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Study on the Response of Rice Yield and Water Consumption to Climate Change in the South China —A case study of the Nanliujiang Catchment

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Abstract. **Rice growth is very sensitive to climate factors such as precipitation, air temperature and carbon dioxide concentration. The change in the global climate has potential risks to rice production and agricultural irrigation in the South China. In this study, the SWAT model is used to analyse the changes of rice yield and water consumption in the Nanliujiang Catchment in Guangxi Province. A method of subbasin delineation is used for the model setup to reflect the differences between irrigation areas in yield and water use of rice，and the simulation values of rice yield, evapotranspiration and runoff are validated. Finally, the outputs of HadGEM2-ES under three RCPs (RCP2.6, RCP 4.5, RCP 8.5) are fed to the SWAT model to study the effects of future climate change on rice yield and water consumption in the Nanliujiang Catchment. The results showed that the SWAT model is an ideal tool to simulate rice growth and water consumption; the yield of irrigated rice under three RCPs decreased by 2.3%, 0.67% and 3.4%, respectively, and the yield of rain-fed rice decreased by 2.7%, 1.0% and 3.7%, respectively. Under the three RCPs, the production water consumption of irrigated rice is reduced by 4.5%, 4.6% and 6.9%, respectively, and that of rain-fed rice is reduced by 3.6%, 2.5% and 5.1%, respectively. This study can provide a scientific basis for the formulation of relevant policies to cope with future climate change in the study area.**

Keywords- climate change; rice production; water consumption; SWAT model; South China

I. Introduction

The global climate has undergone significant changes with global warming over the past decades. Agriculture, serving as the major sector of water utilization (accounting for over 70% of worldwide fresh water consumption), is extremely susceptible to climate changes [1]. With the rise of air temperature, crop evapotranspiration is enhanced, so the water consumption on agricultural irrigation is enlarged. Climate changes will impose pressures on water resources utilization, so as to affect the security of basin water resources and grain security in the future, which brings about major challenges to the stable social development [2]. Therefore, it is very essential to study the influences of climate changes on the grain production and irrigation water.

Crop production and water consumption is a complex botanical process considerably affected by climate factors, among which precipitation, air temperature and CO_2 concentration influence the crop growth most significantly [3]. As crops are very sensitive to the moisture supply, they will be subjected to water stress in case of precipitation reduction, accompanied by the decline of crop yield and increase of irrigation needs. Temperature controls the metabolic rate of crops and influences grain production [3-4]. The photosynthesis, respiratory rate and yield of crops will be elevated with the increase in the CO_2 concentration in the atmosphere. The photosynthetic efficiency of rice, a C3 type plant with low respiratory rate, is more sensitive to high-concentration CO_2 [5-6]. Nevertheless, the crop growth responds complicatedly to the interactions among CO_2 concentration in the atmosphere, air temperature and precipitation. Some studies show that the rice yield can be increased owing to the increasing CO_2 concentration, but high temperature can offset the stimulating effect of CO_2 on the photosynthesis of rice [7]. Hence, the changes in the rice yield under the future climate changes are full of uncertainties.

The South China is an important rice-producing area, while the rice production and irrigation are directly influenced by the climate changes. The grain production and water resource supply problems under the influence of climate changes must be appropriately handled. Hence, it is necessary to investigate the influences of climate changes on the rice production and water resources utilization in the South China. With the Nanliujiang Catchment in Guangxi Province taken for an example, the climate model GCM and distributed hydrological model SWAT were coupled in this study to construct the response models describing the rice production and water consumption in the basin under different climate scenarios in the future, which provided a scientific basis for the basin to formulate reasonable water resource management policies for coping with the future climate changes.

II. Study area

The Nanliujiang Catchment Locates in the southeast of Guangxi province, originates from Darong Mountain, Yulin City, and it is high in the northeast and low in the southwest, with the average slope gradient of 0.35‰ and drainage area of 9,565 km^2 (as shown in Figure 1) [8]. The cultivated area in this basin exceeds 266.67 thousand hectares, where over 70%

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is planted with double-cropping rice. Seated in the south subtropical monsoon climate zone, the Nanliujiang Catchment is featured by abundant precipitation. During 1957-2013, the annual average precipitation reached 16.5 billion m3 and the annual average runoff was 7.494 billion m^3 (above Changle Hydrological Station). But the annual distribution of precipitation in this area is quite nonuniform, the precipitation is mostly concentrated during April-September, and the precipitation in flood season accounts for about 83% of total annual precipitation. Therefore, agricultural irrigation plays an significant role in guaranteeing the normal rice growth and yield in the Nanliujiang Catchment. There are totally 18 irrigated areas in this area, with the effective irrigated area reaching about 1,793 thousand acres [9].

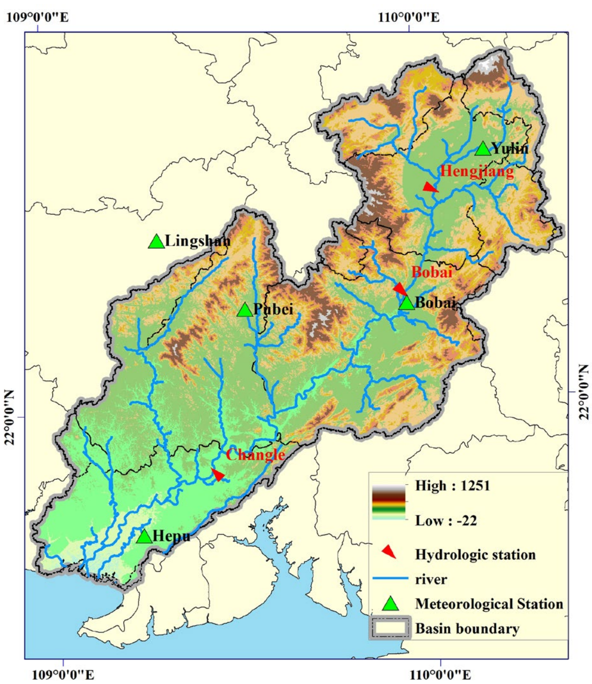


Figure 1. The location and topography of the study area

III.Materials and methods

A. Materials

The data required in this work include the following: spatial data, including DEM (90 m×90 m), land use map (1:100,000), soil distribution map (1:1,000,000), water system map; meteorological data, including daily precipitation, air temperature, wind velocity, solar radiation and relative humidity at four stations—Lingshan, Yulin, Qinzhou and Beihai; hydraulic engineering data, including the parametric data (e.g., dead storage capacity, utilizable capacity and total storage capacity) of 18 reservoirs as well as the monthly inflow and outflow data of three large reservoirs, which are Xiaojiang Reservoir, Wangshengjiang Reservoir and Hongchaojiang Reservoir; cultivated area and irrigated area in the Nanliujiang Catchment; monthly flow data of Hengjiang, Bobai and Changle Hydrological Stations. In addition, the SWAT modelling also involved the irrigation scheduling, irrigation water source, field husbandry and fertilizer application, etc., all of which were related to the crop management measures.

B.Methods

a. Superposed HRU Partitioning. In this study, a nested HRU partitioning method was adopted for the SWAT model [10-12]. The whole basin was divided into 268 natural sub-basins by superposing the irrigated areas. A total of 2,996 HRUs were partitioned by setting the thresholds of land use area, slope and soil area as 10%, 10% and 15%, respectively.

b. Calculation of Crop Water Consumption.

The water consumption in the crop production is calculated through the following formula:

$$WS = WSb + WSg \tag{1}$$

Where, WS is the water consumption of crops within unit area, m^3/ha; WSb represents the blue water consumption of the crop production, m3/ha; WSg stands for the green water consumption of the crop production, m^3/ha.

The green water consumption of the crop production is the minimum value between crop evapotranspiration and effective precipitation[13]

$$WSg = \min(ET,Pe) \tag{2}$$

Where, ET denotes the crop evapotranspiration within unit area during the growth period, m^3/ha; Pe is the effective precipitation within unit area (m^3/ha), with the following expression [14]:

$$Pe = P - RO - DP \tag{3}$$

Where, P is the precipitation within unit area, m^3/ha; RO refers to the runoff yield, m^3/ha; DP indicates the deep percolation within unit area, m^3/ha. All the three parameters could be obtained by the SWAT model simulation.

The blue water consumption of crops is calculated as below:

$$WSb = ET – WSg \tag{4}$$

Where, ET means the crop evapotranspiration within unit area during the growth period, m^3/ha.

c. Selection of Climate Model. Two factors are mainly considered in the selection of climate model: Firstly, the simulation effect of main meteorological parameters in the climate model should be favourable; secondly, the climate model should be of satisfying applicability in Asian regions [15]. In this study, the HadGEM2-ES model[16] showing good precipitation and temperature simulation effects is chosen, and three discharge scenarios (RCP2.6, RCP4.5 and RCP8.5) are taken into account. The precipitation and temperature data during 2000-2040 are selected and input into the SWAT model for simulating the crop production. 2000s (2000-2010) is taken as the benchmark period and 2030s (2030-2040) as the future level years. Meanwhile, the change in the CO_2 concentration is also considered. It is assumed that the CO_2 concentration is 370, 443, 487 and 540 ppm under the RCP2.6, RCP4.5 and RCP8.5 scenarios, respectively.

d. Parameters calibration. The correlation coefficient (R^2) and Nash-Sutcliffe efficiency factor (E_{ns}) are selected to evaluate the applicability of the SWAT model. The correlation coefficient shows how identical is the simulated and the measured value. When the value is close to 1, it means a better simulation result. The calculation formula is as follow:

$$R^2 = \frac{\left(\sum_{i=1}^{n}(Q_{sim,i} - \overline{Q_{sim}})(Q_{obs,i} - \overline{Q_{obs}})\right)^2}{\sum_{i=1}^{n}(Q_{sim,i} - \overline{Q_{sim}})^2 \sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2} \tag{5}$$

Where $\overline{Q_{sim}}$ is the average runoff; $\overline{Q_{obs}}$ is the measured average runoff; n is the number of observations.

The Nash efficiency coefficient indicates that the fitting of the measured value and the simulated value, allowing values vary from 0 to 1. When the value is close to 1, it means a better simulation result. The calculation formula is as follow:

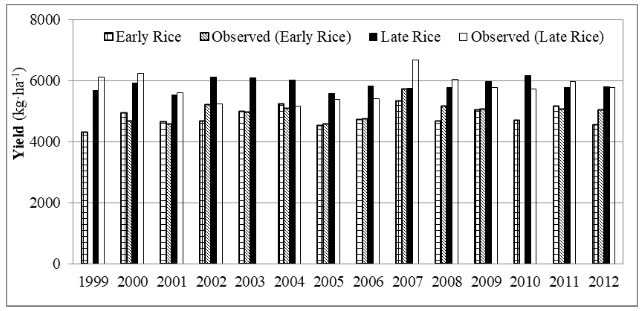
$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2} \tag{6}$$

The relevant studies show that when $R^2>0.6$, $E_{ns}>0.5$, the simulation will get the good effect.

IV.Results and Discussion

A.*Model validation*

a. Validation of Rice Yield. The validation was carried out using the measured rice yield data at Hepu Station. The yield simulation effect was assessed using root mean square error (RMSE) and mean relative error (MRE), as shown in Table 1. The calibration results showed an acceptable performance of the model with RMSE values from 0.24 ton to 0.56 ton and MRE values from 6.83% to 7.15%. Similarly, validation indicated an acceptable model performance with RMSE values from 0.29 ton to 0.49 ton and MRE values from 5.02% to 8.61%. Overall, the results showed that the SWAT model is an ideal tool to simulate rice development at Hepu Station, as shown in Figure 2.



Fgure 2. Comparison of simulated vs. observed rice yield in Hepu station.

Table 1. Model performance for the simulation of rice yield.

Crop Type	Calibration (1999-2006)		Validation(2007-2012)	
	RMSE/ton	*MRE*/%	*RMSE*/ton	*MRE*/%
Early Rice	0.24	7.15	0.29	8.61
Late Rice	0.56	6.83	0.49	5.02

b. Hydrological Validation. Changle Hydrological Station and Hepu Evaporation Gauging Station were taken as the representative stations in the Nanliujiang Catchment to validate the measured runoff and evapotranspiration data. It could be observed from Table 2 and Figure 3 that the simulation results of runoff and evapotranspiration fitted in well with the measured values. During the calibration period, both R^2 and E_{ns} were basically above 0.80 and both of them were above 0.70 during the validation period. Hence, the established SWAT model was applicable to the simulation of hydrology and crop yield in the Nanliujiang Catchment. The finally parameter values were showed in Table 3.

Table 2. Model performance for the simulation of runoff and evapotranspiration.

Type	R^2		E_{ns}	
	Calibration (2000–2005)	Validation (2006–2011)	Calibration (2000–2005)	Validation (2006–2011)
Runoff	0.89	0.78	0.82	0.73
Evapotranspiration	0.87	0.85	0.82	0.79

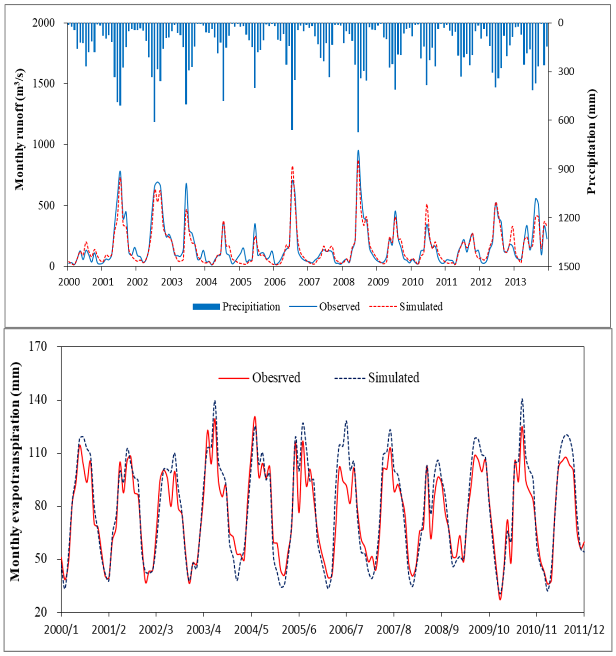


Figure 3. Results of monthly runoff and evapotranspiration form SWAT model.

Table 3. Results from the calibration of SWAT hydrological parameters.

Parameter	Initial Range		Calibrated Value
	min	max	
CN2	-0.3	0.3	0.591
SOL_AWC	-0.3	0.3	0.29
SOL_K	-0.3	0.3	0.15
ESCO	0.4	1.0	1.02
EPCO	0.1	1.0	0.785
GW_DELAY	30	450	317.0
ALPHA_BF	0	1	0.85
GWQMN	0	1500	1074.82
GW_REVAP	0.02	0.2	0.146
REVAPMN	0	500	616.85
RCHRG_DP	0	1	0.551
BIO_E	0	200	28.71
HVSTI	0	1	0.55

B. *Change Analysis of Rice Yield*

The results of average rice yields in the Nanliujiang Catchment under three discharge scenarios (RCP2.6, RCP4.5 and RCP8.5) were as shown in Figure 7. It could be seen that under the three discharge scenarios, the future rice yields always presented the declining trend to different degrees. This is because the normal photosynthesis of rice and dry matter accumulation process are affected by the temperature stress, and this negative impact offsets the positive influence brought by the elevation of CO_2 concentration. As a result, the rice yield did not increase due to the increasing CO_2 concentration, but instead, it was reduced because of temperature stress and shortening growth period. Under the RCP2.6 scenario, the average yield of irrigated rice in the Nanliujiang Catchment was reduced from 4,916 kg/ha in 2000s to 4,805 kg/ha in 2030s, by 2.3%, while the yield of rain-fed rice declined from 3,177 kg/ha to 3,091 kg/ha, by 2.7%; under the RCP4.5 scenario, the decrease amplitude of average rice yield was the minimum, the average yield of irrigated rice was 4,884 kg/ha, which was reduced only by 0.67% in comparison with that in 2000s, and the yield of rain-fed rice was 3,145 kg/ha, which was reduced by 1.0%; under the RCP8.5 scenario, the average yield of irrigated rice was 4,752 kg/ha, which was 3.4% lower than that in 2000s, and the average yield of rain-fed rice was 3,060 kg/ha, which was reduced by 3.7%.

The spatial distribution of rice yield is displayed in Figure 8. It could be seen that no matter in 2000s or 2030s, the average rice yield in the Nanliujiang Catchment kept high in the south and low in the north. Under the RCP2.6 scenario, Hepu and Hongchao irrigated areas in the south of Nanliujiang Catchment reached the highest rice yields, being above 4,800 ka/ha, which were reduced by 4.8%-6.0% in comparison to those in 2000s; the rice yield in the northern area was averagely 58 kg/ha lower than that in the southern irrigated area; under the RCP4.5 scenario, the rice yield was the highest among the three scenarios, because compared with the situation under the other scenarios, the precipitation was the highest and the climate was most appropriate under the RCP4.5 scenario. The rice yield in the southern area ranged from 4,887 to 5,013 kg/ha, being 2.5%-3.5% lower than that in 2000s; the rice yield in the northern area was averagely 74 kg/ha lower than that in the southern irrigated area; the rice yield under the RCP8.5 was the lowest among the three scenarios, because under this scenario, the precipitation was the lowest, the temperature rise amplitude was the maximum, and the temperature stress affected the photosynthesis of rice and reduced the rice yield. The rice yield in the southern area was 4,771-4,796 kg/ha, being 5.8%-6.7% lower than that in 2000s; the rice yield in the northern area was averagely 48 kg/ha lower than that in the southern irrigated area. The rain-fed rice producing areas were mainly distributed in the narrow and long strips of river valley among mountains and hills in the river basin, with rugged topography. The rice planting area was small, presenting sporadic distribution. Due to the lack of water conservancy facilities, rain-feeding was the dominant crop planting mode, and the crop yield was generally not higher than 4,000 kg/ha. It could be seen from the figure that the rain-fed rice yield in the Nanliujiang Catchment was 3,038-3,385 kg/ha, and the yield in the southern area was higher than that in the northern area; under the three discharge scenarios, the rain-fed rice yield also showed a declining trend.

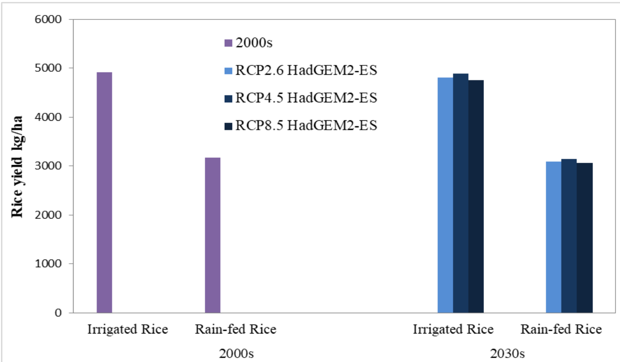


Figure 4. Rice yield with RE and climate change scenarios in 2030s.

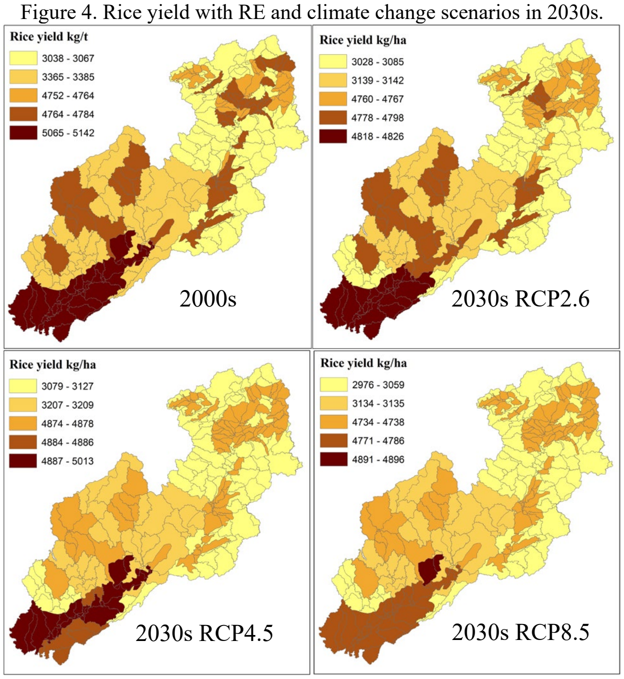


Figure 5. Spatial variations in rice yields under three RCPs in 2030s.

C. *Change Analysis of Rice Water Consumption*

Under the three discharge scenarios, the water consumption of the rice production presented a declining trend in 2030s, which was ascribed to the increasing crop evapotranspiration in the Nanliujiang Catchment in the future (Figure 6). Under the RCP2.6 scenario, the water consumption of irrigated rice production in the Nanliujiang Catchment declined from 3,475 m^3/ha in 2000s to 3,319 m^3/ha in 2030s, by 4.5% and the water consumption of rain-fed rice production was reduced by 3.6% from 2,803 m^3/ha to 2,701 m^3/ha; under the RCP4.5 scenario, the water consumption of irrigated rice production was the lowest, being 3,315 m^3/ha, which was reduced by 4.6% in comparison to that in 2000s, and the average water consumption of rain-fed rice yield was 2,734 m^3/ha with a reduction rate of 2.5%; under the RCP8.5 scenario, the water consumption of irrigated rice production was 3,234 m^3/ha, which was 6.9% lower than that in 2000s, and the average water consumption of rain-fed rice was 2,662 m^3/ha with a reduction rate of 5.1%.

The spatial variations of water consumption by the rice production in the Nanliujiang Catchment under the three discharge scenarios were shown in Figure 7. It could be seen that the water consumption of rice production was always high in the irrigated area and low in the non-irrigated area. The water consumption of rice production in the irrigated sub-basins was evidently higher than that in the non-irrigated sub-basins, because the mountainous area was planted with rain-fed rice, with relatively low production efficiency and quite low water consumption of rice production. The blue water consumption was high in the south and low in the north, which manifested its spatial distribution feature, because the precipitation and temperature were high in the southern area of this river basin. The needs of rice water consumption and irrigation were large, and the water consumption of rice production and blue water consumption were evidently higher than those in the north of the basin. For instance, under the RCP2.6 discharge scenario, the average water consumption of rice production in the northern irrigated area of Nanliujiang Catchment was 3,092 m^3/ha, and that in the southern irrigated area was 4,967 m^3/ha. At the scale of irrigated area, the water consumption of rice production in Hongchaojiang irrigated area was the highest, reaching 5,059 m^3/ha, 5,022 m^3/ha and 5,013 m^3/t under the RCP2.6, RCP4.5 and RCP8.5 scenarios, respectively. Under the RCP2.6 scenario, the water consumption of rice production in Laohukeng irrigated area was the lowest (3,343m^3/ha). Under the RCP4.5 and RCP8.5 scenarios, the water consumption of rice production in Maolin irrigated area was the lowest, being 3,480 m^3/ha and 3,608 m^3/ha, respectively.

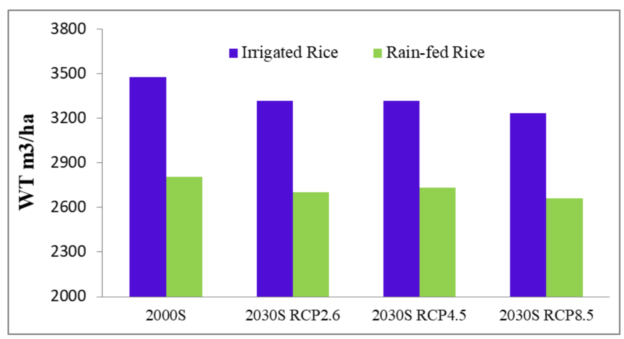
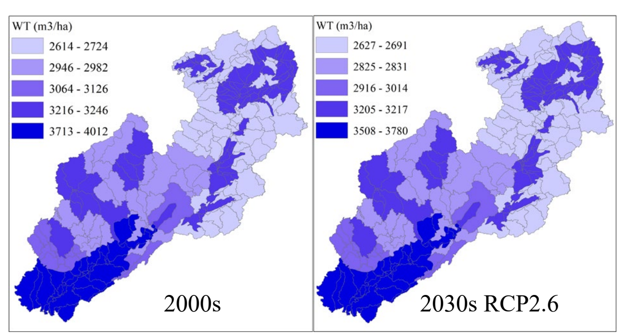


Figure 6. Water consumption of irrigated and rain-fed rice with RE and climate change scenarios in 2030s.



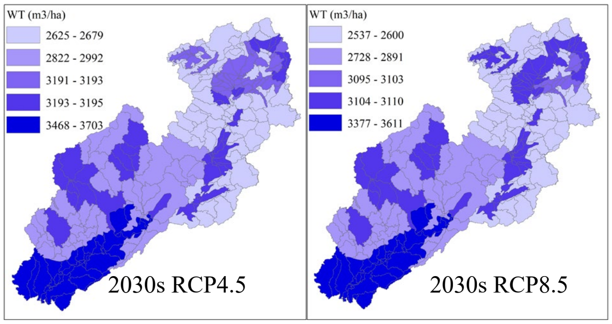


Figure 7. Spatial variations of water consumption of irrigated and rain-fed rice under three RCPs in 2030s.

V.Conclusion

In this study, the HadGEM2-ES model applicable to the related studies of climate changes in Asian region was selected. The SWAT model was used to study the response of rice yield and water consumption to climate Change in the Nanliujiang Catchment under the RCP2.6, 4.5 and 8.5 scenarios. The results showed that the yield and water consumption of both irrigated rice and rain-fed rice in the Nanliujiang Catchment declined to different degrees in 2030s under the 3 scenarios. Under the RCP2.6 scenario, the average yield of irrigated rice was 4,805 kg/ha in 2030s, being 2.3% lower than that in 2000s, and the average yield of rain-fed rice was 3,177 kg/ha with a reduction rate of 2.7%; under the RCP4.5 scenario, the average yield of irrigated rice was 4,884 kg/ha in 2030s, which was reduced by 0.67% in comparison to that in 2000s, and the average yield of rain-fed rice was 3,145 kg/ha, with a reduction rate of 1.0%; under the RCP8.5 scenario, the average yield of irrigated rice in 2030s was 4,752 kg/ha, which was 3.4% lower than that in 2000s, and the average yield of rain-fed rice was 3,060 kg/ha, with a reduction rate of 3.7%. Accordingly, under the three scenarios, the water consumption of irrigated rice production was reduced by 4.5% (156.0 m^3/ha), 4.6% (159.2 m^3/ha) and 6.9% (241.1 m^3/ha), respectively, and that of rain-fed rice was reduced by 3.6% (102.5 m^3/ha), 2.5% (69.8 m^3/ha) and 5.1% (141.7m^3/ha), respectively.

Acknowledgments

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Conflicts of Interest: The authors declare no conflict of interest.

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