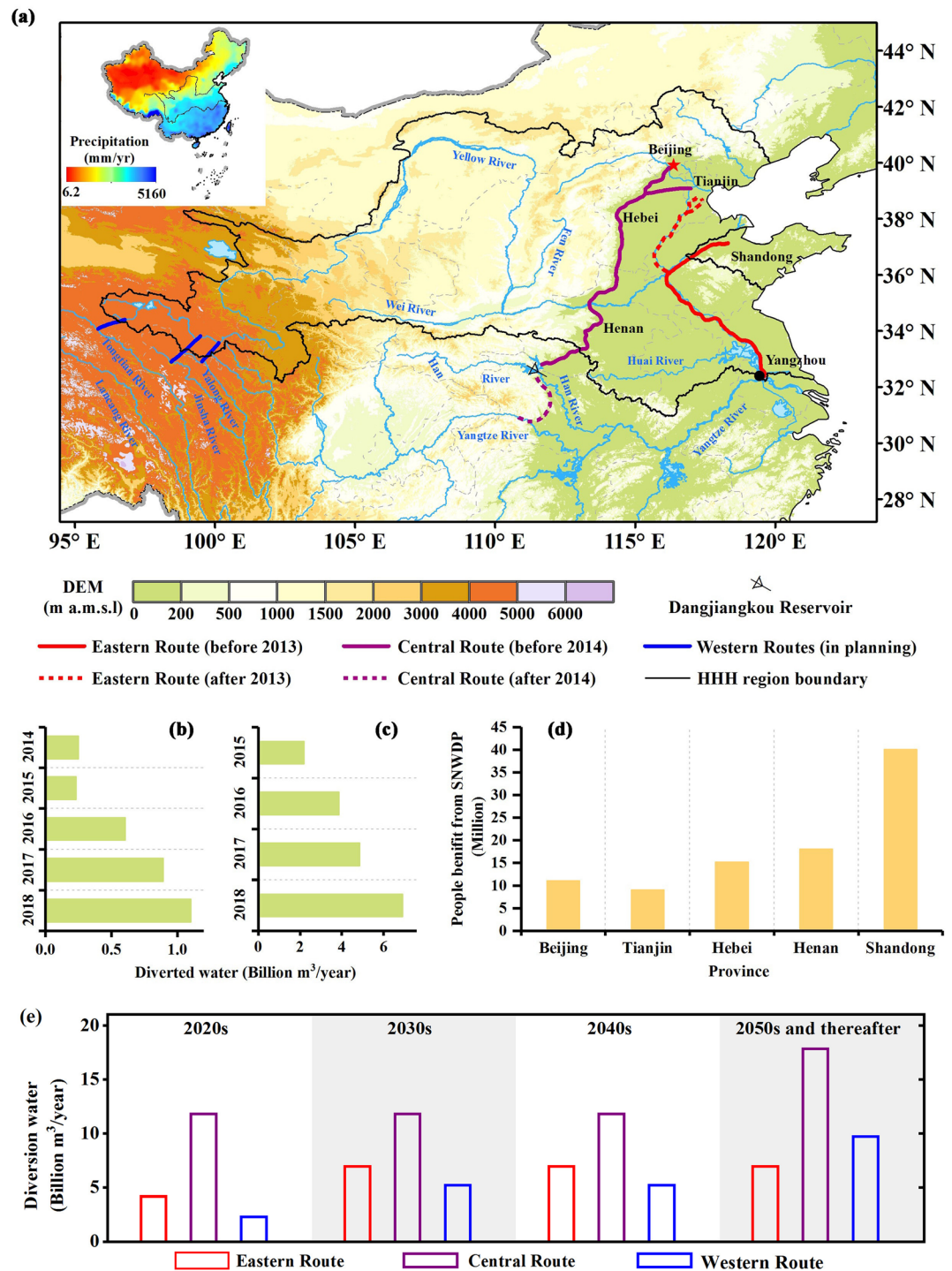


Figure 1. (a) Sketch of the SNWD project in China (CAB-SNWD, 2003). Ultimately, the project aims to channel fresh water annually from the Yangtze River in southern China to the HHH (short for Huang-Huai-Hai) Region in the arid northern China. The inset shows the annual mean precipitation in China (1980–2009). (b) Water diverted by the Eastern Route to Shandong Province since it was put into operation in 2014. (c) Water diverted by the Central Route to the HHH Region since it was put into operation in 2015. (d) People benefiting from the SNWD project in different provinces by the end of 2018, since operation began. The amount of water diverted by and people benefiting from the SNWD project was obtained from the website of South-to-North Water Diversion Project (<http://nsbd.mwr.gov.cn>). (e) Designed quantities of water diverted by the SNWD project in future decades (Wei, 2000; Zhang, 1999).

under the influence of climate change and SNWD on economic and agricultural production at 1.5°C global warming under Representative Concentration Pathway 2.6 (RCP2.6) scenario.

2. Data and Methods

2.1. Data

The data used in this study are summarized in Table 1. The simulated runoff data for the period 1971–2099 and the simulated groundwater recharge and irrigation water withdrawal (IrrWW) data for the period 1980–2099 were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; Warszawski et al., 2014). These simulated data were provided at a spatial resolution of 0.5° and were produced by three global gridded hydrological models (GGHMs, Table S1), namely, H80 (Hanasaki et al., 2008a, 2008b), LPJmL (Bondeau et al., 2007; Rost et al., 2008), and PCR-GLWBW (Wada et al., 2010, 2011). The GGHMs were forced with the bias-corrected climatic variables from the climate projections of the three global climate models (GCMs), namely, HadGEM2-ES, IPSL-CM5A-LR, and GFDL-ESM 2M under RCP2.6 and RCP8.5 scenarios (Table S2). The global irrigated and rain-fed crop area data (MIRCA2000), which consist of all major food crops, such as wheat, rice, maize, and soybean, were also obtained from ISI-MIP. The MIRCA2000 data set refers to the crop area over the period of 1998–2002 (Portmann et al., 2010). Although the cropland area may change in the future due to local adaptation to environmental change, the projection of land use change is beyond the scope of this paper. The cropland map is fixed throughout the 21st century in this study.

The 1-km gridded population and GDP data of China in 2005 were provided by the Institute of Geographic Sciences and Resources Research (IGSRR), Chinese Academy of Sciences (CAS) (Fu et al., 2014; Huang et al., 2014). The annual total population and GDP data of China during 1981–2013 were obtained from the National Bureau of Statistics of China (NBC). The future water demand should be closely related to the growth of GDP and population in the HHH Region, and the SSPs offer the possibility for describing different conditions in terms of future sectoral water demand. As reaching RCP2.6 from the SSP3 baseline was considered impossible (Fujimori et al., 2017; van Vuuren et al., 2014), all SSPs were selected in this study except for SSP3. The quantitative projections of population and GDP for the selected SSP scenarios were developed for the 2010–2099 period based on the SSP Scenario Database, available at <https://secure.iiasa.ac.at/web-apps/ene/SspDb>. The population and GDP projections were provided at country level at 5-year intervals. The projected GDP in U.S. dollars were converted to Chinese Yuan using the official exchange rate provided by the World Bank (WB). The gridded population and GDP data sets during 1981–2099 were generated by spatially and temporally downscaling country-scale population and GDP with a simple linear downscaling method (Figure 2; see Gaffin et al., 2004, and Yin et al., 2017, for details). The observed runoff data over 1971–2000 of 10 major hydrologic stations (Figure S1) at the main stream of the YR, Hai River (HaiR), and Huai River (HuaiR) were collected from the Hydrological Year Book of the MWRC. The total renewable water resources and surface renewable water resources during 1998–2017 of three basins were collected from China's Water Resources Bulletin of MWRC and were used to bias adjust the simulated groundwater recharge. The intensity of IrrWWs and irrigated area were collected from Yearbook of China Water Resources and China's National Bureau of Statistics, respectively.

2.2. Methods

Figure 2 illustrates the research flowchart of this study. A multiplicative adjustment method was used to bias adjust the simulated runoff, groundwater recharge, and irrigation (Text S1). Based on the bias-adjusted runoff, groundwater recharge and irrigation, and the downscaled population and GDP, water supply and demand were calculated. Then, we used the WaSSI (Sun et al., 2008) to analyze the impact of the SNWD project on water supply risk and used a multiobjective genetic algorithm method (Mousavi et al., 2017) to explore the optimal allocation of water among three sectors (i.e., agriculture, domestic, and industry) for the 1.5°C global warming scenario under RCP2.6 (Text S2).

2.2.1. Water Supply and Water Demand

The available water supply was estimated for each basin as the quantity of renewable water resources multiplied by the exploitation index, the sum representing the available water supply for the entire region. To calculate the renewable water resources, the nine scenario realizations of bias-adjusted runoff and groundwater recharge generated from endogenous precipitation were aggregated for the whole region and each basin. The exploitation index refers to the annual net water withdrawal, including the amount transferred to

Table 1
Data Sets Used in This Study

Data sets	Spatial resolution	Year	Source		
Simulated runoff under RCP2.6 and RCP8.5	0.5° × 0.5°	1971–2099	Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP) (Warszawski et al., 2014)		
Simulated groundwater recharge under RCP2.6 and RCP8.5	0.5° × 0.5°	1980–2099			
Simulated irrigation water withdrawal under RCP2.6 and RCP8.5	0.5° × 0.5°	1980–2099			
Simulated yield under RCP2.6 and RCP8.5	0.5° × 0.5°	1980–2099			
Rain-fed and irrigated area	0.5° × 0.5°	2000			
Population data	1-km gridded population of China	1 km × 1 km	2005	Institute of Geographic Sciences and Natural Resources Research, CAS (Fu et al., 2014)	
	Historical population of China	Country	1981–2010		National Bureau of Statistics of China (NBSC)
	Projected population	Country	2010–2100		Organization for Economic Co-operation and Development (OECD)
GDP data	1-km gridded GDP of China	1 km × 1 km	2005	Institute of Geographic Sciences and Natural Resources Research, CAS (Huang et al., 2014)	
	Historical GDP of China	Country	1981–2010		National Bureau of Statistics of China (NBSC)
	Projected GDP	Country	2010–2100		Organization for Economic Co-operation and Development (OECD)
Observed runoff	10 hydrological stations	1971–2010		Hydrological Bureau of the Ministry of Water Resources of China (HBMWRC)	
Total renewable water resources	Basin	1998–2017		China's Water Resources Bulletin	
Surface renewable water resources					
Intensity of irrigation water withdrawals	Province	1997–2013, 2015		Yearbook of China Water Resources	
Irrigated area	Province	1997–2013, 2015		National Bureau of Statistics of China (NBSC)	
Livestock water withdrawals	0.5° × 0.5°	1981–2010		Institute of Geographic Sciences and Natural Resources Research, CAS (Huang et al., 2018)	
Thermoelectric water withdrawals					
Designed quantities of water diverted by the SNWD project	—	—		Zhang, 1999; Wei, 2000	
Domestic and industrial water prices	City	2010		http://price.h2o-china.com/	

other watersheds, in relation to the annual renewable water resources (Food and Agriculture Organization [FAO], 2003; GAQUIQ & SAC, 2009). The exploitation index values of the HaiR, YR, and HuaiR are 126%, 73%, and 62%, respectively (MWRC, 2011a). The renewable water resources and total available water supply of each basin and whole region were calculated for each GCM-GGHM combination for each year of the time period 1981–2099, and 30-year moving averages were computed. There are nine model pairs (3 GCMs × 3 GGHMs) under RCP2.6. Meanwhile, there are six GCM-GGHM pairs under RCP8.5 because the groundwater recharge is missing in PCR-GLBWB simulations.

We estimated the water demand for three main water-consuming sectors: agriculture, domestic, and industry. Agricultural water use includes the demands for irrigation and livestock. Because livestock water withdrawals are very small compared to those for irrigation and the projected livestock data are currently unavailable, we assumed that livestock water withdrawals in the future are equal to the average annual value of water withdrawal over the historical period 1981–2009. The reconstructed livestock water withdrawal data provided by Huang et al. (2018) was aggregated for the whole region and each basin. To calculate the irrigation water use, the bias-adjusted IrrWW was aggregated for the entire region and each basin. Given that IrrWW is missing in PCR-GLBWB simulations under RCP8.5, the multimodel ensemble median of IrrWW was calculated from nine scenario realizations under RCP2.6 and six scenario realizations under RCP8.5. Industrial water use includes two main components: water withdrawal for the manufacturing sector and withdrawal for the cooling of thermoelectric plants in the electricity sector. Currently, thermoelectric water withdrawal data are only available for 1981–2010, and the related projected data are unavailable for the region. Thus, no change in the water withdrawal for the cooling of thermoelectric plants was assumed. The reconstructed thermoelectric water withdrawal data provided by Huang et al. (2018) were aggregated for the entire region and each basin. The method to estimate net manufacturing water withdrawal and net domestic water withdrawal was described in Text S3. The annual water demand was calculated as the sum of the net water withdrawals for agriculture, domestic, and industry. The water demand was assessed for each year of the time period 1981–2099, and 30-year moving averages were computed.

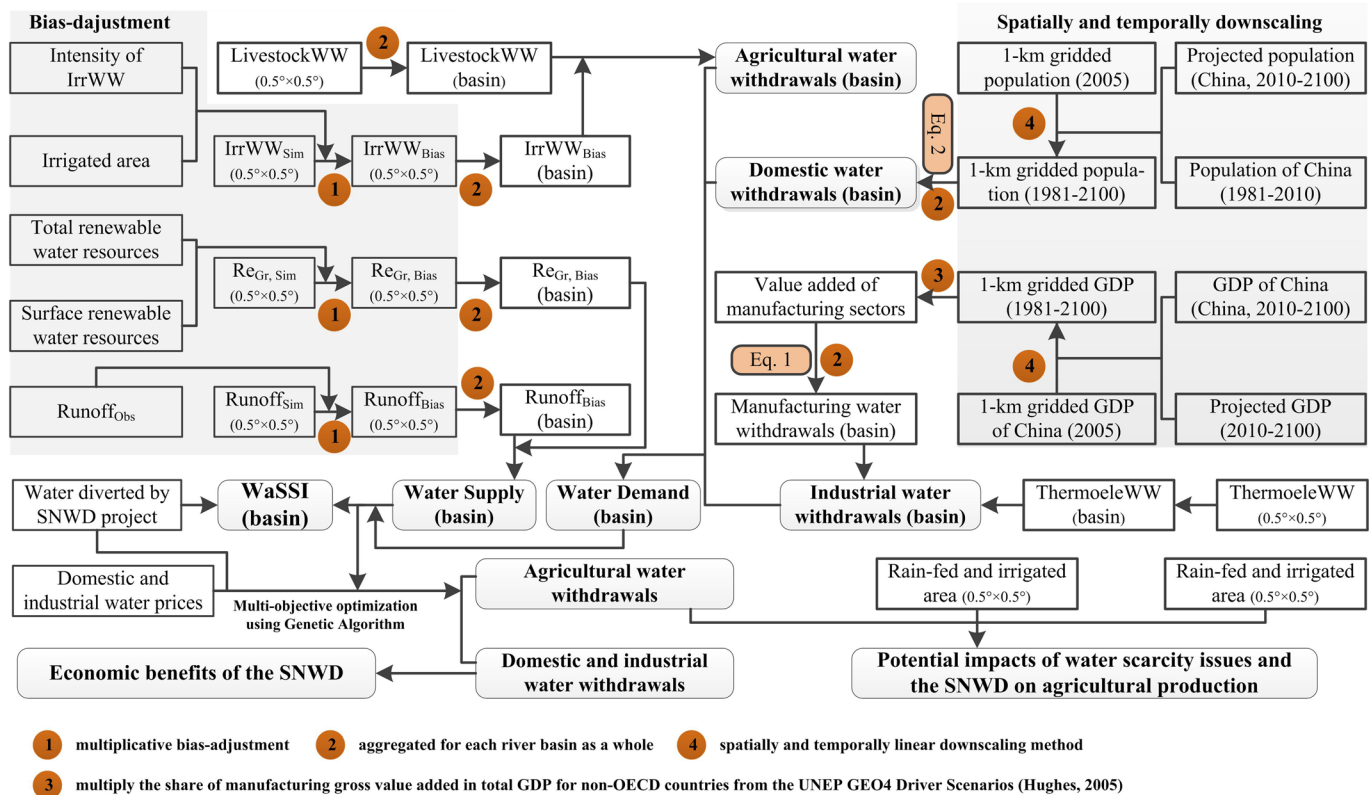


Figure 2. Research flowchart of this study. WaSSI is defined as the ratio of water demand to water supply for a specific basin.

2.2.2. Water supply stress index

To assess whether water supplies are sufficient for concurrently meeting all withdrawal requirements within a watershed, a modified version of the WaSSI was used (Eldardiry et al., 2016; Sun et al., 2008). The metric was formulated as the ratio of annual water withdrawals to the annual total available water supply for a specific watershed (Equation 1). If the WaSSI is greater than 1.0, the water supply cannot sustain socioeconomic development. The WaSSI in the baseline period and its changes during 2009–2099 relative to the values in the baseline period were calculated for each SSP-GCM-GGHM combination. There were 36 scenario combinations under RCP2.6 and 24 combinations under RCP8.5. The WaSSI of each major water use sector was also calculated (Equation 1) to investigate the contributions of different sectors. The supplemental irrigation from SNWD was calculated using the multiobjective genetic algorithm in the following section. To assess the impact of the SNWD on water scarcity issues in the HHH Region, the median WaSSI of all SSP-GCM-GGHM combinations with and without the impact of the SNWD project in different decades of the 21st century was estimated. To eliminate the confusion caused by the GCM-GGHM-SSP combination, the WaSSI without and with the impact of the SNWD under RCP2.6-SSP1 (the sustainable world) and RCP8.5-SSP5 (the no decarbonization world) scenarios was calculated.

$$WaSSI_i = \text{water withdrawal}_i / \text{water supply}, \quad (1)$$

where, i denotes the total water demand or a specific water demand sector, that is, domestic, industrial, and agricultural sectors.

2.2.3. Economic Benefits of the SNWD at 1.5°C Global Warming

To examine the economic impacts of the SNWD project, a multiobjective genetic algorithm using evolutionary algorithms was used to explore the optimal allocation of water among three water sectors (Mousavi et al., 2017; Nouri, 2014). Because the livestock and thermoelectric water withdrawals were assumed to be static, irrigation, domestic and manufacturing uses were considered during the optimal allocation process. The objectives considered in the model include maximizing the total economic benefits and

minimizing the total water deficit. The two objective functions (OFs) and three constraint functions (CFs) in a given watershed are as follows:

$$O.F.1 = \max \sum_{j=1}^m \sum_{i=1}^n (b_{ij} - c_{ij}) \times x_{ij} \times \alpha_j \times \beta_i, \quad (2)$$

$$O.F.2 = \min \sum_{j=1}^m \left[D_j - \sum_{i=1}^n x_{ij} \right], \quad (3)$$

$$C.F.1 \quad \sum_{j=1}^m x_{ij} \leq W_i, \quad (4)$$

$$C.F.2 \quad D_{j\min} \leq \sum_{i=1}^n x_{ij} \leq D_{j\max}, \quad (5)$$

$$C.F.3 \quad x_{ij} \geq 0, \quad (6)$$

wherein m is the number of water sectors; n is the total water resources; i is the resource; j is the sector; b and c are the output and price per cubic meter, respectively; x_{ij} is the amount of water in the j th sector provided by the i th resource; D_j is the amount of water needed by sector j ; W_i is the amount of water provided by resource i ; α is the index representing the priority among all water sectors; and β is the index representing the priority among all water resources. $\max_{1 \leq i \leq n} \{\beta_i\}=1$, $\min_{1 \leq i \leq n} \{\beta_i\}=0$, and $\sum_{1 \leq i \leq n} \{\beta_i\}=1$.

The inequality in Equation 4 controls the volumetric reliability of the water supply to meet the demands. According to Equation 5, the water supplied to every demand sector must be less than or equal to the maximum demand. The output and price per cubic meter for each basin are summarized in Table S4. Considering China's water resources management and policy, among the three main water-consumptive sectors considered, we assumed domestic use having the highest priority and that irrigation the least. The values of the priority index α estimated for domestic use, manufacturing, and irrigation are sorted in descending order and are calculated following Text S4.

According to the constructed models, the future water allocation among the three water sectors with and without the impacts of the SNWD was estimated at 1.5°C global warming for each SSP-GCM-GGHM combination. Table S5 shows the amount of water diverted by the SNWD to each basin.

The economic benefits of industrial and domestic water transferred by the SNWD were estimated with the benefit-sharing coefficient method (Lin, 2003; Liu & Lv, 2012). To make the calculation simple, we assume that the value of the domestic water supply approximately equals the value of the industrial water supply (Liu & Lv, 2012). The benefit is calculated as the product of the amount of industrial and domestic water transferred by the SNWD divided by the water intensity for manufacturing (Table S6) times the sharing coefficient of the water supply benefit for manufacturing which was assumed to equal 0.05 in each basin (Tu, 1998).

2.2.4. Potential Impacts of Water Scarcity and the SNWD on Agricultural Production at 1.5°C Global Warming

If the water resources allocated to the irrigation sector mismatch the IrrWWs in a given year for a specific watershed, irrigation will be constrained by reducing the irrigated fraction of the cropland (Elliott et al., 2014). The agricultural production of the watershed, calculated as the caloric content of the major crop yields, was considered the sum of production over the expanded rain-fed fraction of the cropland and the shrunken irrigated fraction. If the water availability is sufficient in a given year in a specific basin, we assume that no rain-fed areas are converted for irrigation. The simulated crop yield data were taken from four global gridded crop models (GGCropMs; EPIC, GEPIC, LPJ-GUESS, and PEGASUS) (Table S7). For this analysis, we consider wheat, rice, maize, and soybean, four of the most important crops in the HHH Region which account for approximately 80% of the total cropland area. There are 20 model combinations (3 GCMs \times 4 GGCropMs) for maize, wheat, and soybean, and 15 combinations for rice because rice irrigation is missing from the PEGASUS simulations. The total calories per 100 g of wheat, rice, maize, and soybean are 333, 357, 356, and 335, respectively (<http://www.fao.org/3/x5557e/x5557e00.htm>). To clarify how the SNWD project would affect agricultural production, we calculated the irrigation water supply with and without the

SNWD project using the multiobjective genetic algorithm described in section 2.2.3 above. The enhanced production by the SNWD project is the difference in agricultural production with and without the SNWD project.

3. Results

3.1. Projected Changes of Renewable Freshwater Resources During the 21st Century

Changes in runoff and groundwater recharge in the HHH Region under RCP2.6 and RCP8.5 by the end of the 21st century are shown in Figures 3a and 3b. The multimodel median values display increasing trends in both runoff and groundwater recharge during the 21st century. The increases in the annual average runoff and groundwater recharge are statistically significant trends at the 0.05 confidence level by using the linear methods, with rates of 2.54 (2.26) and 0.97 (1.52) billion m^3/year in each decade under RCP2.6 (RCP8.5), respectively. Annual runoff and groundwater recharge are projected to be 154.2 (151.1) (Figure 3a) and 65.6 (66.7) billion m^3/year (Figure 3b) at the end of the 21st century under RCP2.6 (RCP8.5), increases of approximately 14.4% (13.6) and 23.4% (21.8) compared to the values in the baseline period (1980–2009). The total renewable water resources are projected to significantly increase during the 21st century (Figure 3c), and the average rates of increase are 3.5 and 5.1 billion m^3/year per decade under RCP2.6 and RCP8.5, respectively. The annual average total renewable water resources are projected to be 218.6 and 238.1 billion m^3/year at the end of the 21st century under RCP2.6 and RCP8.5 (Figure 3c), increase of 18.7% and 31.4% compared to the value during the period of 1980–2009. The water supply (total renewable water resources multiplied by the exploitation index, which is the ratio of annual net water withdrawals to annual renewable water resources) is shown in Figure 4a. The water supply will increase during the 21st century, and the increase is statistically significant trends at the 0.05 confidence level by using the linear methods, with a rate of more than 2.4 billion m^3/year per decade. The water supply is projected to be 176.5 and 187 billion m^3/year at the end of the 21st century under RCP2.6 and RCP8.5, an increase of approximately 27.9% and 34.9% from that during the baseline period.

3.2. Projected Changes of Sectoral and Total Water Demand During the 21st Century

The total water demand will increase before 2070s and then decrease under both RCP scenarios (Figures 4a, 4b, S11, and S12). The total water demand is projected to increase to approximately 230 billion m^3/year at 2070 and then slightly decrease thereafter, reaching approximately 220 (around 190.9–243.5) billion m^3/year at the end of the 21st century. Assuming that the demands associated with livestock (7.9 billion m^3/year) and the cooling of thermoelectric plants (10.27 billion m^3/year) remain static, the primary drivers of this water demand increase include higher IrrWWs in the early 21st century and manufacturing water withdrawals after the 2020s (Figures S11 and S12). Irrigation is the dominant water use sector accounting for more than 55% of total water use (Figures 4a, 4b, S13, and S14), while manufacturing contributes most to the total increase in water demand after 2010s under four different SSPs considered (Figures S13 and S14). Irrigation-specific water use is projected to increase during 2009–2099, and the increases are statistically significant trends at the 0.05 confidence level by using the linear methods, with rates of 3.0 and 2.4 billion m^3/year in each decade under RCP2.6 and RCP8.5, respectively (Figures 3d and Table S8). At the end of the 21st century, irrigation is projected to reach 124.2 and 120.1 billion m^3/year (Figure 3d), an increase of approximately 30.6% and 21% from the baseline, under RCP2.6 and RCP8.5, respectively. The manufacturing water withdrawals are projected to rapidly increase before approximately 2080 with increasing GDP (Figure S10) and then slightly decrease due to the decrease in the manufacturing water use intensities. This water use is projected to peak at approximately 65.0 (57.9–68.7) billion m^3/year around 2074 (Figures 4a, 4b, S11, and S12). Domestic water withdrawals will increase in the next few decades as both the population and domestic water use intensity increase; then, these withdrawals will decrease due to the predicted population decline, with a peak at approximately 28.0 (27.7–29.7) billion m^3/year around 2071 (Figures 4a, 4b, S11, and S12).

3.3. Water Scarcity Without and With the Impact of the SNWD During the 21st Century

In the baseline period, the water supply scarcity index (WaSSI) is equal to 0.99, meaning that the water supply, which is estimated based on the exploitation index during the 2000s, slightly outweighs the demand for freshwater resources (Figure 4c). Changes in WaSSI relative to the baseline period are shown in Figure S15. The changes in societal changes (increasing population and rapid industrialization) will aggravate the water

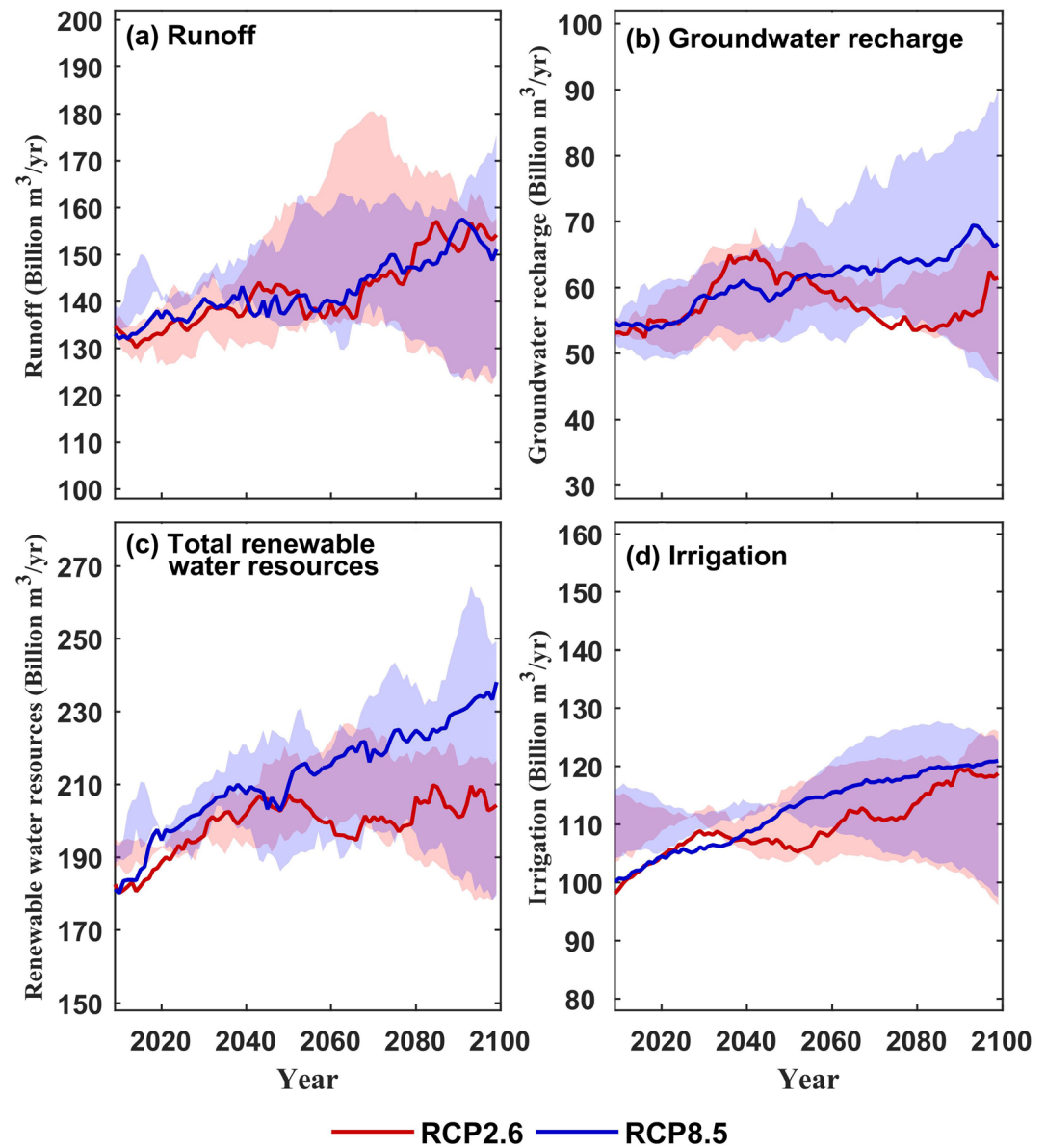


Figure 3. (a) Runoff, (b) groundwater recharge, (c) total renewable water resources, and (d) irrigation in the HHH region for 2010–2100 under RCP2.6 and RCP8.5. The shaded band denotes the interquartile range, and the colored solid line shows the median of the all GCM-GGHM combinations.

scarcity issues in the HHH Region during the 21st century, while climatic change will mitigate the water scarcity issues. Given that the water supply under RCP8.5 is projected to be higher than that under RCP2.6, RCP 2.6 has a greater influence on mitigation water scarcity than RCP 8.5. The WaSSI changes attributed to both climatic and societal changes are projected to rapidly increase, with a peak of 0.53 (0.36) in 2062 (2066) under RCP2.6 (RCP8.5) followed by a slow decrease. However, most of the SSP-GCM-GGHM combinations under RCP2.6 show that climatic change could not mitigate the water scarcity issues, for the increase in IrrWWs due to climate change are projected to be larger than the increase in available renewable freshwater resources.

Since the SNWD project was put into operation in 2013 for ER and 2014 for MR, millions of people have benefited from it. According to the overall plan, water diversion will increase as more conveyance systems and water plants are put into operation in the next few decades. Annual water diversion is expected to

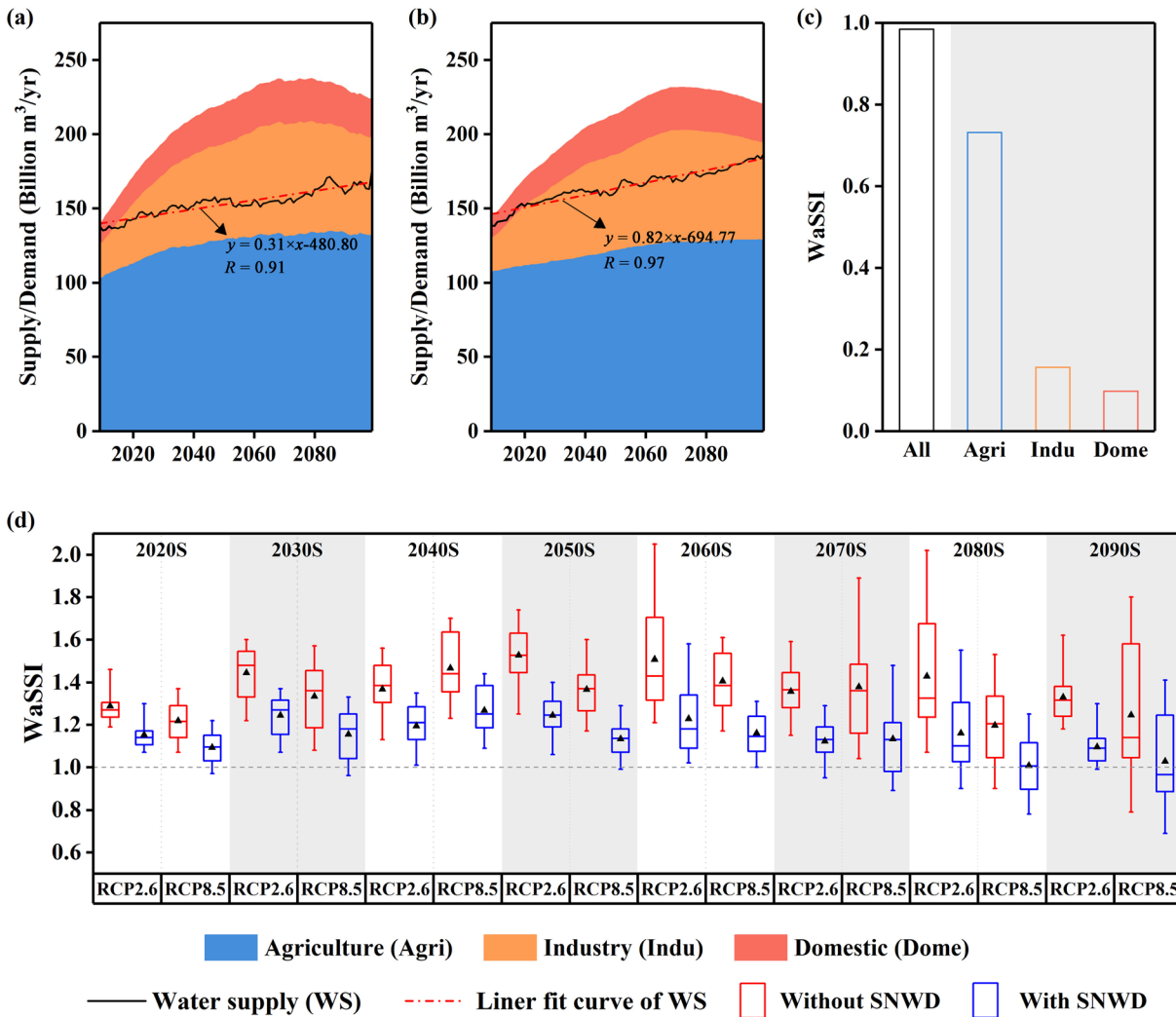


Figure 4. (a) Ensemble median annual water supply and agricultural water demand across the scenario realizations of nine GCM-GGHM combinations, and the median annual industrial and domestic water demand across four SSPs (including SSP1, SSP2, SSP4, and SSP5; while SSP3 is not applicable here) in the HHH region for 2009–2099 under RCP2.6. (b) Ensemble median annual water supply and agricultural water demand across the scenario realizations of six GCM-GGHM combinations, and the median annual industrial and domestic water demand across four SSPs (including SSP1, SSP2, SSP4, and SSP5; while SSP3 is not applicable here) in the HHH Region for 2009–2099 under RCP8.5. (c) Water SupplyStress Index (WaSSI) for all water demands and each major water use sector in the baseline period (1980–2009). (d) WaSSI without (red box) and with the impact of the SNWD (blue box) in the different decades of the 21st century in the HHH Region under RCP2.6 and RCP8.5. The top and bottom whiskers are the maximum and minimum of the all GCM-GGHM-SSP combinations. The top and bottom boxes are the first and third quartiles, and the horizontal solid line inside the box is the median. The black triangle represents the mean of the combinations. There are 36 GCM-GGHM-SSP combinations for RCP2.6 scenario, and there are 24 GCM-GGHM-SSP combinations for RCP8.5 scenario.

reach 18.28 billion m³/year by the 2020s. As the project progresses, the amount of annual water to be diverted to the HHH Region will increase to 23.96 billion m³/year in the 2030s and 34.51 billion m³/year after the 2050s (Figure 1e) (Wei, 2000; Zhang, 1999). With the implementation of the SNWD project, there is an opportunity to mitigate water scarcity issues faced by this region (Figures 4d and S17). Given that compared to the RCP 2.6 emissions scenario, the available renewable freshwater resources under the RCP8.5 emissions scenario are slightly higher, and the IrrWWs are slightly lower; the WaSSI under RCP2.6 is higher than under RCP8.5. In the HHH Region, the median WaSSI of all GCM-GGHM-SSP combinations without the SNWD in each decade of the 21st century is projected to be greater than 1.27 under RCP2.6, while the median without the SNWD is projected to be greater than 1.15 under RCP8.5. The uncertainty of the GCM-GGHM-SSP is larger than the GCM-GGHM. To completely satisfy the water demand, at least 15% of the water supply (approximately 24.3 billion m³/year) has to be provided. The

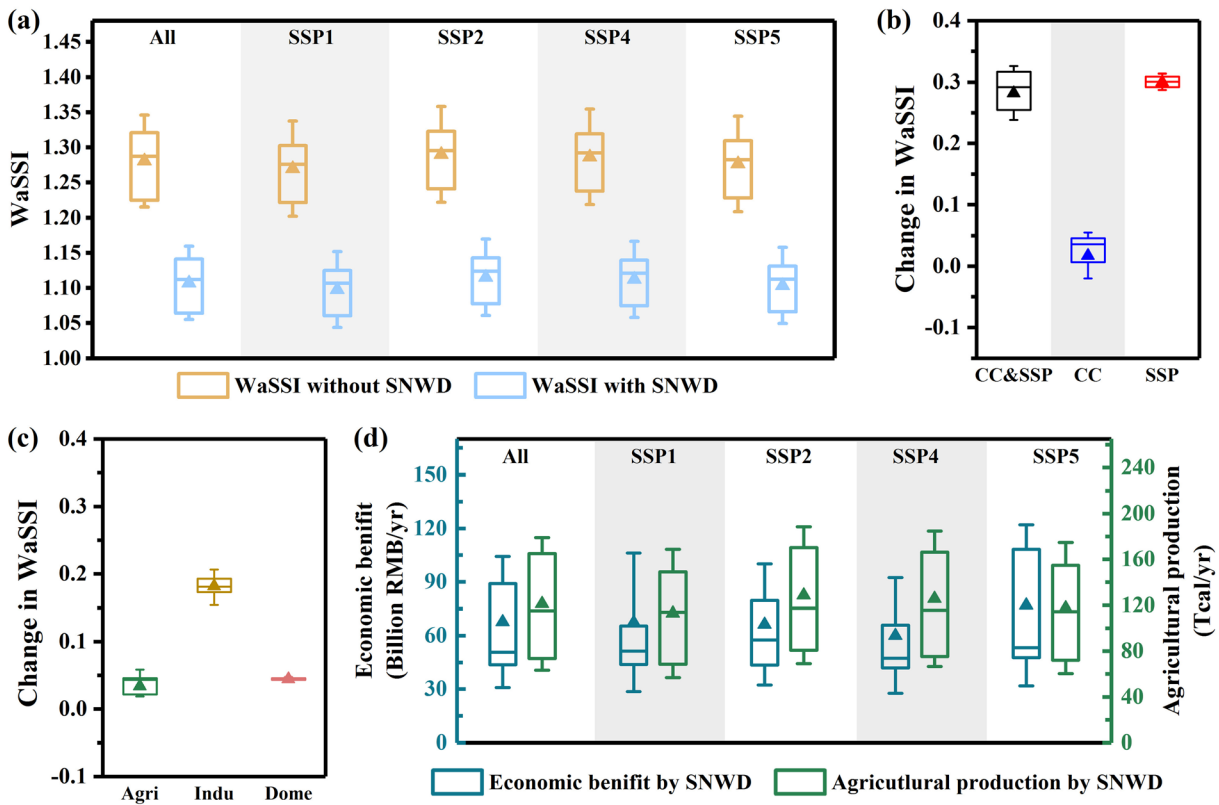


Figure 5. (a) WaSSI without and with the impact of the SNWD project under different SSPs at 1.5°C global warming. There are 38 GCM-GGHM combinations for “all” scenarios, and there are nine GCM-GGHM combinations for each SSP scenario. (b) Proportion of change in the WaSSI caused by climate change and SSPs between the 1.5°C global warming and the baseline period of 1980–2009. (c) Proportion of change in the WaSSI caused by major water use sectors between the 1.5°C global warming and the baseline period. (d) Economic benefit (industrial and domestic water use) and agricultural production (agricultural water use) associated with the SNWD in the HHH region in the 1.5°C global warming. The top and bottom whiskers are the ± 1 standard deviation of the pairs. The economic benefit is calculated based on 36 SSP-GCM-GGHM combinations for “all” and nine subsets of nine for each individual SSP. Agricultural production is calculated based on 144 SSP-GCM-GGHM-GGCM combinations for “all” and respective subsets of 36 for each SSP. The top and bottom whiskers are the ± 1 standard deviation of the pairs. The top and bottom boxes are the first and third quartiles, and the horizontal solid line inside the box is the median. The mean is indicated by solid triangles.

WaSSI with the SNWD in NC will decrease under RCP2.6, and yet the median WaSSI in each decade of the 21st century is projected to be still greater than 1, meaning that diverting water from Yangtze River will significantly reduce water scarcity but will not entirely solve the issue. Under RCP8.5, the median WaSSI with the SNWD is projected to be greater than 1 before 2080s, while the WaSSI with the SNWD is projected to be less than 1 in 2080s and 2090s, meaning that diverting water will entirely solve the issue in the two decades. With the impact of the SNWD, WaSSI is projected to be reduced by at least 0.12 (0.12–0.28) suggesting that more than 12.4–41.9 billion m^3 /year additional water supply is projected to be needed to completely mitigate water scarcity issues in future decades (Table S9).

3.4. Impacts of Water Scarcity on Economic and Agricultural With the SNWD at 1.5°C Global Warming

At the 1.5°C global warming, the median WaSSI without the SNWD is projected to be approximately 1.28 (Figure 5a), and the median change relative to the baseline period is 0.29 (Figure 5b). Population growth and economic development are the major contributions, and the change in WaSSI attributed to these contributions is 0.30, which is about eight times the change attributed to climate change (approximately 0.036). In addition, the contributions to the overall WaSSI changes vary substantially across different water use sectors (Figure 5c). The median WaSSI change attributed to industry is the highest (0.18), suggesting that for the three main water use sectors considered, the abrupt increase in industry is the main factor that contributes to the aggravation of water scarcity issues. The SNWD will reduce the WaSSI, and the median WaSSI with

the SNWD is projected to be 1.1. The WaSSI with and without the impact of the SNWD varies slightly among different SSPs, suggesting that the uncertainty in the WaSSI is mainly caused by GGHMs and the climate projections of GCMs (Figure 5a).

According to the optimal allocation of water among three water sectors, calculated using the multiobjective genetic algorithm method, the economic benefits of industrial and domestic water transferred by the SNWD project in the HHH Region were evaluated (Figure 5d). The median economic benefit calculated from all SSP-GGHM-GCM combinations is projected to be approximately 50.7 billion RMB/year in the 1.5°C global warming. The interquartile range reaches 40.6 billion RMB/year, meaning that the economic benefit varies greatly between SSP-GGHM-GCM results. The benefit variations among different SSPs are small, and the median values are projected to be approximately 51.4, 57.5, 47.3, and 53.3 billion RMB/year for SSP1, SSP2, SSP4, and SSP5, respectively.

Climate change, irrigation water scarcity, and the SNWD will have significant effects on food production in the region. Considering the CO₂ fertilization effect, agricultural production in the HHH Region will be enhanced by climate change and is projected to increase by close to 1.9% compared with production during the historical period (Figure S17). However, irrigation water scarcity can necessitate the reversion of cropland from irrigated to rain-fed management, leading to a decrease in agricultural production. In the HHH Region, considering the CO₂ fertilization effect, irrigation water scarcity could lead to a reduction ranging from 4.3% to 4.8% compared to present-day total production for all SSPs in the 1.5°C global warming (Figure S11). Although the SNWD cannot completely solve the water scarcity problem caused by increased irrigation demand and socioeconomic changes, it will significantly increase agricultural production by approximately 115.3 Tcal/year (Figure 5d). The variations of agricultural production increase among different SSPs are small, and the median values are approximately 113.8, 117.4, 115.6, and 114.3 Tcal/ year for SSP1, SSP2, SSP4, and SSP5, respectively.

4. Discussions and Conclusions

The prediction of the water supply stress provides important information for the decision-making process regarding water resource policies and managements. Uncertainty in GCM-GGHM simulations, which are used to quantify the effect of climate change on renewable water resources and IrrWW, is the main source of uncertainty related to water supply stress prediction. GGHMs are generally not calibrated versus observations and often display considerable bias (Hattermann et al., 2017). Bias adjustment techniques are widely applied to adjust the mean and variance of these ensemble models (Chen et al., 2011) in the post-processing stage, largely reducing the spread among GGHMs (Figures S4–S6). Projections of future runoff, groundwater recharge, and irrigation contain uncertainty due to three key sources: emissions uncertainty, GCM modeling uncertainty, and GGHM modeling uncertainty (Hawkins & Sutton, 2009). The uncertainty (standard deviation) varies with variable and emissions scenario (Figure S18a). In the HHH Region, the standard deviation of each variable in 2090s is more than 1.5 times, compared with the standard deviation in 2030s. For runoff and groundwater recharge, the total uncertainty under RCP8.5 is larger than the uncertainty under RCP2.6. Yet the total uncertainty of irrigation under RCP2.6 is larger than the uncertainty under RCP8.5. The uncertainty of groundwater recharge caused by GGHMs is about five times compared with the uncertainty caused by GCMs in 2090s (Figure S18b). Nevertheless, the uncertainty of runoff caused by GCMs is more 2.3 times than the uncertainty caused by GGHMs in 2090s. For irrigation, the standard deviation caused by GGHMs is larger than that caused by GCM under RCP2.6, whereas the standard deviation caused by GCM is larger than that caused by GGHMs under RCP8.5.

It is difficult to quantify domestic and industrial water withdrawals because future withdrawals are influenced by many social, economic, and political factors. The differences in approaches used to estimate water withdrawals can result in significantly different projections, even with the same set of scenario assumptions (Wada et al., 2016). In China, coal-fired power generation is responsible for approximately 10% of the total freshwater withdrawal (Zhang & Anadon, 2013). Although the projection of water withdrawals for cooling during thermoelectric generation is subject to large uncertainties, the water withdrawals are projected to increase in the HHH Region under different scenarios (Liao et al., 2016; Zhang et al., 2016). In this study, the assumption that thermoelectric cooling water withdrawals are static could lead to an underestimated water supply stress. Moreover, in October 2015, China replaced the universal one-child

policy by a two-child policy. The new policy will affect future demographics and probably increase the GDP, but the impacts have not been adequately understood in detail (Huang et al., 2019; Zeng & Hesketh, 2016). Therefore, the “Family Planning Policy” change makes it harder to accurately estimate domestic and industrial water withdrawals. Moreover, with GDP related to both population growth (duly noted) and increased standard of living in the future, consumption of animal protein in regional diets will increase. Therefore, future livestock water withdrawal will increase (Arnell, 1999; Wada & Bierkens, 2014). In this study, the assumption that livestock water withdrawals are static could lead to an underestimated water scarcity.

Yangtze River is the water-exporting areas of the SNWD project. The Yangtze annual runoff is about 951.3 billion m³, and the exploitation index in 2000s is about 18% (Lei et al., 2010). Once the SNWD project is completed, the annual diversion water would be 44.8 billion m³, accounting for about 5% of the Yangtze annual runoff. In the coming decades, the future streamflow projections will increase with highly increasing trends in long-time horizons and high scenarios (Sun et al., 2019; Yu et al., 2018), and to meet the water demand in the basin and provide necessary water resources for water resources allocation in national wide, the exploitation index will reach 28% (Xiao et al., 2013). Thus, there would be no considerable negative impacts on the whole Yangtze River system. However, the exploitation index of Hanjiang River, which is the source of the central route of the SNWD, will reach more than 54% (Xiao et al., 2013). Moreover, the probability of concurrent drought events in Hanjiang River Basin is highly likely to increase (Liu, Luo, et al., 2015). To meet the water demands in years of concurrent drought in the Hanjiang River, a canal should be built to divert water from the Yangtze River to the middle Hanjiang River (Liu, Luo, et al., 2015).

Whether the SNWD project is economically beneficial and how much benefit brought by the project depend largely on model assumptions and the specific study area (e.g., a water-exporting area, a water-receiving area, or the national scale) (Wilson et al., 2017). The SNWD project could bring billions of eco-economic benefit per year to northern China (Lu et al., 2006; Lin et al., 2012; Wang et al., 2018; Yang et al., 2005). For example, Lin et al. (2012) assessed the environmental benefit of the SNWTP and reported the total eco-environmental benefits 38 billion RMB/year, while the eco-economic benefit of delivered water in Hebei water-recipient area was 5.526 billion RMB/year (Wang et al., 2018). For industrial sectors, the direct economic benefit generated by the SNWD to Beijing will be 38.72 billion RMB/year (Gao & Yu, 2018). Although there is a certain gap between our estimation and previous studies, there are in the same order of magnitude. The water transfer project could provide economic benefits in water-receiving areas but may not provide the benefits in water-exporting areas, which must be studied in the future. Additionally, the transfer project could have impacts on the ecological environment; for example, secondary salinization seems inevitable in some water-receiving areas (Zhang, 2013), and the transfer project could improve water cycle health (Zhang et al., 2017), alleviate groundwater overexploitation (Liang et al., 2019; Zhou et al., 2012), and facilitate ecological restoration (Lin et al., 2012; Liu, 1998) in northern China. However, the ecological dimension is beyond the scope of this study although it is also important for ensuring sustainable developments.

Here, we identify the major factors that contribute to the change of the water supply stress in a changing environment and quantitatively estimate the impact of the SNWD on the water supply stress and benefits in the HHH Region for the 1.5°C global warming. The results show that societal changes, especially economic growth, are the major contributors to the water scarcity aggravation during the 21st century in northern China. The SNWD can greatly alleviate these difficulties but might be insufficient in some cases. Nonetheless, the SNWD could increase economic benefits (more than 50.7 billion RMB/year) and agricultural production (more than 113.8 Tcal/year). Notably, the project could alleviate groundwater over withdrawals in northern China and will be propitious to make the food develop in a sustainable way in HHH Region. In 2009, the “Three Red Lines” of water resources, including the upper limit of water resources allocation, the baseline of utilization efficiency of water resources, and the upper limit of sewage discharge, was proposed in the No. 1 Document by Chinese Government. The effectiveness and impact of the SNWD within the context of the strict water management policies should be paid more attention. Meanwhile, the SNWD could exacerbate water stress issues in water-exporting areas (Zhao et al., 2015).

Conflict of Interest

The authors declare no conflict of interests.

Data Availability Statement

The SSP population data and model outputs of GCMs and GGHMs were provided by the Inter-Sectoral Impact Model Intercomparison Project (<https://www.isimip.org>, ISIMIP). The SSP GDP data were provided by Organization for Economic Co-operation and Development (<http://www.oecd.org/>; OECD). The official exchange rate data of China were provided by the World Bank (<http://data.worldbank.org/>; World Bank). The historical population and GDP data of China were obtained from the National Bureau of Statistics of China (<http://www.stats.gov.cn/tjsj/>; NBSC). The 1 km grid population dataset and 1 km grid GDP dataset of China were provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn>; RESDC). The global gridded monthly livestock water withdrawals and thermoelectric water withdrawals dataset for 1971–2010 is freely available for download from <https://zenodo.org/record/1209296#.XXhk06Iik8Q>.

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