Responses to the Reviewer 1

We truly thank the anonymous reviewer 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.

Some general comments:

- **Question 1:** Although this paper has been excellently prepared as a scientific report, as far as I have observed, the contents are lacking originality and poorly supported by local facts. First, the authors used the WaSSI index. The water scarcity assessment using WaSSI has been established two decades ago by Raskin et al. (1997), Vorosmarty et al. (2000), and Alcamo et al. (2003). Second, the authors used only the output of global hydrological models and highly conceptualized techniques devised for global assessments in this study. I would like to suggest the authors to thoroughly revisit the settings and validate the results of ISI-MIP before using them for local applications. Due to the aforementioned shortcomings, the results and discussion presented in this draft paper are general and not much different from the earlier global water scarcity assessments by Schewe et al. (2014).

- **Answer:** Thank you for the comments and suggestions. WaSSI is a simple and useful index which considers regional trends in both water supply and demand. Since it was established decades ago, it has been widely used as a metric of water supply stress in many references. So we argue that WaSSI is a proper index to be used. As the water scarcity in Yellow River is largely affected by the changes in both water demand and supply sides, we argue that WaSSI is a proper index to be used. This study differs from Schewe et al. (2014) in several important aspects. Firstly, this study assessed water scarcity at sub-basin scale and considered the water flow regulation rule implemented by the local river administration which set limit on water withdrawals for each sub-basin. In contrast, the global study of Schewe et al. (2014) does not consider the regulation rule and cannot assess the effects of water regulation on water stress. Secondly, this study assessed the water stress with the ratio of human water appropriation (RHWA) ranging from 50% to 70% in the Yellow River, which is much higher than the criterion of 40% reduction in discharge that is widely used in the global studies. This localized setting of RHWA enables a more realistic assessment of water scarcity than the global assessment. Thirdly, we have proposed a simple method to correct model simulated water supply. The corrected simulations were evaluated by comparing the ISI-MIP model results against the streamflow observations (see responses to Question 2). Lastly, we further assessed the impacts of water scarcity on agricultural production which was absent in Schewe et al. (2014). As one of the major food production regions in China, the area of cultivated land in the Yellow River basin accounted for 13.3% of the national totals in the year of 2000. Assessing the potential impacts of water scarcity on agricultural production under a changing environment could help shape adaptation approaches. In the revised version, we have clarified the objective and scientific significance of this study in the introduction section.

- **Question 2:** Line 114: “six global gridded hydrological models”: The performance of these models should be validated. In the present form, the authors only showed the mean annual runoff at Lanzhou, Longmen, Sanmenxia, Huayuankou in Supplemental Table S4 without any detailed discussion. At least the reproducibility of monthly river discharge and its inter-annual discharge of MPI-HM and PCR-GLOBWB is approximately half and double of observation in the Yellow River. The rational of adopting these models in this study must be also clearly described.

- **Answer:** Thanks for the constructive comments. The global models are usually not calibrated against streamflow observations, and thus often exhibit considerable biases in monthly discharge simulations. However, a recent study showed that the sensitivity of the global models to climate variability is generally comparable to that of the regional models which are calibrated (Hattermann et al., 2016). It suggests the model results, after correction for bias, may be used to assess climate change impacts on water supply. We have proposed a simple method to correct model simulated water supply. The corrected simulations were evaluated with the ISI-MIP models by comparing the model results against the streamflow observations. The results show that the bias-corrected water supply can reproduce well the reference conditions. We have clarified this issue in the revision.

Reference:

Hattermann, F. F., Krysanova, V., Gosling, S., Dankers, R., Daggupati, P., Donnelly, C., Flörke, M., Huang, S., Motovilov, Y., Buda, S., Yang, T., Müller, C.,Leng, G., Tang, Q., Portmann, F. T., Hagemann, S., Gerten, D., Wada, Y., Masaki, Y., Alemayehu, T., Satoh, Y., and Samaniego, L., 2016. Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins. Climatic Change, accept.

- **Question 3**: Line 121: "The global irrigated and rainfed crop area data (MIRCA2000)": The authors should focus on some of the key simulation settings of ISI-MIP and discuss their validity. For example, ISI-MIP fixed the irrigation and rainfed crop area throughout the 21st century. What is the recent trend in cropland area in this basin? What are the projections by the government and experts? Such local details should be included in this study.

- **Answer:** Thanks for the comments. The cropland area of the Yellow River basin in the 2000s (about 16 million ha estimated by the Ministry of Water Resources of the People's Republic of China, 2013) is quite close to that during the period of 1998-2002 shown in MIRCA2000 (about 16.27 million ha). Although the cropland area may change due to local adaptation to the environmental change, the projection of land use change is beyond the scope of this study. The land use map (i.e. cropland area) is fixed throughout the 21st century in this study. However, the irrigation or rainfed crop area is not fixed. When water shortage occurred (agriculture water availability is not enough for irrigation), we assume the irrigation area would be converted into rainfed. In this way, we can assess the impact of water shortage on agriculture production. We have clarified this in the revised manuscript.

- **Question 4:** Line 167: “the ratio of human water appropriation (hereafter RHWA)”: First, the definition of this term is missing in the current form of text. The definition and background concept should be clearly stated. Second, the rational of the thresholds of 50%, 70%, 90% should be carefully discussed. It should be well noted that in many densely populated river basins, total water withdrawal may exceed the total river discharge since treated waste water in upstream is utilized in downstream. Even if the total water withdrawal exceeds the river discharge, water scarcity never occurs if waste water is properly treated and returned to the stream.

- **Answer:** Thanks for the comments. In this study, the ratio of human water appropriation (RHWA) describes the fraction of net water withdrawal (Yellow River Conservancy Commission of the Ministry of Water Resources (YRCC), 2013) and is defined as the annual net water withdrawal divided by the annual runoff. The net water withdrawal is defined as the total water withdrawal minus the water that returns back to the river channel. The threshold values of 50%, 60% and 70% are three different scenarios of human water appropriation. The net water withdrawals of the runoff were occupied 53% during 1980s (Zhang et al., 2004) and 72% presently (YRCC, 2013). If environmental flow requirements in the river basin have greater priority than human society during the period of the study, we assumed that the ratio of human consumptive water appropriation in the basin is 50%. Otherwise, we assumed that the ratio of human consumptive water appropriation in the basin is 70%. 60% is the medium-level scenario. We have added the relevant content in the revision.

Reference:

YRCC (Yellow River Conservancy Commission of the Ministry of Water Resources), 2013. Comprehensive planning of Yellow River Basin (2012-2030). Zhengzhou: The Yellow River Water Conservancy Press (in Chinese)

Zhang, H. M., Niu, Y. G., Wang, B. X., and Li, S. M., 2004. The Yellow River water resources problems and countermeasures. Hydrology, 24(4), 26-31 (in Chinese)

- **Question 5**: Line 181: "The GGCM estimated irrigation water demand": First, the authors should provide the setting and assumptions of this simulation related to water use. What types of crops were planted in the basin in the simulations? Was the crop type varied during the simulations to adapt to warmer climate? Such settings are crucially sensitive to the results. Then carefully discuss whether such simulation conditions are valid for the study basin, and what should be noted in interpreting the results.

- **Answer:** Thanks for the comments. We have added a table (Table S2 in the Supplemental materials) to show the setting of the GGCM. All the GGCMs simulate wheat, maize, and soybean, and all but PEGASUS simulates rice. This study assessed the four crops only. The planting area of these four crops is more than 80% of total crop area in the Yellow River basin. The crop type is fixed during the simulation -- no adaptation measures were considered. The main purpose of this study is to assess how water shortage would affect agricultural production if no adaptation measures were taken. We have added a brief discussion in the revision.

- **Question 6:** Line 195: “using the historical GDP per capita and industry water use per capita data”: Although the authors claimed that their industrial water model followed Alcamo et al. (2003) and Flörke et al. (2013) in line 187, there is a fundamental difference in explanatory variables (input data). In reality, the explanatory variables of Alcamo et al. and Flörke et al. were electricity production (a rough indicator of the magnitude of manufacturing output) or value added of industrial sectors respectively, not GDP. In general, industrial water grows much gently than GDP in long term (see Alcamo et al., 2003 and Flörke et al., 2013). Note that the usage of GDP might be one the reasons why the industrial water exploded in late 21st century in this study.

- **Answer:** Thanks for the comments. Unfortunately, it is still hard to get the electricity production projection or the value added of manufacturing sectors projection in the Yellow River basin or in China. Alternatively, the GDP projection data over the 21st century is readily available for different socio-economic scenarios. Also, we can obtain the share of manufacturing gross value added in total GDP over the 21st century for OECD and Non-OECD country from the UNEP GEO4 Driver Scenarios (Hughes, 2005). Given that China is a Non-OECD country, we could calculate the value added of manufacturing sector in the 21st century. Based on the industrial net water withdrawal and the calculated value added of manufacturing sector, we have reconstructed the industrial water model followed Flörke et al. (2013) in the revision.

Reference:

Hughes, B. B., 2005. UNEP GEO4 diver scenarios (fifth draft). Josef Korbel School of International Studies, University of Denver, Colorado.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., and Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environment Change, 23, 144-156, doi: 10.1016/j.gloenvcha.2012.10.018

- **Question 7:** Line 200: “In the domestic sector, TC was set as 1% per year”: SSP narrates substantially different view of the world (O’Neill et al., 2014). It is a bit odd to me that a same parameter was used for SSP1 (sustainable world) and SSP3 (unsuccessful fragmented world) in this study. For instance, Hanasaki et al. (2013) set different parameter for each SSP to make parameter and narrative scenario consistent.

- **Answer:** Agreed. We have revised the domestic water use estimates following Hanasaki et al. (2013).

- **Question 8:** Line 203: “ratio of water demand to water supply”: Define this term more precisely. The terms “water demand” and “water supply” are also unclear.

- **Answer:** Thanks for the comments. In this study, the WaSSI was defined as the ratio of annual water demand to annual water supply for a specific watershed. Annual water supply was defined as the total potential surface water available for withdraw from a watershed, and was equal to the annual runoff multiplied by RHWA (the ratio of human water appropriation). Annual water demand represents the sum of net water withdrawals for agricultural, domestic, and industrial uses.

- **Question 9:** Line 279: “the WaSSI for total water demand is large than 1 under each SSP, meaning that the water would be scare at the end of the 21st century”: Again, if the water withdrawn in upstream is properly treated upstream and returned to the stream, water scarcity doesn’t occur even if WaSSI exceeds one. Elaborate what are the key problems in the basin in reality, and what can be represented by the WaSSI index.

- **Answer:** In this study, the WaSSI represents water stress only with respect to net water withdrawals, which is defined as the total water withdrawal minus the water that returns back to the river channel, and measures whether water supplies are sufficient for all net withdrawal requirements within a watershed to be met concurrently. We have added those explanations in the section of Method of the revised manuscript.

- **Question 10:** Line 265: "The water resource shortage is most serious under the conventional development scenario (SSP5)": This is contradictory to the original narrative story line of SSP5 (O'Neill et al., 2014) which depicts a technology-oriented world with high capability of adaptation (humans would control negative consequences of environmental problems by technology). Water does "SSP" mean in this study? Is this mean that authors only took the projection of GDP and population from SSP database?

- **Answer:** Thanks for the comments. Each SSP contains a quantitative scenario and a qualitative scenario. The qualitative scenario includes the degree of technological change, overall environmental consciousness and so on. We agree that it is not reasonable to consider GDP and population only. We have taken into account of the effect of technological change and recalculated the water demands following Hanasaki et al. (2013) in the revision.

Reference:

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., and Kanae, S., 2013. A global water scarcity assessment under Shared Socio-economic Pathways – Part 1: Water use. Hydrology and Earth System Sciences, 17, 2375-2391, doi:10.5194/hess-17-2375-2013

Some minor comments:

- **Question 11:** Line 66 “a grant figure”: What is this?

- **Answer:** Corrected.

- **Question 12:** Line 114: “H08”, “PRC-GLOBWB”: “H08” and “PRC-GLOBWB” respectively

- **Answer:** Revised.

- **Question 13:** Line 267: “meaning than water demand outstrip supply water”: Rephrase this part.

- **Answer:** Thanks for the comments. In the revision, we have replaced “meaning than water demand outstrip supply water” with “meaning that demand for water outstrips supply”.

Responses to the Reviewer 2

We truly thank the anonymous reviewer 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.

Some general comments:

- **Question 1:** The writing may need to be improved.

- **Answer:** Thanks for the comments. We have carefully polished the language and grammar thoroughly.

- **Question 2:** I have doubts about the function of GDP's VS. industrial water demand used by the authors, which leads to my doubts about the outcomes of this study.

- **Answer:** Thank you for the comments. In this study, the industrial water demand means the industrial net water withdrawal which was defined as the total water withdrawal minus the water that returns back to the river channel. The industrial water demand includes manufacturing water demand and thermoelectric water demand. As we are unable to get the electricity production projection in the Yellow River basin or in China, we assumed that the industrial water demand only include manufacturing water demand in this study. The manufacturing water demand is positively correlated with the economic metric manufacturing gross value added (Dziegielewski et al., 2002). It is more reasonable to estimate industrial water demand with manufacturing gross value added in total GDP than GDP. Based on the obtained GDP projection data and the share of manufacturing gross value added in total GDP over the 21st century from the UNEP GEO4 Driver

Scenarios (Hughes, 2005), we have calculated the value added of manufacturing sector from 2010 to 2099. In the revision, we have rebuilt the function of the value added of manufacturing sector and industrial water demand followed Flörke et al. (2013) and recalculated the results.

Reference:

Dziegielewski, B., Sharma, S. C., Bik, T. J., Margono, H., and Yang, X., 2002. Analysis of water use trends in the Unites States: 1950-1995. Special Report 28. Illinois Water Resources Center, University of Illinois, USA.

Hughes, B. B., 2005. UNEP GEO4 diver scenarios (fifth draft). Josef Korbel School of International Studies, University of Denver, Colorado.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., and Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environment Change, 23, 144-156, doi: 10.1016/j.gloenvcha.2012.10.018

Some specific comments:

- **Question 3:** L139: the full name of “SSP” should be provided before the use of abbreviations (e.g. L136)

- **Answer:** The full name of “SSPs” is “Shared Socio-economic Pathways”. Corrected in the text.

- **Question 4:** L162-164: There are only 6 GGHMs right? This 7th GGHM is shown as GGHM-GCMs in Table S4. Could the authors provide some explanation about this 7th GGHM?

- **Answer:** Corrected.

- **Question 5:** L164-165: Based on Table S4, only WBM has “simulated runoff agrees well with the observed runoff”. Maybe add discussion about the performance of different GGHMs and the reasoning of performance difference.

- **Answer:** We have provided the setting and assumptions of the global gridded hydrological models and have added discussion about the performance of different GGHMs. The global models are usually not calibrated against streamflow observation, thus often show a considerable bias in monthly discharge. However, a recent study showed that the sensitivity of the global models to climate variability is in general similar as that of the regional models which are calibrated (Hattermann et al., 2016). It suggests the model results, after correction for bias, may be used to assess climate change impacts on water supply. We have proposed a simple method to correct model simulated water supply. The corrected simulations were evaluated the ISI-MIP models by comparing the model results against the streamflow observations. The results show that the bias-corrected water supply can reproduce well the reference conditions.

Reference:

Hattermann, F. F., Krysanova, V., Gosling, S., Dankers, R., Daggupati, P., Donnelly, C., Flörke, M., Huang, S., Motovilov, Y., Buda, S., Yang, T., Müller, C.,Leng, G., Tang, Q., Portmann, F. T., Hagemann, S., Gerten, D., Wada, Y., Masaki, Y., Alemayehu, T., Satoh, Y., and Samaniego, L., 2016. Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins. Climatic Change, accept.

- **Question 6:** L192: It should be “Figure S3 (a)”.

- **Answer:** Corrected.

- **Question 7:** Figure S3: Typos in X-axis, change “pre” to “per”, change “captia” to “capita”

- **Answer:** Corrected.

- **Question 8:** L196: As I mentioned earlier. The relationship of GDP and industrial water demand has significant impact on the trend of water demand in the projection period, and therefore it has dominating effect on the outcome of this study. The authors should provide better literature review and methodology explanation about this relationship to future validate their results. One concern I have about this hyperbolic curve is that the range of GDP per capita that the curve is based on, as shown in Figure S3, is not matching with the GDP per capita range in the projection period as shown in Figure S2. After 2050, all the SSPs have GDP per capita greater than 50000 yuan, which is the maximum in Figure S3. As a result, for most part of the projection period, the GDP vs. industrial water demand relationship is at the plateau part of the curve, suggesting a linear increase of industrial water use with GDP increase. I’m not sure if this is a valid assumption, which leads to my doubts about the study outcome that industrial water demand will be the main contributing factor to water scarcity in the future.

- **Answer:** Thank you for the comments and suggestions. A number of models have been developed to calculate the industrial water demand quantitatively (e.g. Alcamo, 2003; Hanasaki et al., 2006, 2008; Flörke et al., 2013). Dziegielewski’s work (2002) showed that the manufacturing water demand is positively correlated with the economic metric manufacturing gross value added. We have rebuilt the function of the value added of manufacturing sector and industrial water demand and have recalculated the results (see responses to Question 2).

Reference:

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S., 2003. Development and testing of the WaterGAP 2 global model of water use and availability. Hydrological Sciences Journal, 48, 317-337.

Hanasaki, N., Kanae, S., and Oki, T., 2006. A reservoir operation scheme for global river routing models. Journal of Hydrology, 327, 22-41.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K., 2008. An integrated model for the assessment of global water resources--Part 1: Model description and input meteorological forcing. Hydrology Earth System Sciences, 12, 1007-1025.

Dziegielewski, B., Sharma, S. C., Bik, T. J., Margono, H., and Yang, X., 2002. Analysis of water use trends in the Unites States: 1950-1995. Special Report 28. Illinois Water Resources Center, University of Illinois, USA.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., and Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environment Change, 23, 144-156, doi: 10.1016/j.gloenvcha.2012.10.018

- **Question 9:** L198-202: The effect of technologic advance on water use efficiency is considered in the study as explained here. It seems pretty minimal based on the results. I would suggest linking TC with GDP growth or at least test the sensitivity of industrial water demand to TC.

- **Answer:** Thanks for the suggestion. We have taken into account of the effect of technological change and recalculated the water demands following Hanasaki et al. (2013).

Reference:

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., and Kanae, S., 2013. A global water scarcity assessment under Shared Socio-economic Pathways – Part 1: Water use. Hydrology and Earth System Sciences, 17, 2375-2391, doi:10.5194/hess-17-2375-2013

- **Question 10:** The writing in Section 4.1 and 4.2 needs to be improved. To list a few: L251 Please revise this sentence; L267 Please revise this sentence; L283: Please revise this sentence.

- **Answer:** We have read through the manuscript and improved English writing with help from English editors.

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 an 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 but 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 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.

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

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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 support the 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, the 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.

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.

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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. 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 adaptation strategy development 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 of 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 observations. Fourthly,

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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.

2 Study area and Data

2.1 Study area

The YR originates in 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 temperature ranges from -5°C to 15°C in 1981-2010 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 ranges from 60mm to 900mm in 1981-2010, 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).

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),

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and may alter runoff (Sterling et al., 2013). However, interactions among land cover change, climate change, and hydrological cycle are complicated. The fixed land cover map was used in this study, which focuses on runoff responses to climatic variations.

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) was 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). 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 model 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 (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

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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 growth 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 data 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. 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.,

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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 resource (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 well the streamflow 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). In order to maintain the river in a desired environmental condition, we assume only a part of the renewable water resource can 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 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,

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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.

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

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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 the water withdrawal for 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} preson^{-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.

Annual water demand was calculated 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

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删除的内容: demands. Technological advance, which could lead to improvements in the efficiency of water use and a decrease in water intensity, was accounted for using a technological change (TC) rate. In the domestic sector, TC was set as 1% per year. In the industry sector, TC was set to 2.4% per year between 1981 and 1999, and 1% per year thereafter following Flörke et al. (2013).

删除的内容: The water supply stress index (WaSSI), defined as the ratio of water demand to water supply (McNulty et al., 2010; Averyt et al., 2013), (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, the greater the water scarcity. 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 was 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 abundance in a given year for a given sub-basin, we assume that no rain-fed areas were converted for irrigation.

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The water supply and demands were assessed for each year but the 30-year moving averages during 1981-2099 were 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 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

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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, with increasing by about 17.8% compared with the water supply 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.

4.2 Changes of total and sectoral water demand

Figure 4 and Figure 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 and then decrease during 1995-2084. Industrial water withdrawal is projected to rapidly increasing before 2050 and then is projected to decrease slightly. The irrigation water withdrawal is projected to increase 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 not increase substantially during 1995-2030, and is projected to decrease during 2031-2084, with decreasing by close to 16% compared with the irrigation water in 1995. 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

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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 water demand increase during the 21st century. Under RHWA50, the YR basin is projected to have a WaSSI greater than 1 after after 2000s for all SSPs, meaning than water demand for water outstrip 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 the water would be abundant, 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, a water resource scarcity would begin to occur later. When the RHWA reaches to 70%, the water would be abundant 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 large 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 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. With the increase of RHWA, WaSSI as well contribution from the water demand sectors to WaSSI would go down (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

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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.

4.4 Agricultural loss due to irrigation water scarcity

The climate change and the scarcity of water available for irrigation 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 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 climate and water supply stress impact, the reduction of agriculture production in 2050 only 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.

5 Discussion

The renewable water resource 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 in varying degrees due to the impact of temperature and precipitation rise over the 21st century (see Figure S1 in Supplemental material). However, the true water shortage might be larger

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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.

To quantify domestic and industrial water withdrawal is difficult because the future water withdrawals will be influenced by a combination of social, economic, and political factors. However, a few of the 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). The study might underestimate the water scarcity and the contribution of industrial water withdrawal to water scarcity.

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 could be adopted.

In order to solve the problem of water resource 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

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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.

6 Conclusions

In this study, we assessed the change in renewable water resource 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. 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 the water use sectors beginning 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 resource shortage is most serious under SSP2 and 60% of the 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 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 change in water use for thermal power industry was not considered in this study. This might lead

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to an underestimation of the water scarcity. 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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Table captions

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

Sub-basins		Area (×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.

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删除的内容：Note: LYX (Longyangxia), LZ (Lanzhou), HKZ (Hekouzhen), LM (Longmen), SMX (Sanmenxia), HYK (Huanyuankou), LJ (Lijin), YL basin (Yellow River basin). Sub-basin consists partly of the river basin but also includes irrigation districts outside the basin that have water supplied by the river. .

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	
Popu-lation 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

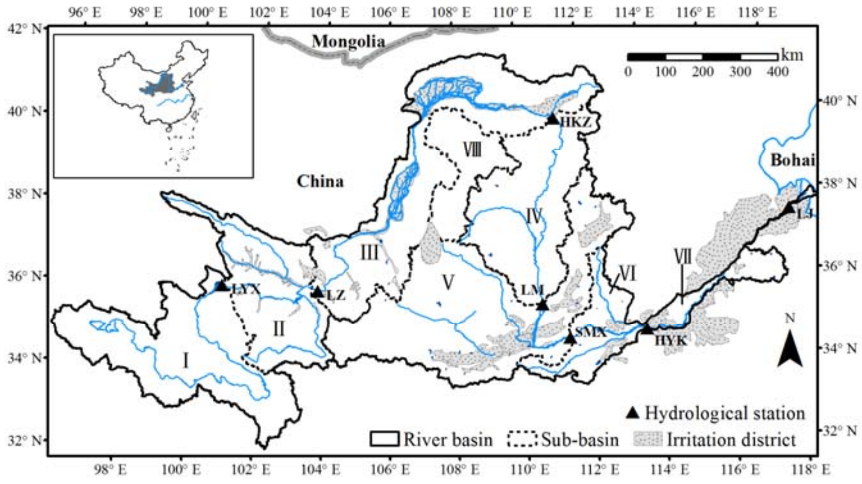
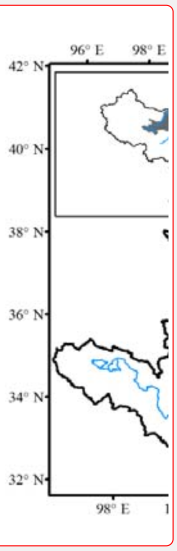


Figure 1 The Yellow River (YR) basin, the eight sub-basins, and location of Longyangxia (LYX), Lanzhou (LZ), Hekouzhen (HKZ), Longmen (LM), Sanmenxia (SMX), Huanyuankou (HYK), and Lijin (LJ) hydrological stations. The insert panel shows the location of the YR basin in China.



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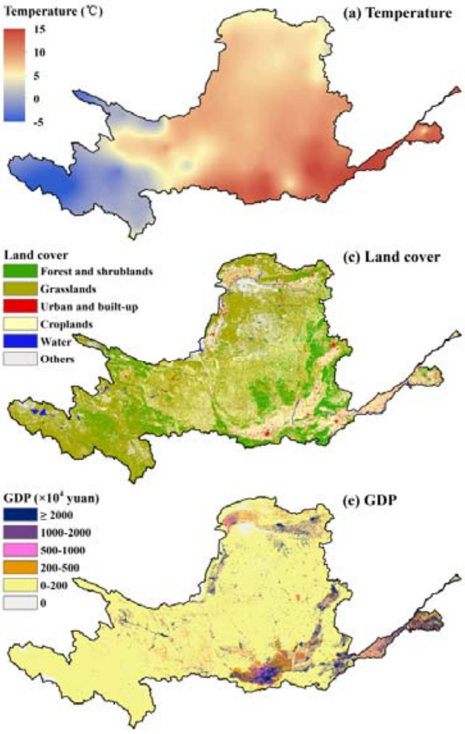

Figure 2 (a) Mean temperature (1981-2010), (b) annual mean precipitation (1981-2010), (c) land cover in 2010, (d) population in 2010, and (e) gross domestic product (GDP) in 2010 in the YR basin.

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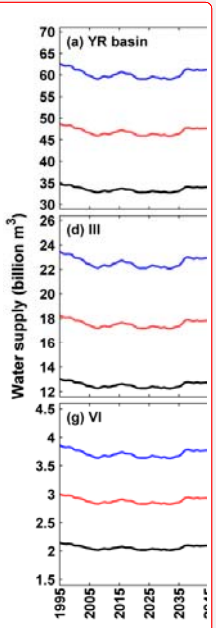

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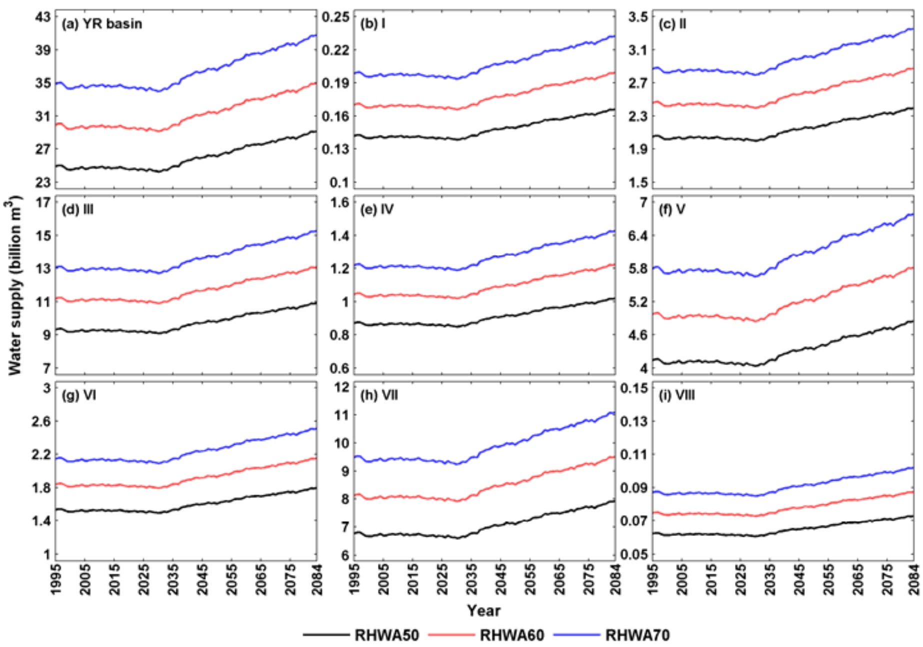

Figure 3 Annual water supplies in the YR basin and eight sub-basins during the 21st century. The water supply was estimated with RHWA values of 50%, 60% and 70%, respectively.

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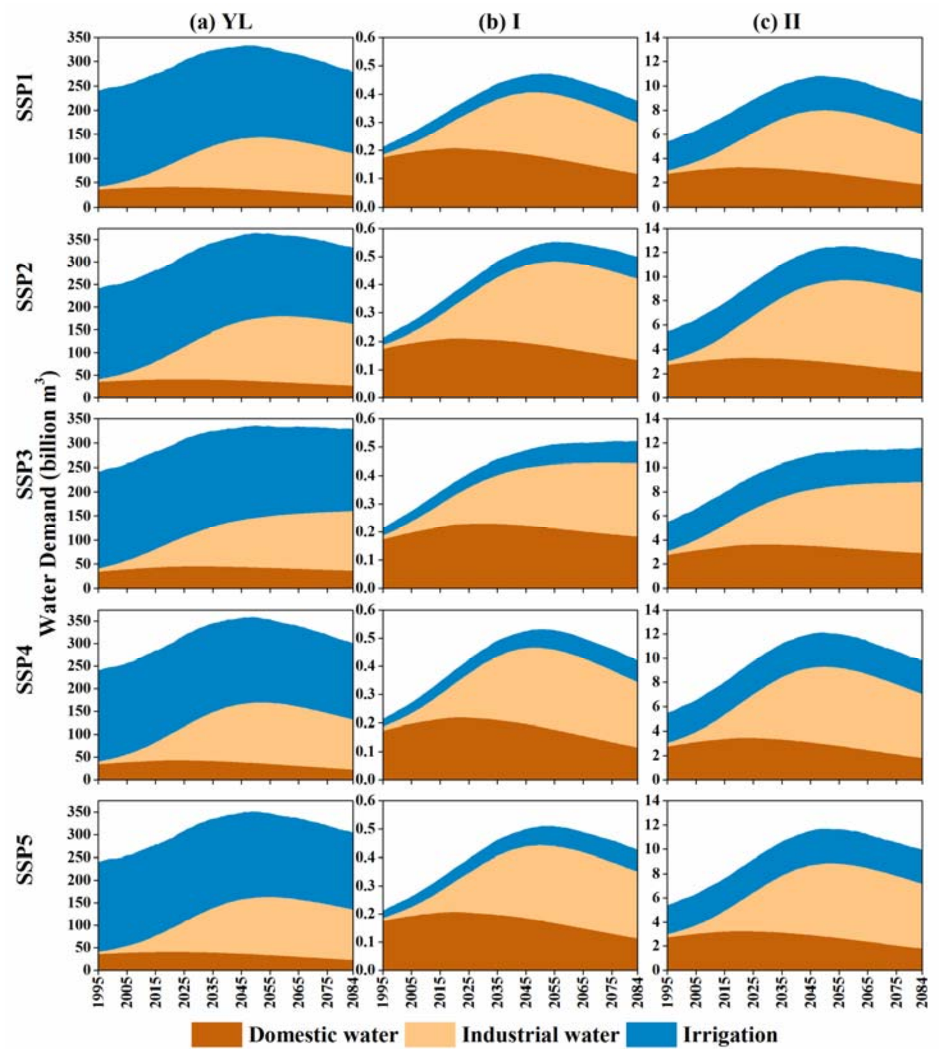
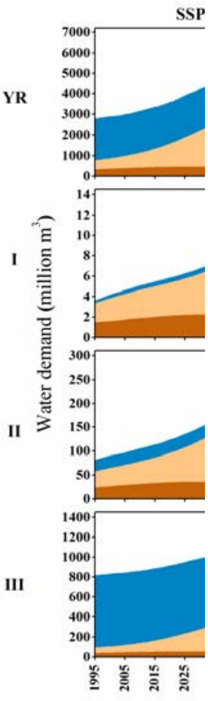


Figure 4 Estimated sectoral (domestic, industrial and irrigation) and total annual water demand (million m^3 yr^{-1}) in the YR basin, and sub-basin I and II during the 21st century.



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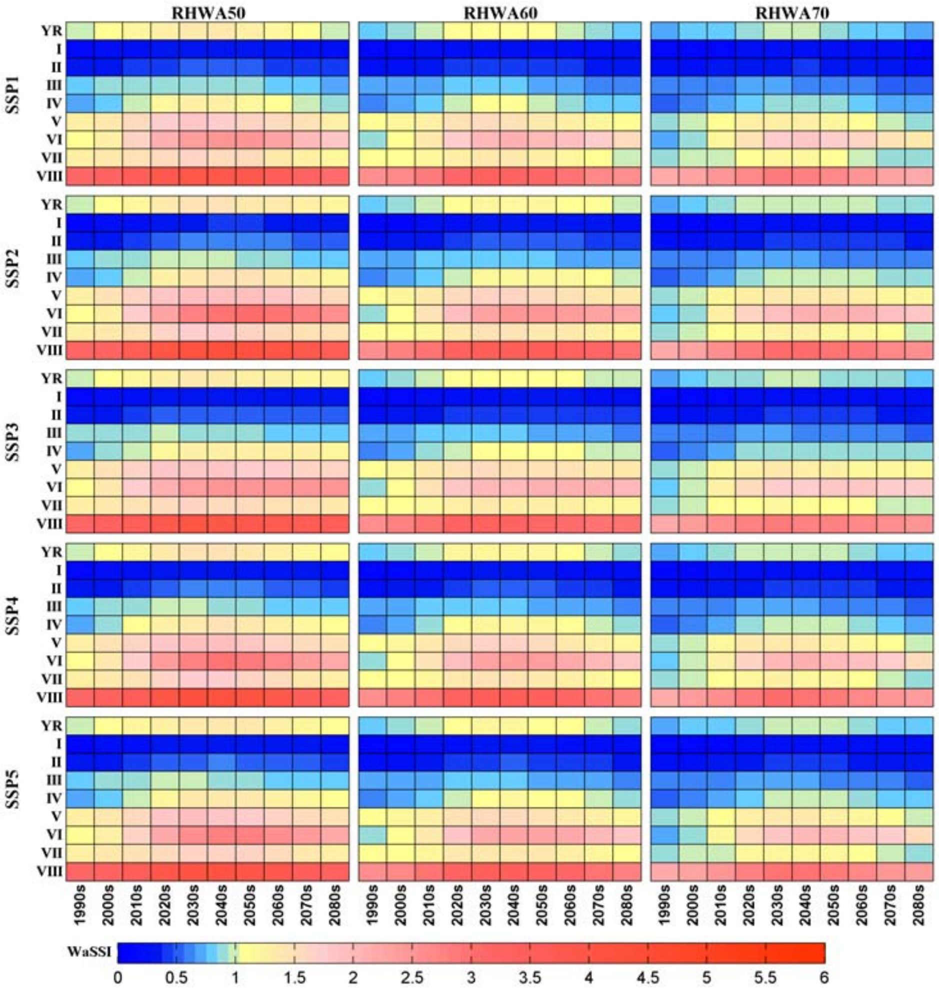
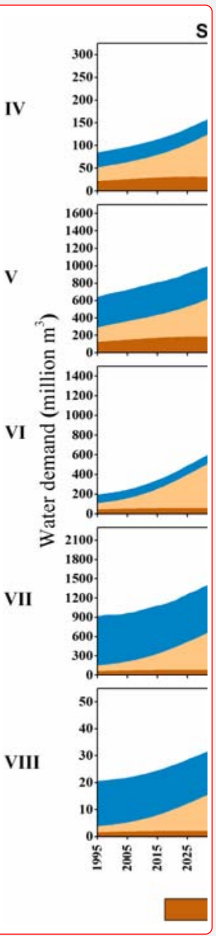


Figure 5 Average annual water supply stress index (WaSSI) for the YR basin and eight sub-basins throughout the 21st century under five different SSPs. Water supply was estimated with RHWA value of 50%, 60%, and 70% in the left, center, and right column, respectively. The WaSSI is calculated for each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



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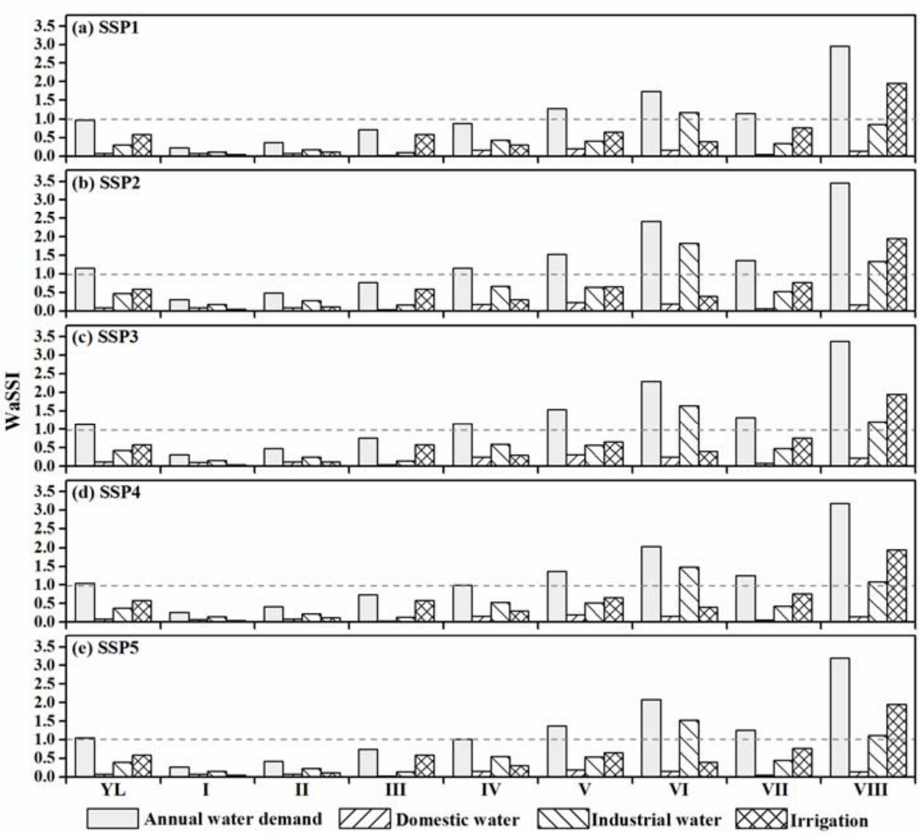

Figure 6 WaSSI calculated as the ratio of annual water demand and sectoral (domestic, industrial and irrigation) water withdrawals to annual water supply for the YR basin and eight sub-basins at the end of the 21st century under the five different SSPs. The annual water supply was estimated with an RHWA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

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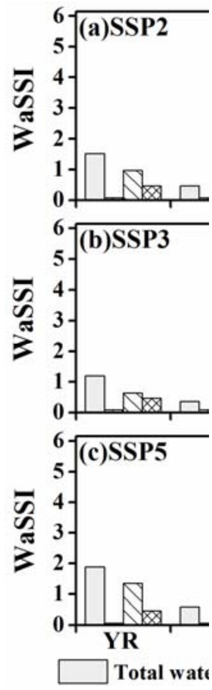

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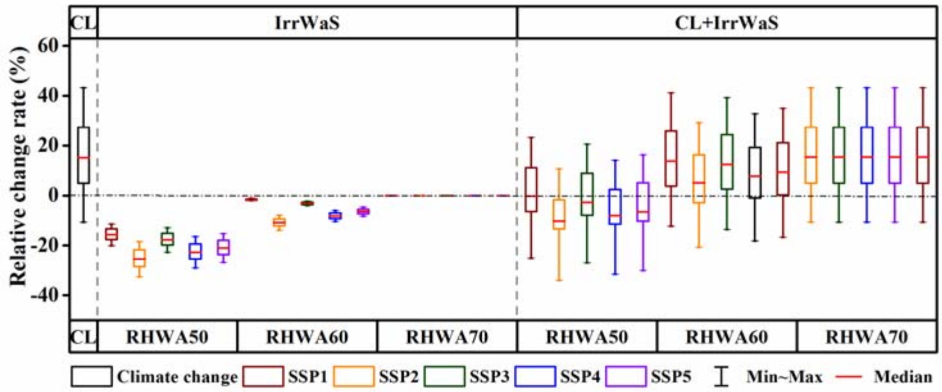
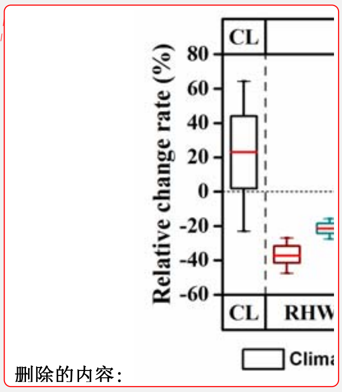


Figure 7 Comparison of relative change of agriculture production with only climate impact (CL), only irrigation water scarcity impact (IrrWaS), and combined climate and irrigation water scarcity impact (CL+ IrrWaS) in the YR basin in the 2050s (%).



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2035, but industry is the dominant water use sector during the period 2036-

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demand accounts for less than 13%, and

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The domestic water demand is projected to change from 3 billion m^3 yr^{-1} in 1995 to 2.8, 3.6, and 2.3 billion m^3 yr^{-1} in 2084 under SSP2, SSP3 and SSP5, respectively. The industrial water demand is projected to increase from 4.6 billion m^3 yr^{-1} in 1995 to about 35, 23, and 50 billion m^3 yr^{-1} in 2084 under SSP2, SSP3 and SSP5, respectively.

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during the 21st century. The rate of industrial water demand is about 4.3, 2.4 and 6.2 billion m^3 per ten years.

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demand is also projected to increase, and the domestic water demand is

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during

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Domestic water consumption data of Yellow River Basin	Yellow River basin; 1997, 1999-2013	China Water Resources Bulletin (1997, 1999-2013)
Manufacture water consumption data of Yellow River Basin	Yellow River basin; 1997, 1999-2013	

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Estimated sectoral (domestic, industrial and irrigation) and total water demand in sub-basins in the middle and lower reaches from 1995 to 2085 in million m^3 yr^{-1}.

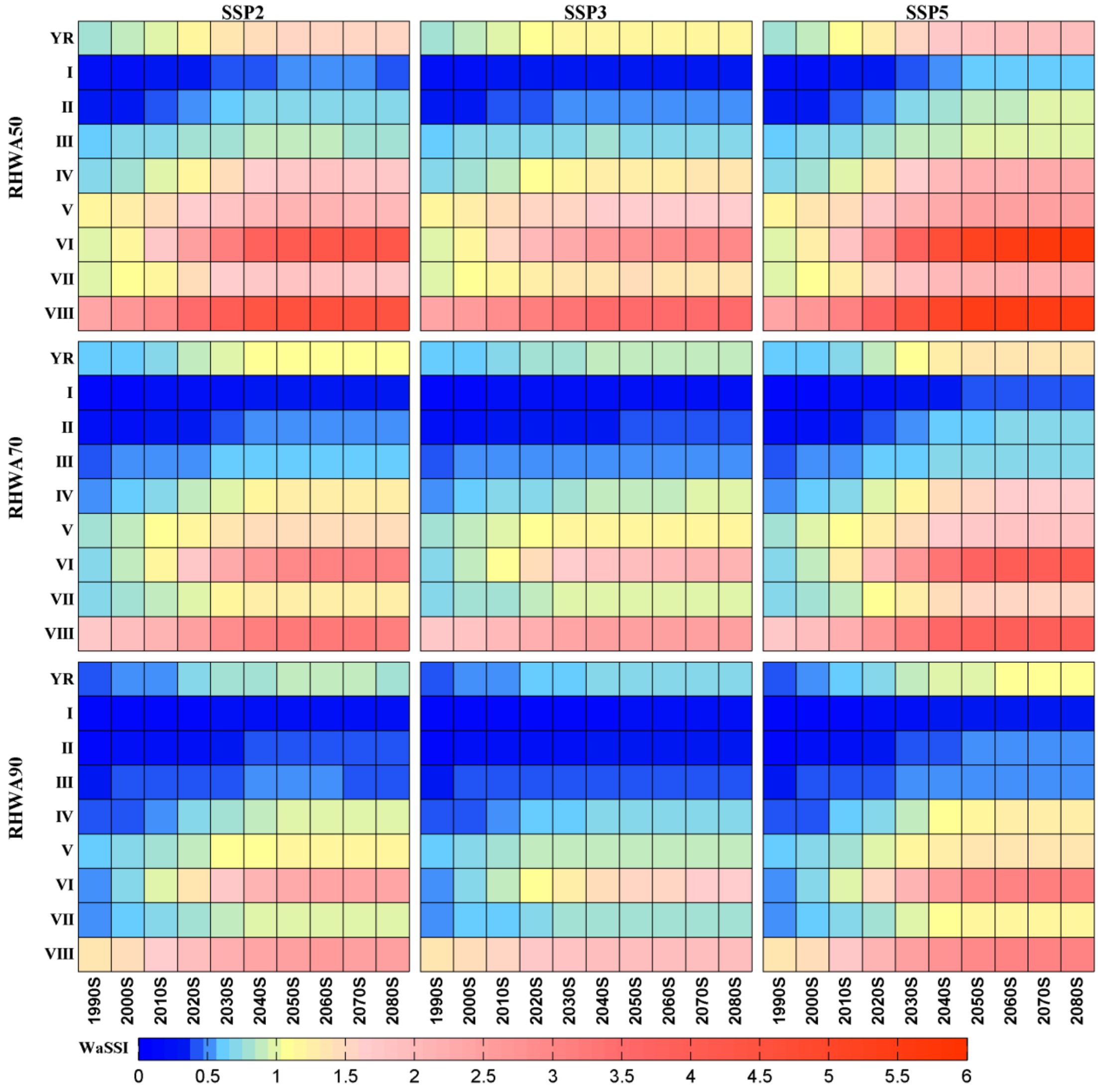

Figure 6

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ratios of human water appropriation (

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) and three different Shared Socio-Economic Pathways (SSPs).