Responses to the Reviewer

We truly thank the editor and the anonymous reviewers for their constructive comments and suggestions for improving our work. We have addressed all the comments in our revised manuscript. The point-by-point responses to the comments are provided below.

Specific comments:

- **Question 1:** Line 80: Change “outupts” to “outputs”.
- **Answer:** Corrected.

- **Question 2:** Line 92: I suggest change “The mean temperature ranges....” to “The mean annual temperature in 1981-2010 ranges spatially from -5 °C to 15°C...”.
- **Answer:** Thanks for the suggestion. We have revised the sentence.

- **Question 3:** Line 94-95: Similar revision suggestion on the mean annual precipitation description.
- **Answer:** Corrected.

- **Question 4:** Line 107: Remove “was”.
- **Answer:** Removed.

- **Question 5:** Line 108-110: As shown in Figure S2 (a), the population in the YR basin has a significant decreasing trend in all SSPs. Maybe add some explanation here about this decreasing population projection.
- **Answer:** China’s population has been greatly affected by its fertility policy. Under the current fertility policy, many studies have suggested that China’s population will continue to grow, and

then begin to decrease as the aging of population accelerates (Peng, 2010; Chen and Liu, 2009). We have added a brief discussion about the population projection in the revision.

References：

Peng, X. China's demographic history and future challenges. Science, 333(6042), 581-587, 2011

Chen, W., and Liu, J. J. Future population trends in China: 2005-2050. Centre of Policy Studies (COPS), Monash University, Wellington Road, Australia, 2009

- **Question 6:** Line 231: Change "preson" to "person".
- **Answer:** Corrected.

- **Question 7:** Line 271-289: Section 4.2 describes water demand projections. Maybe add some explanation about the reasoning behind the trends of water demands. For example, why will industrial water demand increase before 2050 and then decrease slightly?
- **Answer:** Thanks for the suggestion. We have added the reasons along with a brief discussion on the changes in the revision.

- **Question 8:** Line 308: Change "large" to "larger".
- **Answer:** Corrected.

- **Question 9:** Line 312-313: Please revise this sentence.
- **Answer:** We have rewritten the sentence in the revision.

- **Question 10:** Table 2: In row "Official exchange rate data", column 2, change "country" to "Country".
- **Answer:** Corrected

- **Question 11:** Figure 4: In column 1, it should be “YR”, not “YL” right?

- **Answer:** It should be “YR”. Corrected in the revision.

Water Scarcity under Various Socio-economic Pathways and its Potential Effects on Food Production in the Yellow River Basin

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Abstract: Increasing population and socio-economic development have put great pressure on water resources of the Yellow River (YR) basin. The anticipated climate and socio-economic changes may further increase water stress. Many studies have investigated the changes in renewable water resources under various climate change scenarios, but few have considered the joint pressure from both climate change and socio-economic development. In this study, we assess water scarcity under various socio-economic pathways with emphasis on the impact of water scarcity on food production. The water demands in the 21st century are estimated based on the newly developed Shared Socio-economic Pathways (SSPs) and renewable water supply is estimated using the climate projections under the Representative Concentration Pathway (RCP) 8.5 scenario. The assessment predicts that the renewable water resources would decrease slightly then increase. The domestic and industrial water withdrawals are projected to increase in the next a few decades and then remain at the high level or decrease slightly during the 21st century. The increase of water withdrawals would put the middle and lower reaches in the conditions of severe water scarcity beginning in the next a few decades. If 40% of the renewable water resources were used to sustain ecosystems, a portion of irrigated land would have to be converted to rain-fed agriculture, which would lead to a 2-11% reduction in food production. This study highlights the links between water, food and ecosystems in a changing environment and suggests that trade-offs should be considered when developing regional adaptation strategies.

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Key words: water scarcity; Shared Socio-economic Pathways; climate change; Yellow River basin

1 Introduction

The Yellow River (YR) is the second-longest river in China and is regarded as the cradle of Chinese civilization. The YR plays an important role in the development of the regional economy as the major source of freshwater for a large amount of people living there. As of 2010, there were 113.7 million inhabitants and 12.6 million hectares of cultivated land in the basin (Yellow River Conservancy Commission (YRCC), 2013). In addition, the lower reaches of the river supply freshwater for 2.86 million hectares of irrigated area and a population of 54.73 million located outside the basin (Fu et al., 2004). Increasing population and socio-economic development have put great pressure on the water resources of the basin. Anticipated climate and socio-economic changes may further increase water scarcity. The water managers of the basin will face great challenges meeting the human and environmental requirements for water. This water crisis in the YR basin has received much attention for many years.

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Climate change and human water use are two major reasons for water crisis in the YR basin (Fu et al., 2004; Tang et al., 2008a; Wang et al., 2012). Numerous studies have investigated the changes in water supply due to climate change. Since the 1950s, streamflow of the river has decreased partly because of the decrease in precipitation and increase in temperature (Tang et al., 2008b; Xu, 2011; Wang et al., 2012). Some recent studies showed that there has been a substantial recovery of natural runoff over the past decade as a response to changes in precipitation, radiation, and wind speed (Tang et al., 2013; Liu et al., 2014). Climate projections suggest that temperature will continue to rise, but renewable water resources might decrease over the next few decades (Leng et al., 2015). Renewable water resources of the YR are likely to decrease due to both precipitation decrease and temperature increase over the next few decades (Li et al., 2012; Davie et al., 2013; Haddeland et al., 2014). However, water resources might increase by the end of the 21st century due to an increase of precipitation (Liu et al., 2011; Leng et al., 2015). The change in water availability under climate change suggests the need for adaptation.

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Along with rapid economic development and population growth, water withdrawals from the YR basin for industrial and household use have increased significantly. Water consumption for irrigation has induced a streamflow decrease by about half in the past half century (Tang et al., 2007; Shi et al., 2012). The lower reaches of the YR frequently ran dry (i.e. no streamflow in the low flow season) in the 1980s and 1990s (Tang et al., 2008b). Thereafter, the YRCC implemented a water flow regulation rule, which enforced an upper limit on water withdrawals for the eight provinces that rely on water supply from the river (Cai and Rosegrant, 2004). The expected increase in economic prosperity together with a growing population, both within and outside of the basin, will increase water demand from the river and thus water scarcity may impose further constraints on development and social well-being (Schewe et al., 2014). As water becomes increasingly scarce, there will be more competitions and conflicts among different water use sectors and regions (provinces). The current water flow regulation rule, which has been enforced since the late 1980s, might not be applicable in the 21st century.

Many studies have investigated the changes in water supply under various climate change but few have considered the joint pressure from both climate change and socio-economic development (Tang and Oki, 2016). It becomes important to develop qualitative scenario storylines to assess future water scarcity in a changing environment at the regional scale. These storylines would facilitate assessment of the water use competitions among different sectors and regions and thus aid development of adaptation strategy for the river basin. A few studies have tried to describe the main characteristics of future climate change scenarios and development pathways at the global scale (Elliott et al., 2014; Schewe et al., 2014). These efforts, though important, are too coarse for vulnerability assessment at the regional scale in the following aspects. Firstly, the global studies do not consider the water flow regulation rule implemented by the local river administration which sets limit on water withdrawals for each sub-basin. Secondly, the global studies usually set a strict criterion on discharge reduction for human water use such as 40% (Schewe et al., 2014) while human water use in the YR basin has already exceeded the criterion (YRCC, 2013). Thirdly, the global studies often exhibit considerable biases in water supply assessment as most global models are not validated using streamflow

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observations. Fourthly, the YR river supplies water for irrigation districts not only inside the river basin, but also those located outside of the basin. The water demands outside the basin are generally not considered in the global scale assessments. In this study, we use streamflow observations in the YR basin to bias-correct global model outputs (Ho et al., 2012; Hawkins et al., 2013), and present a multi-model analysis of water supply and demand narratives under different climate change scenarios and socio-economic pathways at the sub-basin scale (Figure 1 and Table 1). The objectives of the analysis are: i) to describe the water supply and demand changes in a changing environment; ii) to identify the possible time horizon when current management practices may no longer be sustainable; iii) to investigate the contributions of different water demand sectors to water scarcity; and iv) to assess the potential impacts of water scarcity on agricultural production.

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2 Study area and Data

2.1 Study area

The YR originates from the northern foothills of the Tibetan Plateau, runs through nine provinces and autonomous regions, and discharges into the Bohai Gulf (Figure 1). Total area of the basin is 75.2 thousand km^2. The YR basin lies in a temperate continental climate zone, and most parts of the basin belong to arid or semi-arid regions. The mean annual temperature in 1981-2010 ranges spatially from -5°C to 15°C in the basin, and it increases from north to south as consequence of the decrease in latitude to the south (Figure 2 (a)). Precipitation has large spatial variation within the whole river basin. The mean annual precipitation in 1981-2010 ranges spatially from 60mm to 900mm in the basin, and shows an increasing trend from northwest to southeast (Figure 2 (b)). The temperature and precipitation are projected to increase during the 21st century under the Representative Concentration Pathway (RCP) 8.5 emission scenario (see Figure S1 in Supplemental material).

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There are six land cover types in the basin (Figure 2 (c)). The dominant land cover types are grasslands (47.6%), croplands (26.1%), and forest and shrub-lands (13.4%). The urban and built-up lands are concentrated along the river. The croplands are mainly distributed in the lower reach of the YR. The land-cover changes influence the hydrological cycle (Tang et al., 2008b; Tang et al., 2012), and may alter runoff (Sterling et al., 2013). However, interactions among land cover change, climate change, and hydrological cycle are complicated. To focus on runoff responses to climatic variations, the fixed land cover map was used in this study.

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In 2010, the population within the basin boundary was more than 100 million, representing about 9% of China's population. The basin's gross domestic product (GDP) represented 8% of China's GDP in 2010. Both population and GDP are concentrated along the river (Figure 2 (d) and (e)). The projected population increases first and then decreases during the 21st century (see Figure S2 (a) in Supplemental material). China's population has been greatly affected by its fertility policy (Peng, 2011). Under the current fertility policy, China's population would continue to grow, and then begin to decrease as the aging of population accelerates (Chen and Liu, 2009; Peng, 2010). The range of projected population at the end of the 21st century varies from 50 million to more than 100 million, with Shared Socioeconomic Pathway (SSP) 5 at the bottom of the range and SSP3 at the top. The range of projected GDP at the end of the 21st century varies from 21,000 billion Yuan to more than 40,000 billion Yuan. SSP5, with its focus on development, has the highest GDP projections, and SSP3 representing the scenario with lowest international co-operation has the lowest income projection (O'Neill et al., 2015).

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2.2 Data

The data used in this study are summarized in Table 2. The simulated runoff data for the period 1971-2099, and the simulated irrigation water use and crop yield data for the period 1981-2099 were obtained from the Inter-Sectoral Impact Model Intercomparision Project (ISI-MIP) (Warszawski et al., 2014). These simulated data were provided at a spatial resolution of 0.5°×0.5°. The runoff data were produced by ten global gridded hydrological models (GGHMs), namely DBH, H08, LPJmL, MacPDM, MATSIRO, MPI-HM, PCR-GLOBWB, VIC, WaterGAP, and WBM (see Table S1 in Supplemental material). The irrigation water use and crop yield data were produced by six global gridded crop models (GGCMs), namely EPIC, GEPIC, LPJmL, LPJ-GUESS, pDSSAT and PEGASUS (see Table S2 in Supplemental material). Forcing data, bias-corrected by the ISI-MIP team for the GGHMs and GGCMs, were derived from climate projections of five global climate models

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(GCMs), namely HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1 (see Table S3 in Supplemental material) under the RCP 8.5 scenario (Warszawski et al., 2014). 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 dataset refers to the crop area over the period of 1998-2002 (Portmann et al., 2010). According to the survey by the Ministry of Water Resources (MWR) of China, the cropland area of the YR basin in the 2000s is 16 million ha. The MIRCA2000 dataset shows that the cropland area is 16.27 million ha, a value quite close to the MWR estimate. Although the cropland area may change in the future due to local adaptation to the 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 gridded population and GDP datasets over China were provided by the Institute of Geographic Sciences and Resources Research (IGSRR), Chinese Academy of Sciences (CAS). The population and GDP datasets refer to the conditions in 2005 (Fu et al., 2014; Huang et al., 2014). The datasets were developed based on remote sensing-derived land use data and the statistical population and GDP data of each county in China. The population and GDP data were provided with a spatial resolution of 1 km and were resampled to 0.5° in this study with ArcGIS. The annual total population and GDP data of China during 1981-2013 were obtained from the National Bureau of Statistics of China (NBC). Using a simple linear downscaling method (Gaffin et al., 2004), we downscaled the annual total population and GDP data to the gridded maps. The future water demand should be closely related to the growth of GDP and population in the basin, and the SSPs offer the possibility for describing different conditions in terms of future sectoral water demand. Quantitative projections for population and GDP were developed for the 2010-2099 period based on the Shared Socioeconomic Pathways (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 five-year intervals. The country level population data were gridded to 0.5° according to the 2010 Gridded Population of the World (GPWv3) dataset provided by the Center for International Earth Science Information Network (CIESIN), Columbia University. The country-level GDP data were provided in U.S. dollars at five-year intervals.

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The GDP data were converted to Chinese Yuan using the official exchange rate provided by the World Bank. The GDP data from the SSP Scenario Database were regridded to the 0.5° GDP of China grid and were linearly interpolated in time to obtain annual values (Gaffin et al., 2004). The assumption underlying the downscaling method is that the annual growth rate of GDP at each grid, at any year, is equal to the growth rate of China. The observed runoff data over 1971-2000 of four major hydrologic stations at the main stream of the YR (Lanzhou (LZ), Longmen (LM), Sanmenxia (SMX) and Huanyuankou (HYK)) were collected from the Hydrological Year Book of the Ministry of Water Resources of China.

3 Method

The river basin was divided into eight sub-basins in order to understand the regional patterns of water abundance and scarcity (Figure 1). The area of sub-basins varies from 40 to 185 thousand km^2 (Table 1). There are seven sub-basins along the main stream of the basin and one endorheic basin (sub-basin VIII) that does not flow to the main stream of the river. Because the irrigation districts located outside of the basin in lower reaches get water supply from the river, the sub-basin in the lowest reaches (sub-basin VII) consists of one part in the river basin and these irrigation districts.

The mean annual runoff, including both the subsurface and surface runoff, is assumed to be the renewable water resources (Oki and Kanae, 2006). Because the bias of GGHMs is usually large (Hattermann et al., 2016), we used the streamflow observations at the YR basin to bias-correct the model simulated runoff (see Supplemental Methodology in Supplemental material). We compared the bias-corrected runoff of ten GGHMs with the streamflow observations at the four selected hydrological stations (see Figure S3 in Supplemental material). The bias-corrected runoff can reproduce the streamflow well in the reference period (1971-2000). The bias-corrected runoff was aggregated for each sub-basin and the river basin as a whole (see Figure S4 in Supplemental material).

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In order to maintain the river in a desired environmental condition, we assumed that only a part of the renewable water resources could be appropriated by human. The net water withdrawal, i.e. water withdrawal minus return flow, accounts for 53% of renewable water resource in the 1980s (Zhang et

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al., 2004) and 72% in the 2010s (YRCC, 2013). Annual water supply was estimated as annual runoff multiplied by the ratio of human water appropriation (RHWA), i.e. the proportion of renewable water resource that is allowed to be used by human. Because water supply is largely determined by RHWA, water supply was estimated with RHWA values of 50%, 60%, and 70%, respectively. The water flow regulation rule currently implemented by YRCC (YRCC, 2013) sets the upper limit on water withdrawals for each sub-basin. According to the rule, the maximum water use proportion is prescribed for each sub-basin (Table 1). The annual water supply was calculated for each GCM-GGHM pair. There were five GCMs and ten GGHMs, making 50 model pairs. The multi-model-ensemble median of water supply from all the available model pairs was calculated.

On the water demand side, the consumptive agricultural, domestic and industrial water demands were considered. Agricultural water demand consists of the demands for irrigation and livestock. As the livestock demand is relatively small and the related statistical data were unavailable in the basin (YRCC, 2013), only irrigation demand was considered. The irrigation water demand was estimated by the GGCM. Table S2 shows an overview of the six GGCMs. Four crops, i.e. wheat, rice, maize and soybean, were taken into account because these crops accounted for over 80% of total cropland area in the YR basin. The irrigation water demands were aggregated for each sub-basin and the river basin as a whole to get irrigation water withdrawal (IrrWW). The multi-model-ensemble median of IrrWW from all the available GCM-GGCM pairs (five GCMs × six GGCMs) was calculated.

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Net domestic and industrial water withdrawals were linked to the main driving forces of water in the domestic and industrial sectors, i.e. population, GDP and electricity production, respectively (Alcamo et al., 2003). Following Hanasaki et al. (2013a), the annual net domestic water withdrawal was calculated using Equation 1.

$$W_{dom} = Pop \times (i_{dom,t0} + s_{dom,cat} \times (t - t0)) \times 0.365 \qquad \text{(Equation 1)}$$

where W_{dom} is the net domestic water withdrawal (m^3 yr^{-1}), *Pop* is the population, $i_{dom,t0}$ is the domestic water intensity for the base year (L day^{-1} $preson^{-1}$ yr^{-1}), $s_{dom,cat}$ is the domestic water intensity change rate (L $person^{-1}$ day^{-1} yr^{-1}), and the multiplier 0.365 is applied for unit conversion.

Industrial water use includes two main components: water withdrawal for the manufacturing sector and for cooling the thermoelectric plants in the electricity sector. The manufacturing water withdrawal is positively correlated with the economic metric manufacturing gross value added (Dziegielewski et al., 2002). Following Flörke et al. (2013) and Wada et al. (2016), the annual net industrial water withdrawal depends on the value added of manufacturing sectors and the water use intensities (Equation 2).

$$W_{ind} = GDP_{manu} \times i_{ind,t0} \times (1 - s_{ind,cat})^{(t-t0)} \qquad \text{(Equation 2)}$$

where W_{ind} is the net industrial water withdrawal (m^3 yr^{-1}), GDP_{manu} is the value added of manufacturing sectors (Chinese Yuan), $i_{ind,t0}$ is the industrial water intensity for the base year (m^3 per ten thousand Yuan), $s_{ind,cat}$ is the industrial water intensity change rate (%). The value added of manufacturing sectors is calculated by multiplying the GDP projection by the share of manufacturing gross value added in total GDP for Non-OECD country from the UNEP GEO4 Driver Scenarios (Hughes, 2005). Change in water withdrawal for thermal power industry is not considered in this study for two reasons. First, water conservation technology, such as dry cooling has been widely adopted in northern China, and thermal power industry is not the major water user in the YR basin (Zhang et al., 2016). Second, projection of future change is subject to large uncertainties as increase in demand is complicated with the advanced water conservation technologies (Zhang et al., 2016).

The change rates of domestic and industrial water intensity are dependent on the technology scenario of the SSPs. High technology scenario was set for SSP1 and SSP5, medium for SSP2, and low for SSP3 and SSP4 (O'Neill et al., 2015). For domestic water use, SSP1 and SSP5 would be more efficient, whereas SSP3 and SSP4 would be less efficient. SSP2 would be intermediate between the two groups (Hanasaki et al., 2013a). The domestic water intensity change rate was proposed in Table S4 (Hanasaki et al., 2013a). For industrial water use, the change rate is set 1.1% for SSP1 and SSP2, 0.6% for SSP2 and SSP4, and 0.3% for SSP3 (Wada et al., 2016). In this study, the base year is 2005. The domestic water intensity for the base year is 83.6 (L day^{-1} $person^{-1}$ yr^{-1}), while the industrial water intensity for the base year is 205.4 (m^3 per ten thousand Yuan) in the YR basin.

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Annual water demand was calculated as the sum of net water withdrawal requirement for agricultural, domestic, and industrial uses. In order to measure water supply stress, the water supply stress index (WaSSI) was used. WaSSI is defined as the ratio of annual water demand to annual water supply for a specific watershed. It measures whether water supplies are sufficient for all net withdrawal requirements within a watershed to be met concurrently. The WaSSI was calculated for each sub-basin and the whole basin to assess water abundance/scarcity condition. To investigate the contributions of different water demand sectors to water scarcity, WaSSI was calculated for the major sectors, i.e., domestic, industrial and agricultural (denoted as irrigation hereafter because only irrigation was considered) sectors, at the end of the 21st century. If the WaSSI is projected to be is greater than 1, water resources cannot sustain the socio-economic development and water scarcity occurs. The greater the WaSSI value is, the greater water scarcity is expected. We assume that irrigated agriculture has the lowest priority of all water consumers under water scarcity. When water scarcity occurs 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 calorie content of the major crop yields, would be the sum of production over the expanded rain-fed fraction of the cropland and the shrunken irrigated fraction. If water is sufficient in a given year for a given sub-basin, we assume that no rain-fed areas will be converted for irrigation.

The water supply and demands were assessed for each year during 1981-2099. However, the 30-year moving averages were also computed and illustrated. The 30-year window ensures that year-to-year variability dose not dominate the signal. The center year of the 30-year moving average was used to denote the 30-year period. For example, the average of the historical period of 1981-2010 was denoted as 1995.

4 Results

4.1 Changes of water supply

Figure 3 shows the estimated water supply in the YR basin and eight sub-basins in the 21st century. With the increase of RHWA, the water supply is projected to increase during the 21st century in the

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YR basin. The average water supply is 24.7, 29.8, and 34.8 billion m^3 per year during the historical period under three RHWA -- 50, 60 and 70%, respectively. The water supply is projected to decrease slightly from 1995-2035 due to the increase of air temperature (see Figure S1 in Supplemental material), and is projected to increase from 2036-2084 due to the increase of precipitation under all RHWAs (see Figure S1 in Supplemental material). The result is consistent with the conclusions from Zhao et al. (2009). The water supply is projected to be 29.1, 34.9 and 40.6 billion m^3 per year at the end of the 21st century under RHWA50, RHW60 and RHWA70, respectively, increasing by about 17.8% from that during the historical period. The water supply is projected to first decrease and then increase in all the sub-basins during the 21st century. The average water supply of sub-basin III has the maximum value of 9.3 billion m^3 per year during the historical period and rises to 10.9 billion m^3 per year by the end of the 21st century under RHWA50. The average water supply of sub-basin VIII has the minimum value of 0.06 billion m^3 per year during the historical period and rises to 0.73 billion m^3 per year by the end of the 21st century under RHWA50.

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4.2 Changes of total and sectoral water demand

Figure 4 and Figures S5 and S6 show the estimated total and sectoral (domestic, industrial and irrigation) water demand in the YR basin and eight sub-basins under five SSPs in the 21st century. In the YR basin, the total water demand is projected to increase from 24 billion m^3 yr^{-1} in 1995 to close to 27.8, 33.1, 23.8, 30.0 and 30.3 billion m^3 yr^{-1} in 2084 under SSP1, SSP2, SSP3, SSP4 and SSP5, respectively. This increase is primarily driven by the growth in the industrial water withdrawal, accounting for at least 32% of the total in 2084. Irrigation is the dominant water use sector during the period 1995-2084. Domestic water withdrawal is projected to increase before 2025 as both population and domestic water use intensities would increase, and then to decrease due to decrease in population (see Figure S2 (a) in Supplemental material). Industrial water withdrawal is projected to rapidly increase before 2050 as the value added of manufacturing sectors would increase (see Figure S2 (b) in Supplemental material), and then is projected to decrease slightly due to decrease in industrial water use intensities. The irrigation water withdrawal is projected to decrease from 20 billion m^3 yr^{-1} in 1995 to close to 17 billion m^3 yr^{-1} in 2084 under RCP 8.5. Irrigation water withdrawal is projected to

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increase slightly during 1995-2030, and is projected to decrease during 2031-2084. The total water demand, domestic and industrial water withdrawals are also projected to increase and then decrease in each sub-basin during the 21st century under all SSPs. In the sub-basin III, V, VII and VIII, although the industrial water withdrawal would increase rapidly, irrigation is always the dominant water use sector during the 21st century. In the sub-basin I, II, IV, and V, the irrigation and domestic are the dominant water use sectors at the beginning of the 21st century, while the industry would become the dominant water use sector after the 2030s.

4.3 Water abundance/scarcity and sectoral contributions to water scarcity

Figure 5 shows the average annual WaSSI for the YR basin and eight sub-basins throughout the 21st century under the five different SSPs. The WaSSI is projected to increase due to the increase of demand during the 21st century. Under RHWA50, the YR basin is projected to have a WaSSI greater than 1 after 2000s for all SSPs, meaning that water demand outstrips supply. The WaSSI is projected to decrease with the increase of RHWA. Under RHWA70, the water scarcity would not occur in the 21st century for all SSPs. The upper reaches of the YR basin (sub-basins I, II, and III) are projected to have a WaSSI less than 1, meaning that water supply would be more than water demand during the 21st century for all SSPs under all RHWAs. The endorheic basin of the YR basin (sub-basin VIII) is the only region in which the WaSSI is always larger than 1, meaning that the water would be scarce during the 21st century for all SSPs under all RHWAs. In the middle and lower reaches of the YR basin (sub-basins IV, V, VI, and VII), the WaSSI would begin to be large than 1 at the beginning of the 21st century under RHWA50. With the increase of RHWA, water scarcity would occur later. When the RHWA reaches 70%, water supply would be more than water demand during 1995-2084 in sub-basins IV under all SSPs.

Figure 6 shows the WaSSI calculated as the ratio of annual water demand and sectoral (domestic, industrial and irrigation) water withdrawals to annual water supply under RHWA50 for the YR basin and eight sub-basins at the end of the 21st century under the five different SSPs. In the YR basin, the WaSSI calculated as annual water demand to water supply is larger than 1 under all SSPs except SSP1, meaning that the water scarcity would occur at the end of the 21st century. Among the three different

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water demand sectors, irrigation is projected to contribute most (about half) to WaSSI for all SSPs, and domestic sector is projected to have the smallest contribution to WaSSI (less than 0.1) for all SSPs except SSP3. Both WaSSI and contributions from the water demand sectors to water scarcity would decrease with the increase of RHWA. With the increase of RHWA, more water can be used to meet water demands. Consequently, WaSSI becomes smaller with higher RHWA (see Figure S7 and S8 in Supplemental material). In sub-basins III, V, VII and III, irrigation is the main contributing factor to WaSSI, and the industrial sector is another important contributing factor. Increase of GDP would make the industrial sector become the main contributing factor to WaSSI for sub-basins I, II, IV, and VI. Because both population and GDP are concentrated in the middle and lower reaches, the estimated WaSSI is larger than one in those sub-basins, but smaller than one for the sub-basins in the upper reaches.

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4.4 Agricultural loss due to irrigation water scarcity

The climate change and irrigation water shortage in the YR basin would have significant implications for the food security of these regions. Considering the CO_2 fertilization effect, the agricultural production would be enhanced by climate change, and is projected to increase by close to 15.1% compared with the production during the historical period in the YR basin at the middle of the 21st century (Figure 7). Irrigation water scarcity could necessitate the reversion of cropland from irrigated to rain-fed management, and would lead to decreased agricultural production. Under RHWA50, irrigation water scarcity in the basin could necessitate the reversion of about half of cropland from irrigated to rain-fed management by the middle-of-21st-century. Considering the CO_2 fertilization effect, irrigation water scarcity would lead to 15.7%, 25.4%, 17.7%, 22.7%, and 21% of present-day total production reduction under SSP1, SSP2, SSP3, SSP4, and SSP5, respectively, in 2050 (Figure 7). The change rate of production is projected to decrease with the increase of RHWA. Under RHWA60, the reduction of agriculture production in 2050 might be 1-11% of present-day total production reduction. Under RHWA70, the reduction of agriculture production in 2050 wouldn't occur under all SSPs. Considering the impacts of climate and water supply stress, the reduction of agriculture

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production in 2050 occurs for all SSPs under RHWA50. Under RHWA60 and RHWA70, the agriculture production is projected to increase under each SSP at the middle of the 21st century.

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5 Discussion

The renewable water resources will be affected by projected changes in precipitation and temperature (Schewe et al., 2014), and the RHWA. The water supply in the YR basin would first decrease and then increase due to the impact of temperature and precipitation changes over the 21st century (see Figure S1 in Supplemental material). However, the true water shortage might be larger because the CMIP5 models may overestimate the magnitude of precipitation in the YR basin during the 21st century (Chen and Frauenfeld, 2014). The RHWA of the YR basin has increased to 75.6% during the beginning of the 21st century (Shi et al., 2012) from about 50% in 1980s (Zhang et al., 2004). The increase in RHWA tends to result in increase in water supply and reductions in irrigation water scarcity and loss of agriculture production (Figure 1 and Figure 7). Therefore, improvement of the RHWA could alleviate the water shortages in this region. However, because of the different geographical and economic conditions among the sub-basins, the impact of the RHWA should be considered when we analyze the water resource of the sub-basins.

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To quantify the domestic and industrial water withdrawal is difficult because the future water withdrawals are influenced by a combination of social, economic, and political factors. However, a few hydrologic modeling frameworks have integrated methods to estimate the water withdrawals, e.g. H08 (Hanasaki et al., 2010; Hanasaki et al., 2013a and 2013b), PCR-GLOBWB (Wada et al., 2011; Wada et al., 2014, Wada et al., 2016), WaterGAP (Flörke et al., 2013). The differences in these approaches result in significantly different projections even with same set of scenario assumptions (Wada et al., 2016). Our study does not consider the change in water for thermal power industry which accounts for about 30% of industrial water use in the YR basin (Zhang et al., 2016). It might lead to underestimation of the contribution of industrial water withdrawal to water scarcity.

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With the currently implemented water flow regulation rule, water is projected to be scarce in sub-basins located the middle and lower reaches of the YR basin characterized by a generally large population and GDP, while water is projected to be abundant in sub-basins located in the upper reaches of the YR basin characterized by a small population and GDP during the 21st century. In order to alleviate the water shortages in the middle and lower reaches, a new water flow regulation rule should be adopted.

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In order to solve the problem of water resources shortages in the more arid and industrialized north of China, the South-to-North Water Diversion Project has been undertaken. One aim of the project is to channel the fresh water from the Yangtze River in southern China to the YR basin (YRCC, 2013). By 2030, about 9.7 billion m^3 of fresh water from the Yangtze River would be drawn to the YR basin (YRCC, 2013). This could alleviate the water shortage in the YR basin to some degree.

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6 Conclusions

In this study, we assessed the change in renewable water resources of the YR basin under climate change and the changes in domestic and industrial water withdrawals in the basin under socio-economic change in the 21st century. The results show that the renewable water resources are projected to decrease slightly first and then increase in the YR basin and each sub-basin with the increase of temperature and precipitation under RCP 8.5 in the 21st century. Irrigation is the dominant water use sector before the 2030s, but irrigation and industry sectors are the dominant water users thereafter. With social and economic development, domestic and water withdrawals are projected to increase first and then remain at high level or decrease slightly during the 21st century.

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Water is always scarce in the endorheic basin, while water is always abundant in the sub-basins located in the upper reaches of the YR basin in the 21st century under all RHWAs and SSPs. Due to water withdrawal increase in industrial sectors, the available water resources cannot sustain all water use sectors in the next a few decades in the YR basin and the sub-basins located in the middle and lower reaches of the basin. The water resources shortage is most serious under SSP2, and use of 60% renewable water resources cannot sustain all the water use sectors in the YR basin. With the three water demand sectors considered, the industrial water withdrawal is the main contributing factor to

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water scarcity in sub-basin I, II, IV and V, while the irrigation water withdrawal is the main contributing factor to water scarcity in sub-basin III, V, VII and VIII.

Although climate change may have a positive impact on agriculture through the CO_2 fertilization effect in most regions of the YR basin (Yin et al., 2015), irrigation water scarcity would lead to the net loss of agricultural production. With the CO_2 fertilization effect, if more than 40% of the renewable water resources are used to sustain ecosystems, a portion of irrigated land would have to be converted to rain-fed agriculture, which would lead to a 2-11% reduction in food production. It should be noted that the change in water use for thermal power industry was not considered in this study. This might cause underestimation of the water stress index. Nevertheless, this study highlights the linkage between water and food security in a changing environment in the YR basin, and suggests that the trade-off should be considered when developing regional adaptation strategies.

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Acknowledgement

This research is supported by the National Natural Science Foundation of China (41425002), the Key Research Program of the Chinese Academy of Sciences (ZDRW-ZS-2016-6-4), and the National Youth Top-notch Talent Support Program in China. We would like to thank anonymous reviewers and the editor for their valuable and constructive suggestions. Thanks are due to Dr. Huijuan Cui for her comments.

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Table captions

Table 1 The eight sub-basins of the Yellow River (YR) basin.

Sub-basins		Area ($\times 10^3$ km^2)	Water use proportion (%)	Irrigated area (km^2)	Rain-fed area (km^2)	Note
Upper reaches	I	127	0.57	219	27	Above LYX station
	II	87	8.23	2, 680	1, 706	LYX to LZ
	III	157	37.45	23, 692	2, 106	LZ to HKZ
Middle reaches	IV	107	3.5	1, 591	3, 940	HKZ to LM
	V	185	16.64	25, 422	12, 311	LM to SMX
	VI	40	6.16	5, 717	2, 956	SMX to HYK
Lower reaches	VII	50.6	27.2	42, 824	2, 430	HYK to LJ, including irrigation districts outside the basin but receiving water from YR
Endorheic basin	VIII	42	0.25	446	225	Endorheic basin

Note: The sub-basins and names of hydrological stations are given in Figure 1.

Table 2 Datasets used in this study.

Datasets		Spatial and temporal resolution	Source
Simulated runoff data		0.5°×0.5°, 1971-2099	The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)
Simulated yield data		0.5°×0.5°, 1971-2099	
Simulated irrigation water data		0.5°×0.5°, 1971-2099	
Rain-fed and irrigation area data		0.5°×0.5°, 2000	
Population data	1 km grid population dataset of China	1km×1km, 2005	Institute of Geographic Sciences and Natural Resources Research
	Historical population data of China	Country, 1981-2013	National Bureau of Statistics of China
	SSP population data[a]	0.5°×0.5°, 2010-2099	ISI-MIP
GDP data	1 km grid GDP dataset of China	1km×1km, 2005	Institute of Geographic Sciences and Natural Resources Research
	Historical GDP data of China	Country, 1981-2013	National Bureau of Statistics of China
	SSP GDP data[a]	Country, 2010-2099	Organization for Economic Co-operation and Development (OECD)
Official exchange rate data		Country, 2005	World Bank
Observed runoff data		1971-2000	Hydrological Bureau of the Ministry of Water Resources of China

Note: a SSP is short for Shared Socioeconomic Pathways.

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Figure captions

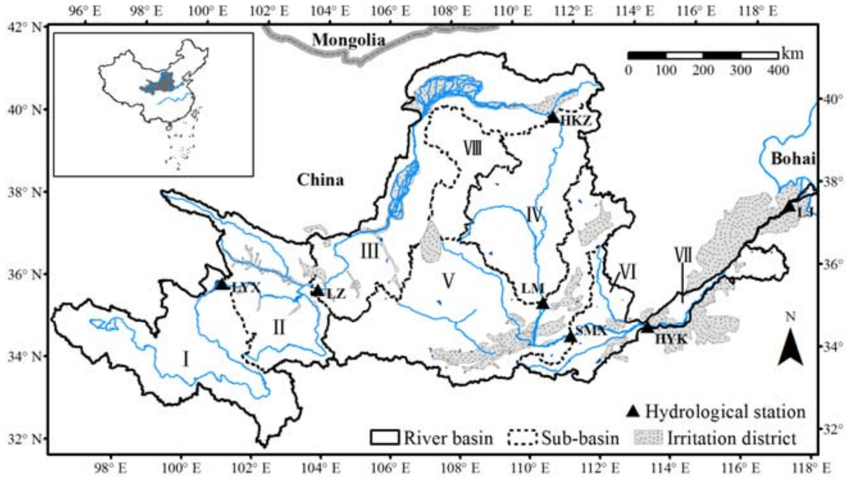

Figure 1 The Yellow River (YR) basin, the eight sub-basins, and location of Longyangxia (LYX), Lanzhou (LZ), Hekouzhen (HKZ), Longmen (LM), Sanmenxia (SMX), Huanyuankou (HYK), and Lijin (LJ) hydrological stations. The insert panel shows the location of the YR basin in China.

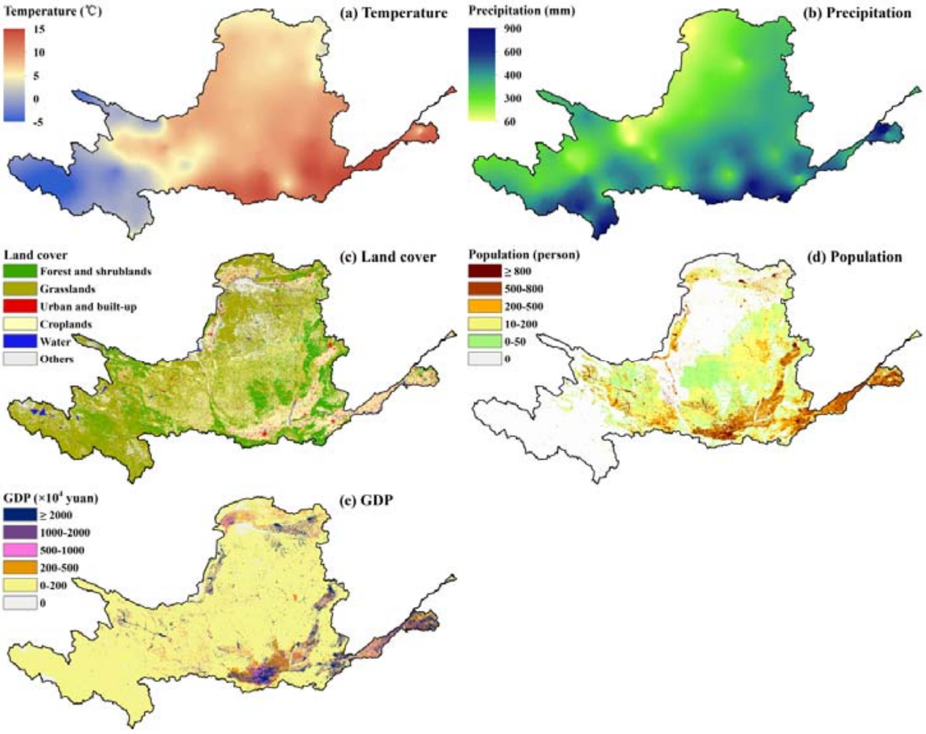

Figure 2 (a) Mean temperature (1981-2010), (b) annual mean precipitation (1981-2010), (c) land cover in 2010, (d) population in 2010, and (e) gross domestic product (GDP) in 2010 in the YR basin.

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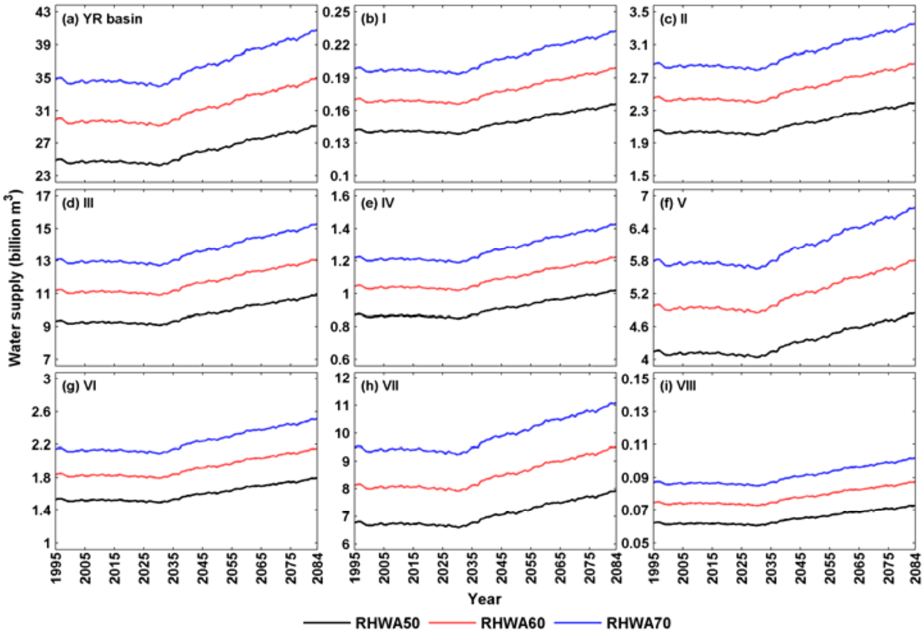


706 Figure 3 Annual water supplies in the YR basin and eight sub-basins during the 21st century. The
707 water supply was estimated with RHWA values of 50%, 60% and 70%, respectively.

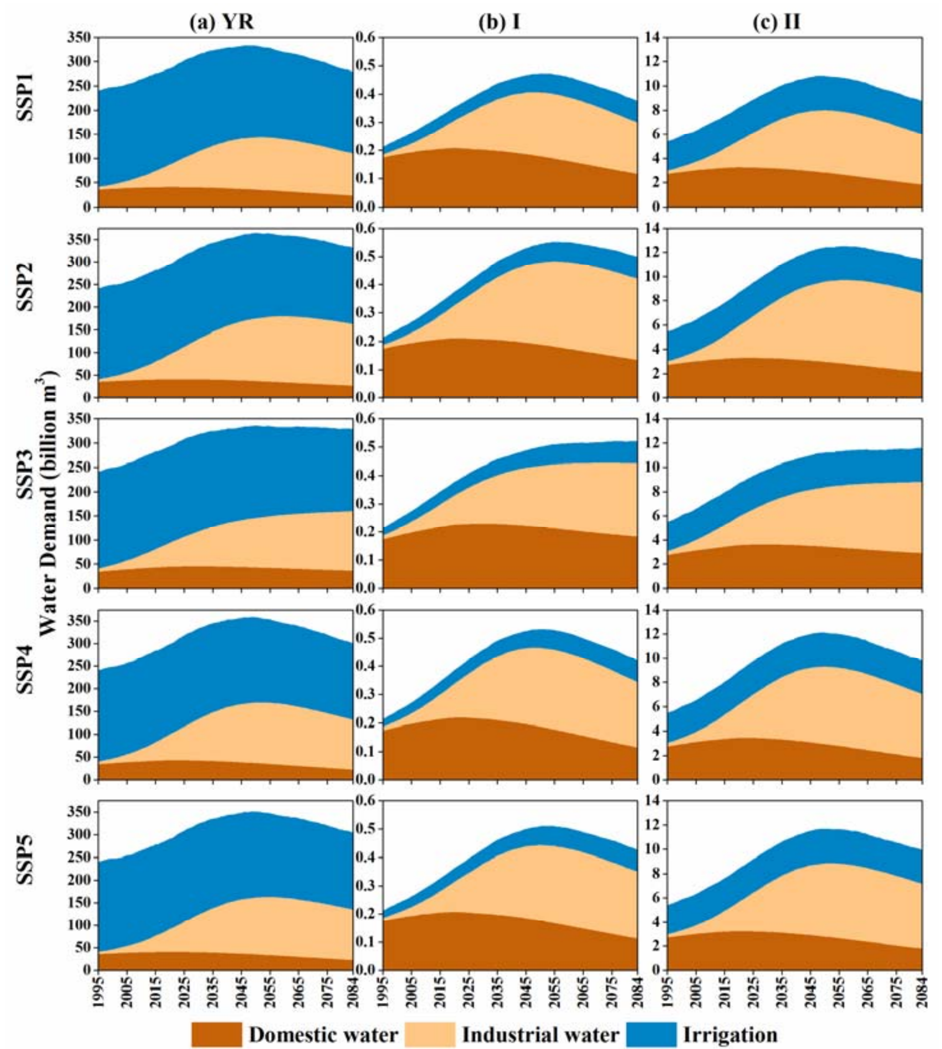
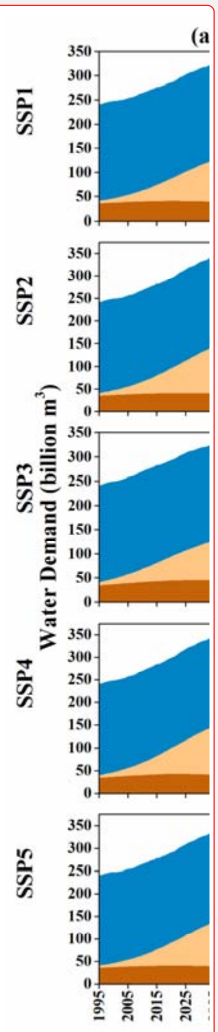


Figure 4 Estimated sectoral (domestic, industrial and irrigation) and total annual water demand (million m^3 yr^{-1}) in the YR basin, and sub-basin I and II during the 21st century.



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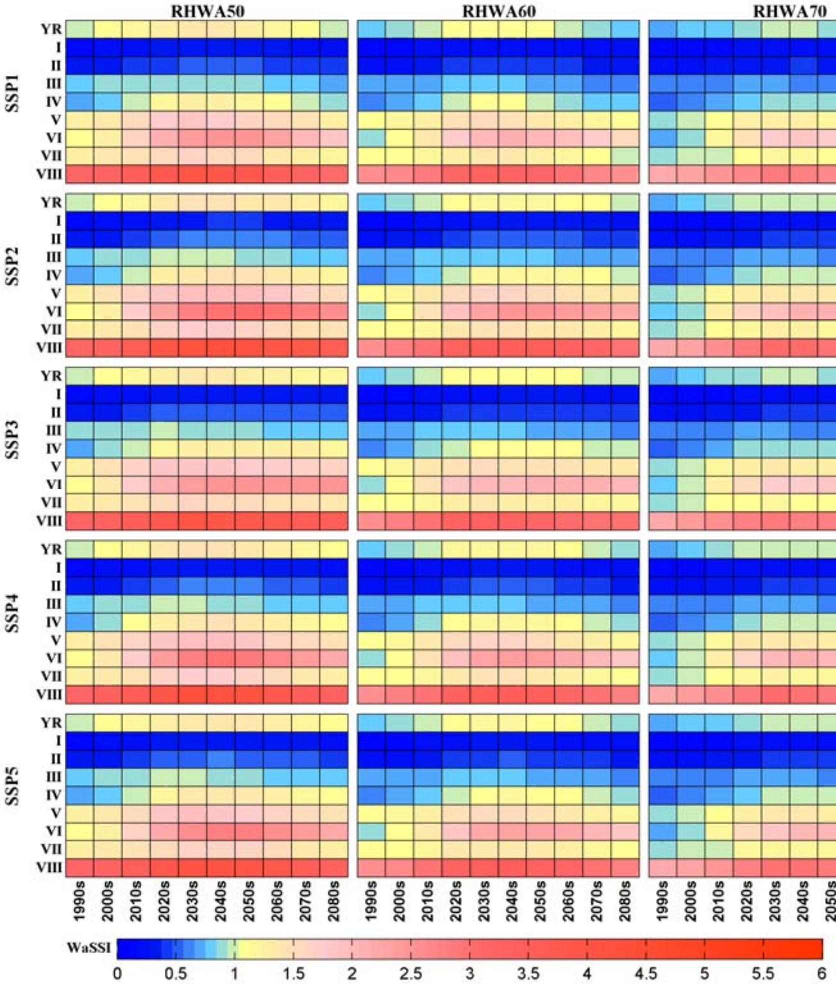

Figure 5 Average annual water supply stress index (WaSSI) for the YR basin and eight sub-basins throughout the 21st century under five different SSPs. Water supply was estimated with RHWA value of 50%, 60%, and 70% in the left, center, and right column, respectively. The WaSSI is calculated for each decade. The water scarcity occurs in a given basin when WaSSI is greater than one.

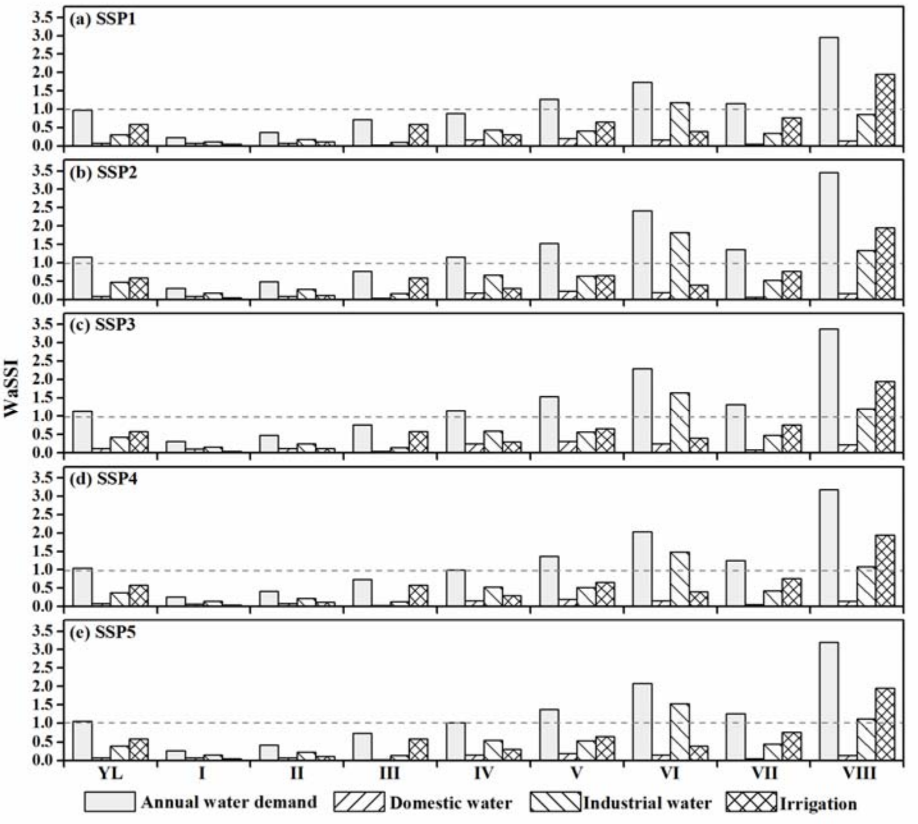

Figure 6 WaSSI calculated as the ratio of annual water demand and sectoral (domestic, industrial and irrigation) water withdrawals to annual water supply for the YR basin and eight sub-basins at the end of the 21st century under the five different SSPs. The annual water supply was estimated with an RHWA value of 50% (RHWA50).

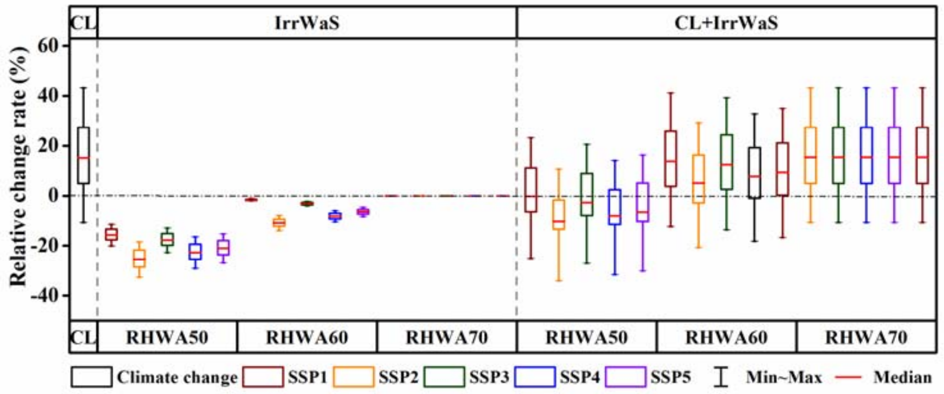

Figure 7 Comparison of relative change of agriculture production with only climate impact (CL), only irrigation water scarcity impact (IrrWaS), and combined climate and irrigation water scarcity impact (CL+ IrrWaS) in the YR basin in the 2050s (%).