Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of mekong river delta

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--Manuscript Draft--

Manuscript Number:	RECYCL-D-20-02055R1
Article Type:	VSI:Food-Energy-Water Nexus
Keywords:	FEW nexus; impact analysis; climate change; socio-economic development; Mekong River Delta
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Abstract:	Food, energy, and water (FEW) resources are critical concerns to achieve long-term sustainability. Climate change and socio-economic development both affect the FEW Nexus, but the combined impacts of these two factors on a Nexus system is not well understood. An integrated management model was applied to quantify the combined impacts on the FEW Nexus through rice yield, power generation, and water withdrawal. Five scenarios from the Coupled Model Intercomparison Project Phase 6 were chosen as the inputs of the integrated model in the Mekong River Delta (MRD). Results showed that rice yields will be vulnerable to extreme climate events. The minimum autumn rice yield, 4.7 ton/ha in 2023 under the SSP1-2.6 scenario, will be as low as the yield of the 2016 drought year (4.6 ton/ha). Power generation will increase sharply due to socio-economic development. The power generation of SSP5-8.5 in 2050 will be about 10 times higher than that in 2010. The average total water withdrawal in 2050 was estimated to increase by 40% compared to that in the 2016 drought year and will be more than 3 times higher than the average withdrawal of 1995-2010. Nexus analysis found water is a central resource that connects food and energy sectors in MRD. Regional sustainability analysis showed that climate change and socio-economic development both have a significant impact through affecting the FEW Nexus. Specifically, the energy and water sectors will be more vulnerable to the combined impacts than the food sector due to the coal-fired power plants planned in the MRD.

Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of Mekong River Delta

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Highlights

- Rice yield will be vulnerable to climate change and socio-economic development
- Energy plan could trigger conflicts with food sector due to high water demand
- There are strong relationships in the food-water and energy-water Nexus in MRD
- Water plays a central role in the FEW Nexus in MRD
- Climate change and socio-economic development both affect regional sustainability

Author's Response to Peer Review of

Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of Mekong River Delta

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We appreciate the efforts that have been made by the Editor and Management Team in finding reviewers under such a difficult time. We thank the Editor and Reviewers for their insightful and helpful comments on our paper. We believe that their detailed reviews have helped to improve the quality of our submission, especially its communication of our method and validation process. The table below lists the peer review comments in the left column and our responses in the right column.

Comments from Peer Reviewer 5	**Authors' Response**
line 13: please be specific about what you mean by "combined impacts".	Thank you for this suggestion. We revised the sentence as: *"Climate change and socio-economic development both affect the FEW Nexus, but the combined impacts of these two factors on a Nexus system is not well understood."* Please see line 12-14 in the revised draft.
line 22-26: these conclusions/implications are very general and can be applied to almost any case. What are the specific implications to the MRD?	Thanks for this suggestion. We revised the last sentence of the abstract as: *"Specifically, the energy and water sectors will be more vulnerable to the combined impacts than the food sector due to the coal-fired power plants planned in the MRD."* to highlight the specific finding in the MRD. Please see line 24-26 in the revised draft.
Section 2: It is better to discuss any broader implications of your study on areas/cases beyond the MRD.	This is a good suggestion. We added a sentence at the end of Section 2. *"Although the MRD was focused on this research, the comprehensive understanding could contribute to identifying sensitive resource sectors and supporting policy assessment and planning under the impact of*

	climate change and socio-economic development in regions that face similar issues." Please see line 107-110 in the revised draft.
Figure 2 can be a good reference in the Appendix, but is too busy and too complex for the main text here. Suggest to replace with a conceptual diagram that shows the subsystems, key components within each subsystem, and key connections between subsystems.	Thanks for this comment. We moved Figure 2 to Appendix A as Figure S1, and detailed model information is also provided in the Appendix. As suggested, we updated Figure 2 with key components and connections between the subsystem and added an explanation of the general model structure to help the readers get a clear picture of the model. Please see updated Figure 2 and line 132-146 in the revised manuscript.
Figures are not clear in PDF. Please make sure high resolution in the revision.	Thanks for this suggestion. We updated the figures with higher resolution following the requirements of the Journal's Author Guide.
You like to use "while" in a simple sentence (non-compound sentence). Technically it is fine. But there are better words to express the same meaning in a simple sentence (e.g., nevertheless, however or simply removing depending on the context). "While" is common in compound sentences.	Thanks for this comment. We deleted/replaced "while" with alternatives in the revised manuscript.

Comments from Peer Reviewer 9	**Authors' Response**
The largest issue of this paper is the model is a blackbox to reviewers and readers. It is hard to understand how the model is formulated, therefore it is difficult to understand the validity and applicability of the results. The authors did provide references of their previous paper related to the model. But you cannot expect the reviewers and readers are able to synthesize these references in a meaningful way relevant to this study. It is better to provide a concise but sufficient description of the model beyond just want are inputs and what are outputs. What are important to understand the model include mechanisms driving variable changes, interaction mechanisms, and key assumptions, among others.	Thanks for this comment, and we do agree with it. We added further model descriptions in terms of variables, equations, mechanisms, interactions among sectors, and assumptions in Appendix A due to the Journal's word limitation. Additionally, Figure 2 was moved to the appendix as Figure S1 with key variables of each sector bolded to help the readers get a clear picture of the model. Figure 2 in the main text was updated with a conceptual diagram as suggested by another reviewer. Please see Figure S1 and the information provided in the related section in Appendix A.
Related to this, the sensitivity and uncertainty of the modeling need to be analyzed and presented. Currently there is no discussion on these critical topics.	Thanks for this suggestion. We add an example of extreme condition tests as well as model sensitivity analysis to improve

	confidence in model performance in Appendix A. Please see the second section of Appendix A.

Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of Mekong River Delta

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Abstract:

Food, energy, and water (FEW) resources are critical concerns to achieve long-term sustainability. Climate change and socio-economic development both affect the FEW Nexus, but the combined impacts of these two factors on a Nexus system is not well understood. An integrated management model was applied to quantify the combined impacts on the FEW Nexus through rice yield, power generation, and water withdrawal. Five scenarios from the Coupled Model Intercomparison Project Phase 6 were chosen as the inputs of the integrated model in the Mekong River Delta (MRD). Results showed that rice yields will be vulnerable to extreme climate events. The minimum autumn rice yield, 4.7 ton/ha in 2023 under the SSP1-2.6 scenario, will be as low as the yield of the 2016 drought year (4.6 ton/ha). Power generation will increase sharply due to socio-economic development. The power generation of SSP5-8.5 in 2050 will be about 10 times higher than that in 2010. The average total water withdrawal in 2050 was estimated to increase by 40% compared to that in the 2016 drought year and will be more than 3 times higher than the average withdrawal of 1995-2010. Nexus analysis found water is a central resource that connects food and energy sectors in MRD. Regional sustainability analysis showed that climate change and socio-economic development both have a significant impact through affecting the FEW Nexus. Specifically, the energy and water sectors will be more vulnerable to the combined impacts than the food sector due to the coal-fired power plants planned in the MRD.

Keywords: FEW Nexus; impact analysis; climate change; socio-economic development; Mekong River Delta

1. Introduction

Food, energy, and water (FEW) resources are critical concerns to achieve the United Nations 2030 Sustainable Development Goals (SDGs, Liu et al., 2017a). Achieving food, energy, and water security is under increasing pressure owing to climate change as well as socio-economic development. Food demand is projected to increase by 50% from 2015 to 2050 due to population growth, urbanization, and personal income increases (FAO, 2017). Additionally, energy demand is projected with a factor of 1.7-2.8 increase above current uses by 2050 due to socio-economic developments (Van Ruijven et al., 2019). On top of that, climate change makes water become a growing constraint for food production and energy generation. An additional 120 million people are projected to be at risk of undernourishment as a result of climate change (FAO, 2017). Drought reduced hydro- and thermal-power generation by 5.2% and 3.8% compared to the long-term average during 1981-2010 at a global scale (Van Vliet et al., 2016). Therefore, understanding the impacts of both climate change and socio-economic development through food, energy, and water resources is not only important for the SDG2 (zero hunger), SDG6 (clean water and sanitation), and SDG7 (affordable and clean energy) but also critical for the other SDGs which are closely linked to these three resources (Liu et al., 2020).

The nexus approach, which "integrates management and governance across sectors and scales" was first introduced in the Bonn 2011Conference and was recognized as an effective approach to achieving sustainable management of food, energy, and water resources (Hoff, 2011). Thus, there is an increasing number of Nexus research since 2011(Zhang et al., 2020). Great progress has been made in understanding the interaction among food, energy, and water systems, which laid a solid foundation for the theoretical research and practical process of sustainable development (Leck et al., 2015; Endo et al., 2017; Galaitsi et al., 2018; Van Vuuren et al., 2019). The research content has moved from the single and the interaction of two sectors to the Nexus approach (Endo et al., 2017). Research questions have shifted from how the change of a single sector affects the other two sectors to the impact of multiple sector changes on the Nexus (Tashtoush and Shah, 2019). Further, an increasing number of researchers adopt quantitative methods instead of qualitative analysis (Albrecht et al., 2018).

However, there is still insufficient understanding of the FEW Nexus especially a comprehensive understanding of the impacts of both climate change and socio-economic development (Liu et al., 2017b). On the one hand, climate change poses severe impacts on the FEW Nexus through altering crop yields, changing hydro-power potential and cooling water usage, and affecting the hydrological cycle due to the changing temperature and precipitation at both spatial and temporal scales (Howells et al., 2013; Conway et al., 2015; Mpandeli et al., 2018). On the other hand, FEW Nexus such as resource demand and consumption are affected by the socio-economic development through the population and economic growth, technological improvement, land-use changes, and resources management (Lawford et al. 2013; OFID, 2017; Velasco-muñoz et al., 2019). The understanding of the combined impact of climate change and socio-economic development through FEW Nexus is still limited (Evers and Pathirana, 2018) due to the difficulties to develop scenarios considering both climate change and socio-economic development in the future and to quantify the interconnections of food, energy, and water systems.

In this research, an integrated water resources management model (Wang et al., 2019) was adopted to simulate the regional rice production, power generation, and water demands under various scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6) that consider both climate change and socio-economic pathways. The various model results were further used to quantify the overall impacts on regional sustainability through the FEW Nexus.

2. Study Area

The Mekong River Delta (in Vietnam) is located downstream of the Mekong River Basin (Figure 1) with an area of 40,500 km^2 and is the home of 17.8 million people in 2018 (MDP, 2020; GSO, 2020). As the “rice bowl” of the nation, the delta is critical for the national food security with more than 56% rice production of Vietnam in 2015 (GSO, 2016), and thus plays a key role in Southeast Asia and global context through food trade (MDP, 2020). The delta has two seasons, which are the dry season from November to April and the wet season from May to October. The annual average rainfall is about 1400-2200 mm, and the average monthly flow is from 6.1 km^3 to 69.2 km^3 (Tuu et al., 2019). Hydropower is not the energy source of MRD (Yoshida et al., 2020; World Bank Group, 2014), and the delta is planned as a thermal power center with 14 new coal-fired plants by 2030 due to the nation’s high growth power demand, which increased more than 10% per year during 1990-2010 (Kyushu Electric Power, 2015).

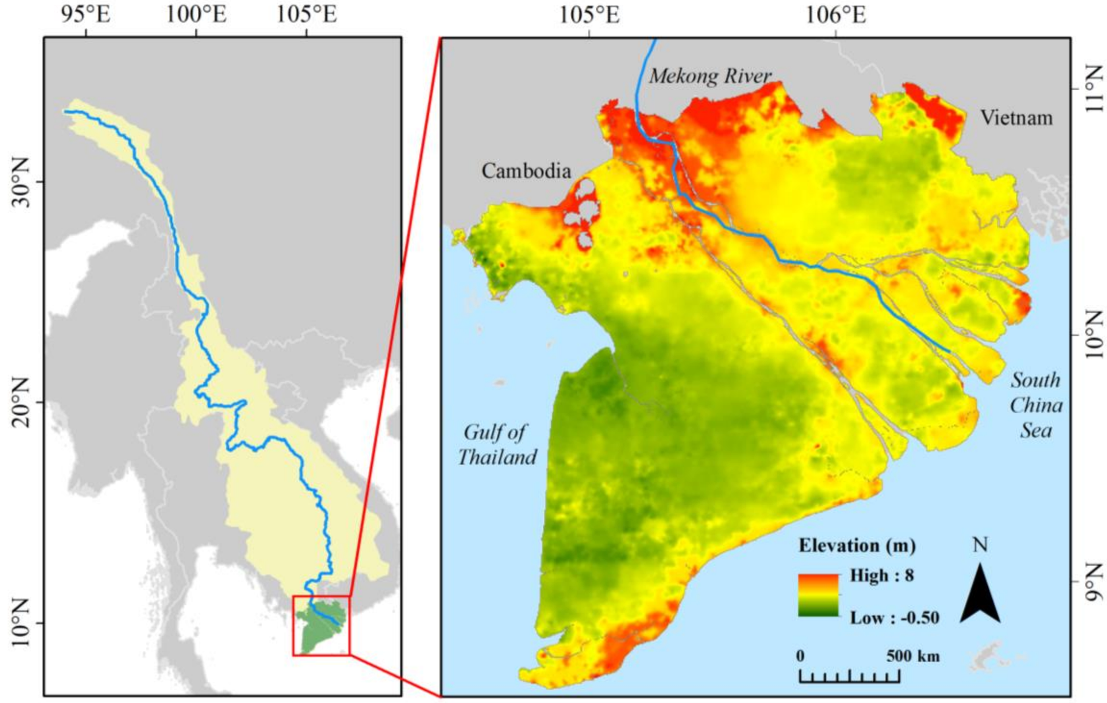

Figure 1. The Mekong River Delta

The delta is facing growing challenges due to climate change and socio-economic development. The annual rainfall has experienced a 30% increase and the average temperature increased by 0.5°C in the past 30 years (MDP, 2020). Climate change is projected to increase the average temperature by 1.1~3.6°C, and the maximum and minimum monthly flow are projected to increase and decrease, respectively (MDP, 2020). This will result in a high risk of flood during the wet season and water shortages during the dry season. Further, new planned thermal plants are expected to cause adverse impacts on the environment and intensify water conflicts among various water-use sectors (Kyushu Electric Power, 2015). Thus, a comprehensive understanding of the impacts of climate change and socio-economic development through the FEW Nexus is extremely important to achieve regional resource security and long-term sustainability (MDP, 2020). Although the MRD was focused on this research, the comprehensive understanding could contribute to identifying sensitive resource sectors and supporting policy assessment and planning under the impact of climate change and socio-economic development in regions that face similar issues.

3. Method

3.1. An IWRM-based Model

An integrated management model was used in this research to quantify climate change and socio-economic development impacts through the FEW Nexus. The model was developed using system dynamics (SD) methodology to capture the interactions among the disparate but interconnected subsystem at an annual scale, as SD is useful for integrating physical processes, socio-economic, and environmental systems to support integrated resources management (Davies and Simonovic, 2011). SD has been widely used to improve understanding of complex system behaviours by identifying their root causes, and assess the effectiveness of alternative policies through scenario building, sensitivity analysis, and gaming approaches (Savic et al., 2016; Wang and Davies, 2018).

The model was developed for Integrated Water Resources Management (IWRM) and includes main water use sectors: agricultural, municipal, industrial, environmental, and recreational water uses, as well as the water supply (Wang et al., 2019). These sectors are connected through water allocations and various land, water, and technical management policies. The model simulates water balance including water demands, allocation, and consumption, and further generates socio-economic and environmental indicators for sustainability assessment at the basin scale.

This research adopted the agricultural, industrial, water use, and supply sectors to quantify the changes of FEW Nexus under various climate change and socio-economic scenarios (Figure 2). Rice accounts for about 80% of surface irrigation withdrawal and is recognized as a major driving factor of water competition in the MRD (Nhan et al., 2007). Coal-fired power will be the main energy source, which will take over 50% of power capacity (Kyushu Electric Power, 2015). Therefore, the agricultural and industrial sectors simulate rice yield and thermal power generation, and water withdrawal is thus used for irrigation and cooling purposes. The water sector connects food and energy sectors through water allocation based on available water each year, and competition between food and energy sectors happens when their demands cannot be fully satisfied. Various RCP-SSP scenarios were set to drive the changes of rice planting area, thermal power demand, available water for allocation, and climate variables such as precipitation. These changes further affect irrigation and cooling water requirements, rice yield, and power generation. Detailed information of each sector including equations, mechanisms, interactions, and assumptions is provided in Appendix A. Please also refer to Wang et al. (2019) and Wang and Davies (2015) for a further description of the IWRM-based model structures.

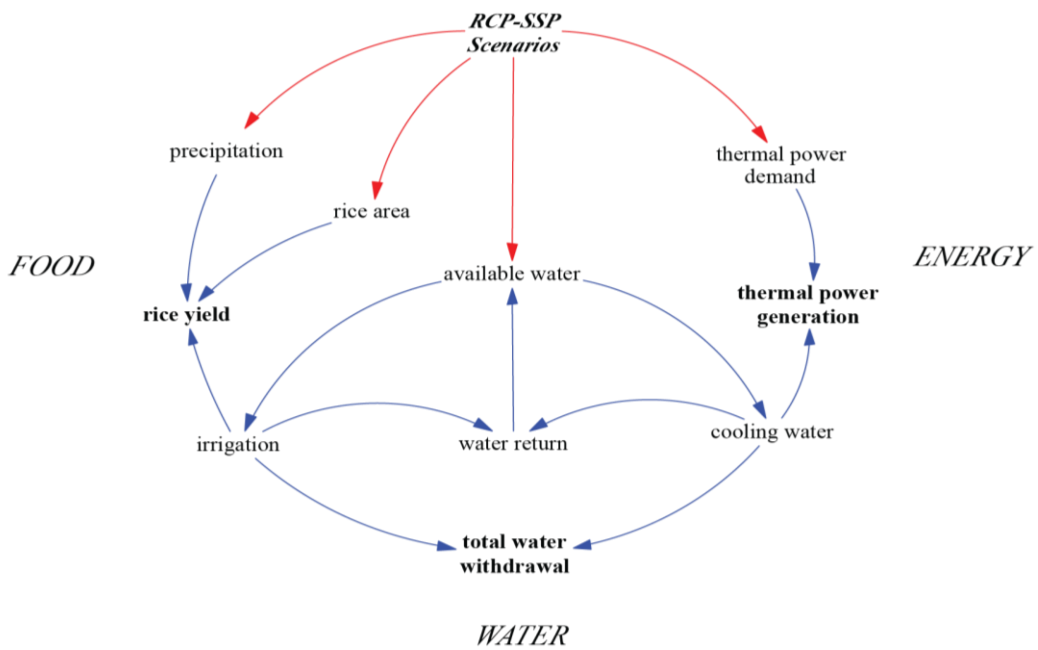

Figure 2. The conceptual structure of the integrated water management model used for MRD with bolded key variables and scenarios impact in red arrows.

3.2. Data Sources

The integrated management model was adapted to the Mekong River Delta using the following data sources. Crop parameters were from Nhan et al. (2007) and Arthi et al. (2018), and the rice yields and area data were from GSO (2020). Socio-economic data such as population and GDP were from Riahi et al. (2017) and GSO (2020). Hydrology and climate data were from the Mekong River Commission (MRC, 2020) and CMIP6 (O'Neill et al., 2016). Water-use data were estimated based on Huang et al. (2018). Energy demand and water efficiency were initialized based on Kyushu Electric Power (2015) and Nguyen et al. (2018).

3.3. Sustainability Index

The simulated results were adopted to evaluate the sustainability of the five scenarios under the context of climate change and socio-economic development. According to Kulat et al. (2019), the sustainability index (SI) of each scenario was calculated based on the resources index (RI) and weighting factors (*Wf*), see Equation (1). Therefore, scenarios can be compared according to the index values, which means a higher index represents more sustainable conditions. Each scenario has three resources index which was normalized by using the output of this scenario divided by the maximum output of all scenarios for a variable such as power demand and water withdrawal (Equation 2). The resource index for food was calculated using Equation (3) as a higher yield represents more sustainability. The weighting factor was used to reveal the importance of the resources to scenario sustainability.

$$SI = 1 - \sum RI \times Wf \qquad (1)$$

$$RI = \begin{cases} \dfrac{Output}{max(Output)} & (2) \\ 1 - \dfrac{Output}{\max(Output)} & (3) \end{cases}$$

3.4. Scenario Setup

This study adopted SSP-RCP (SSP: Shared Socioeconomic Pathway, RCP: Representative Concentration Pathway) scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6), whereby, SSP described socio-economic futures and RCP described climate futures. The integration of climate and socio-economic futures allows CIMIP6 scenarios to be used to explore the future conditions of the FEW Nexus comprehensively (O'Neill et al., 2016).

According to levels of socio-economic challenges for mitigation and adaptation, five SSPs are defined for IPCC Sixth Assessment Report (AR6), from the most sustainable SSP1 (low levels of challenges for both mitigation and adaptation) to the most fossil-fueled SSP5 (high levels of challenges for both mitigation and adaptation). RCPs are labeled after the projected radiative forcing values in 2100 induced by greenhouse gas emissions in the years to come. For example, RCP2.6 represents the projected 2.6 W/m^2 radiative forcing in the year 2100. To quantify the concurrent effects of socio-economy and climate, the future scenario setting in this study comprises five representative SSP-RCP combinations. Specifically, SSP5-8.5 represents the case of future pathways with high emissions of greenhouse gas and a high challenge to mitigation and adaptation. SSP4-6.0 is in the range of medium forcing pathways with a high challenge to adaptation, and SSP3-7.0 represents medium-high future mitigation and forcing pathway. SSP2-4.5, the middle of the road, combines intermediate challenges for mitigation and forcing signal. Finally, SSP1-2.6 is the case with low societal vulnerability and forcing level.

To reduce projection uncertainties, ensemble modelling results of future precipitation and temperature were used as inputs of the integrated management model. The modelling results were simulated by five Earth System Models (ESMs) under CMIP6 experimental protocol (Pincus et al., 2016), including CESM2, GFDL-ESM4, GISS-E2-G, HadGEM3, and MIROC.

Additionally, future trends of national GDP and population from the five scenarios were used to drive the changes in power demand and rice planting area, respectively. Next, simulation results were normalized to calculate the resources index (*RI*) and further multiplied by weighting factors (*Wf*) to obtain the sustainability index (*SI*) of the five scenarios. Four types of weighting factors (Table 1), which represent the importance of the resources to regional sustainability, were used to enable ranking the five scenarios concerning the priority for food, energy, and water resources as well as all equal conditions. Note that, values set for weighting factors in Table 1 were used to show examples of different resource importance and enable ranking the scenarios, and actual weighting factors can be determined by stakeholders' view.

Table 1. Weighting factors for food, energy, and water resources

	Food-first	Energy-first	Water-first	All Equal
Food	0.50	0.25	0.25	1/3
Energy	0.25	0.50	0.25	1/3
Water	0.25	0.25	0.50	1/3

4. Results and Discussion

4.1. Model Validation

Modified to the Mekong River Delta, the model was tested under several extreme conditions to ensure it generated reasonable results even with extreme model parameters. Further, a sensitivity analysis was also used to investigate model responsiveness to important uncertainties of model equations and parameters to improve confidence in model performance. Examples of extreme condition texts and sensitivity analysis are provided in Appendix A.

Key model outputs such as rice yields, water withdrawal, and power generation were compared with historical data and trends for the Mekong River Delta in Figure 3 to ensure the model could replicate historical behaviour. The coefficient of determination (R^2) and normalized root mean square error (NRMSE) were used to evaluate the magnitude of variance explained by the model compared with the total observed variance, and the percentage of differences (between simulated and observed values) in the mean actual value. In general, the model outputs explained most of the actual data with acceptable errors, see Figure 3a and Figure 3c. Note that, the simulated rice irrigation withdrawal was compared with the total irrigation withdrawal, including rice and other crops, as the actual irrigation withdrawal for rice was not available. As a result, the simulated withdrawal for rice had the same trends of regional total withdrawal for most of the years (Figure 3b). The difference between the trends of rice and total withdrawal could due to regional crop pattern changes. For example, rice withdrawal in 1998 decreased due to more precipitation than in 1997, and the total irrigation increased because of the expansion of many water-intensive crops such as cotton, sugarcane, soya, and fruit (GSO, 2020).

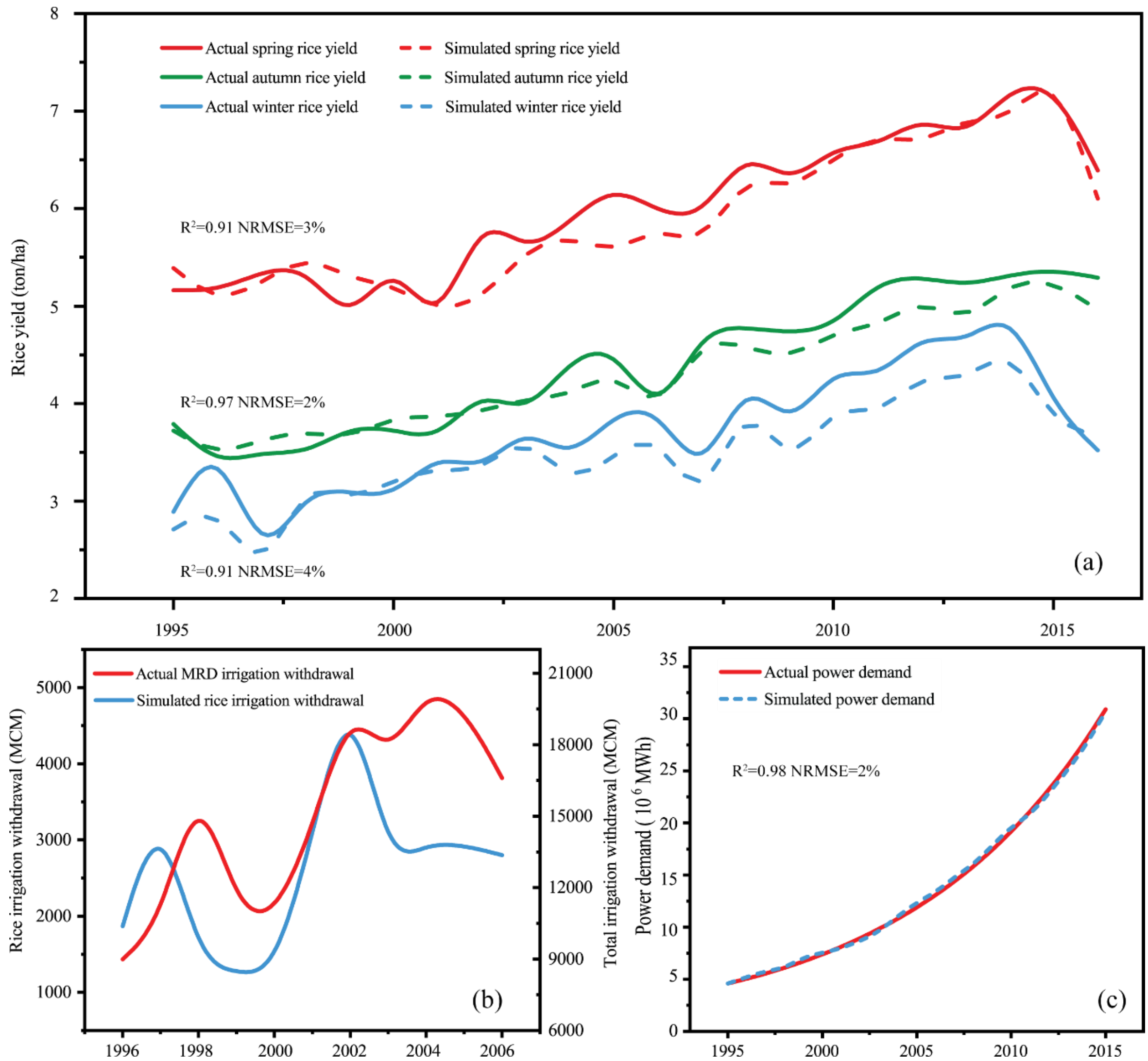

Figure 3. Model simulation and observed data

4.2. Model Results

This section explores the impacts of climate change and socio-economic development through the FEW Nexus system. The five SSP-RCP scenarios represent a wide range of plausible climate and socio-economic conditions in the Mekong River Delta and were used to explore their impacts on the food, energy, water sectors, and FEW Nexus, see Figure 4-6. Further, SI of five climate and socio-economic scenarios under food-, energy-, and water-first as well as all equal conditions during 2020-2050 are shown in Table 2.

Figure 4 shows rice yield, power generation, and precipitation of five SSP-RCP scenarios from 2020 onwards. On the one hand, the increased yield trends of three rice types in all scenarios were due to the technical improvement, whose impacts were assumed based on the historical data. To maintain the yield growth trend is a challenging task, and the Vietnam government recognizes technical improvement, especially biotechnology, as a decisive strategy to achieve long-term food security (Thang and Hoa, 2016). On the other hand, yields of all three rice types were vulnerable to future climate and socio-economic changes, and this finding agrees with the results found by Thuy and Anh (2015). Specifically, spring rice yields were projected to follow the historical growth trend with several low yields under SSP1-2.6 and SSP5-8.5 scenarios (Figure 4a). Future climate and socio-economic development will pose severe impacts on autumn rice yields with many extremely low yield events projected by all five scenarios. For example, the minimum yield, 4.7 ton/ha in SSP1-2.6 in 2023, is as low as the yield of the 2016 drought year, which was 4.6 ton/ha (Figure 4b). Finally, winter rice was projected to have many extreme yields, especially in the SSP4-6.0 scenario with a maximum value of 7.1 ton/ha and a minimum value of 4.4 ton/ha (Figure 4c). Note that, the increasing number of low yield events resulted from water shortage could also trigger conflicts with energy and other water use sectors during growing seasons. Thus, mitigation strategies for the Nexus instead of a single sector should be highlighted.

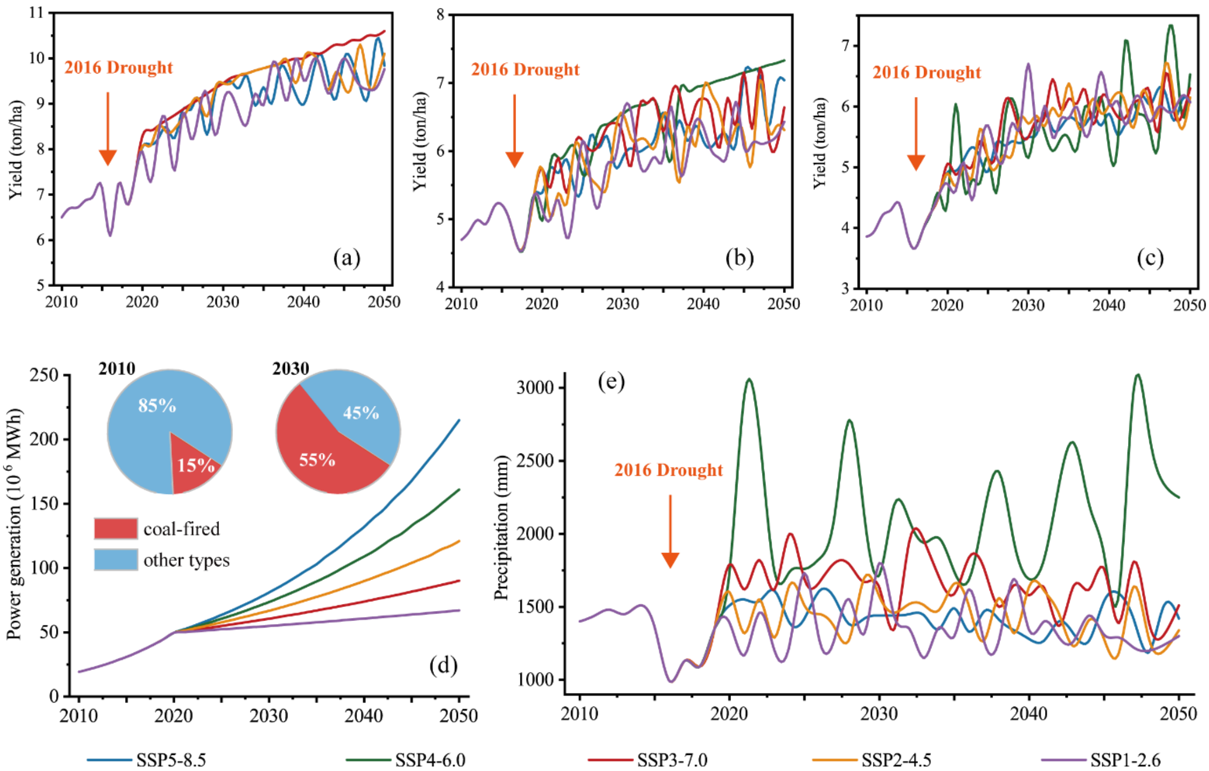

Figure 4. The yield of spring (a), autumn (b), and winter (c) rice, power generation (d), and precipitation (e) in different climate and socio-economic scenarios

Future power generations of five pathways are shown in Figure 4(d). SSP5-8.5 projected the highest power demand, 215 MWh in 2050 (about 10 times of the generation in 2010), as the SSP5 is a resource and energy-intensive scenario. SSP1-2.6 is oriented toward a low energy and resource consumption, and thus provided the lowest projection, which is about 2 times of the generation in 2010. Power generation of the other three scenarios fell between SSP1-2.6 and SSP5-8.5. The Electricity and Renewable Energy Authority in Vietnam estimated the national energy consumption will increase by about four times from 2017 to 2050 (EREA and DEA, 2019), which is in the middle range of the five scenarios in this research. Note that, the power generated by the coal-fired power plants will increase from 15% in 2010 to 55% in 2030 based on the national estimation of MDP (2020) and Kyushu Electric Power (2015), as MRD will be Vietnam's thermal power center and the coal-fired plant is favored by the national government. The growth of coal-fired power plant generation will inevitably increase water use for cooling purposes and intensify conflicts with irrigation use during growing seasons. Figure 4(e) shows the impacts of five scenarios on the precipitation during growing seasons. SSP1-2.6 projected a decreased trend with minimum precipitation of 1150 mm in 2033. The other four scenarios projected increased precipitation with several extreme wet years such as the SSP4-4.6 scenario. In general, future precipitation was estimated to increase, but more extreme high and low events were also projected. Therefore, the MRD was assessed to experience increasing flood risk in the wet season and water shortage during the dry season, which was also found by other research (Bong et al., 2018; MDP, 2020).

The total water withdrawal, as well as the rice irrigation and coal-fired power plant withdrawal, are shown in Figure 5. On the one hand, the growth of power generation and the ratio of the coal-fired plant (Figure 4d) will result in the increased trends of total water withdrawal (Figure 5a). The average value of total water withdrawal in 2050 (11412 MCM) will increase by 40% of the 2016 drought year withdrawal (8020 MCM) and will be more than 3 times higher than the average withdrawal (3225 MCM) during the 1995-2010 period. On the other hand, climate change will result in increased growing season precipitation, which might reduce the irrigation water demand in wet years and provided more available water to make the expansion of coal-fired plants available (Figure 5b). However, the high cooling water demand in dry years could also trigger conflicts between the food and energy sectors. The once-through cooling method was assumed for all existing and planned plants in the MRD in this research, and the water use efficiency (149 m^3/MWh) estimated according to Kyushu Electric Power (2015) is higher than the middle-level efficiency (138 m^3/MWh) of coal-fired plants adopting once-through method (Davies et al., 2013). Therefore, water-saving technologies such as air cooling and the use of non-surface water instead of the once-through method are suggested for the new thermal power plants to mitigate the impacts of climate change and socio-economic development on the Nexus system. However, the adoption of these technologies could be limited by high cost and the geographic availability to access to the water sources, which are the main trade-offs of the coal-fired power plants (Zhang et al., 2017).

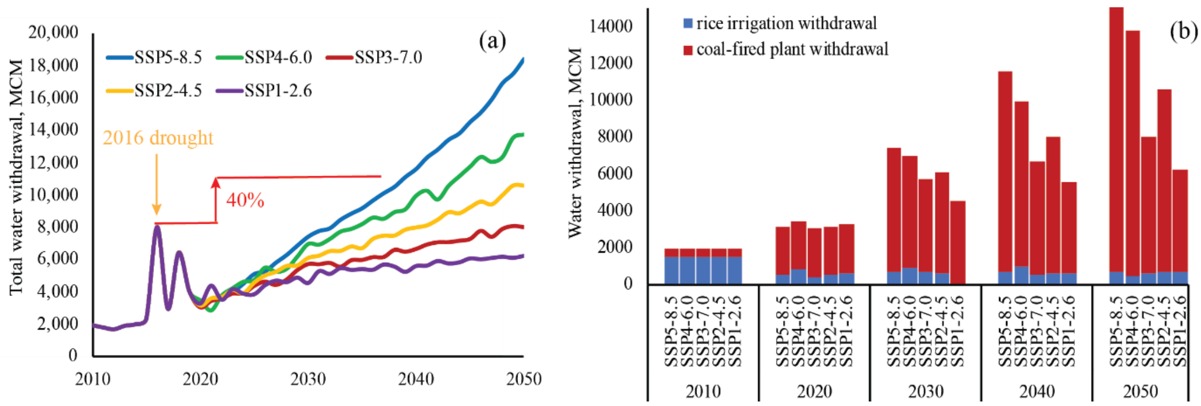

Figure 5. Water withdrawal of the MRD (a) and rice and coal-fired plant withdrawal (b)

Figure 6 shows the rice yield, coal-fired power generation, and water withdrawal (Figure 6a) as well as the trend lines between each of the two FEW resources (Figure 6b, c, d) under five climate change and socio-economic scenarios in the MRD. The clear trends in the three-dimensional relationship (Figure 6a) of the five scenarios revealed a strong connection among food, energy, and water systems in the MRD. Figure 6b demonstrates a clear linear trend between coal-fired power generation and water withdrawal under five scenarios. This trend represents that water is a constraint of the coal-fired power plants, and water withdrawal is also affected by the amount of power generated by coal-fired plants. Such a strong connection between the water and energy sector also implies the possible pressure on the local water system due to power plant development, which has already received quite a lot of concerns (MDP, 2020). When the withdrawal was lower than 8000 MCM, rice yield increased with water withdrawal (Figure 6c), which reveals that the rice cultivation in the MRD heavily relies on irrigation (MRC, 2018), and the rice yield is quite vulnerable to water availability (Figure

4). However, yield seldom increased when the water withdrawal was higher than 8000 MCM as the energy generation accounted for most of the water withdrawal especially under SSP5-8.5 and SSP4-6.0 scenarios (Figure 6b). The relationship between the food and energy sector is relatively weak. The linear trend shown in Figure 6d was due to the water availability which both increase rice yield and coal-fired plant generation. Therefore, water plays a key role in the FEW Nexus as it connects both the food and energy sectors in the MRD.

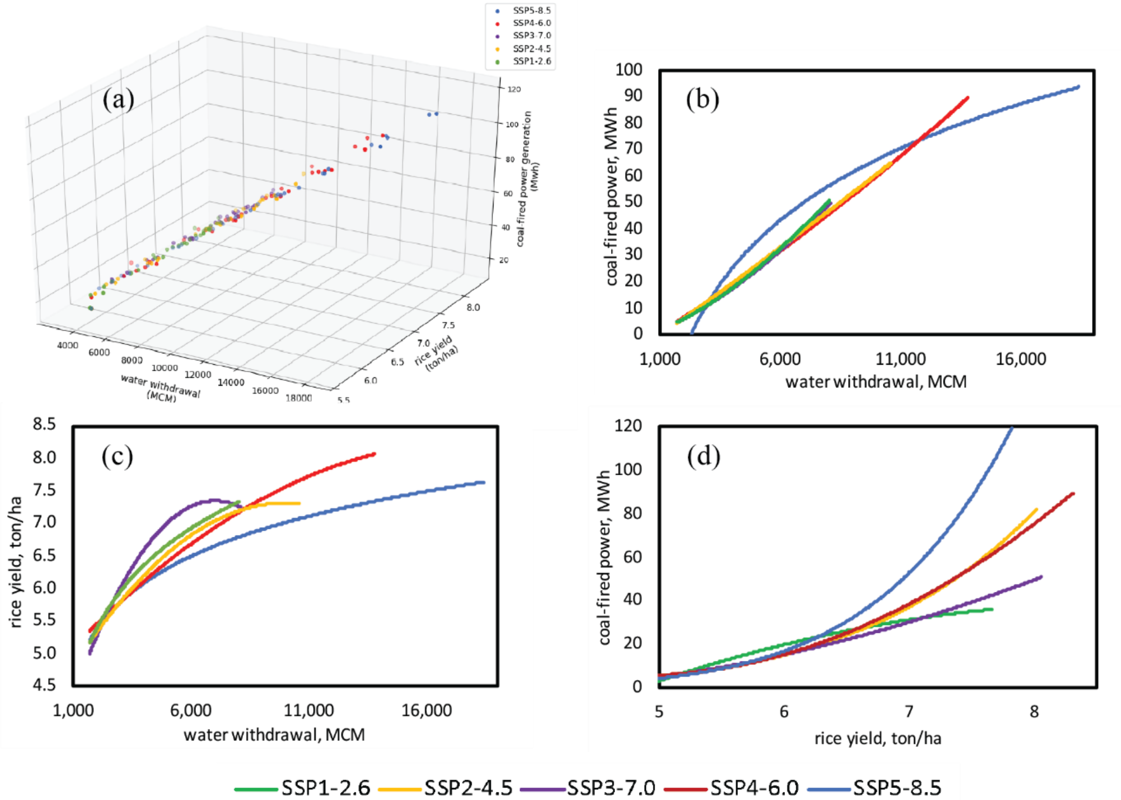

Figure 6. FEW nexus (a), food-energy (b), food-water (c), and energy-water (d) relationship in the MRD

Table 2 showcases the SI of five climate and socio-economic scenarios under food-, energy-, and water-first as well as all equal conditions during the 2020-2050 period. Note that: values in the brakes are absolute changes relative to the average SI of each condition. SSP1-2.6, which has a sustainable and low future forcing pathway, had the highest SI values under all conditions followed by SSP3-7.0. SSP5-8.5 had the lowest SI value due to its high consumption of water and energy resources. SSP4-6.0 and SSP2-4.5 scenarios were in the middle range of SI among five scenarios, and thus are commonly recognized as the “middle of the road”. In summary, the scenario ranking based on SI is clear, straightforward, and agrees with the categorizations of the SSP-RCP scenarios according to O’Neill et al. (2016). The SI changes under the following conditions revealed that climate change and socio-economic development both will affect regional sustainability through the Nexus system significantly. Specifically, the absolute changes in the food-first condition were lower than the other three conditions followed by the all-equal condition. The energy- and water-first conditions were quite similar and were the highest in terms of SI changes. Thus, the energy and water sectors will be more vulnerable to climate change and socio-economic development than the food sector, and the future resources management should more focus on the national energy plan and water availability in the MRD.

Table 2. Sustainability Index (absolute changes relative to mean SI) during 2020-2050

	Food-First	Energy-First	Water-first	All-equal
SSP5-8.5	0.48 (19%)	0.24 (41%)	0.24 (40%)	0.33 (31%)
SSP4-6.0	0.56 (6%)	0.34 (15%)	0.34 (15%)	0.42 (11%)
SSP3-7.0	0.65 (11%)	0.49 (22%)	0.49 (22%)	0.55 (17%)
SSP2-4.5	0.59 (1%)	0.42 (3%)	0.42 (3%)	0.48 (2%)
SSP1-2.6	0.66 (13%)	0.53 (31%)	0.53 (30%)	0.58 (23%)

5. Conclusions

Understanding the future conditions of the FEW Nexus is critical to achieving regional sustainability, especially for the MRD that experiencing high uncertainties in terms of socio-economic pathways and climate change. This research adopted an integrated management model to explore climate change and socio-economic development impacts through the FEW Nexus. Five scenarios of CMIP6 were adopted to quantify the impact on rice yield, energy generation, water withdrawal, and FEW Nexus. The outputs were further integrated to evaluate scenarios' sustainability under various conditions of resource importance.

Rice yields were estimated to increase if the technical improvement continues in the future, and the yields were vulnerable to climate changes due to the increasing extreme events such as floods and droughts. Power generation was projected to increase due to the growth of GDP and the population of all five scenarios. In 2050, the power generation of SSP5-8.5 will be about 10 times of the 2010's generation as the scenario is energy and resource-intensive. Water withdrawal will increase sharply, and the average value of the five scenarios in 2050 was estimated to increase by 40% of the 2016 drought year withdrawal and is more than 3 times higher than the average withdrawal during the 1995-2010 period. Climate change will increase the growing season precipitation and reduce the pressure of irrigation demand during wet years. This situation might make more water available for the increasing coal-fired plants' water withdrawal and make it possible to achieve the national energy plan. Therefore, water is the key resource to achieve sustainable management of regional resources. However, the increased coal-fired power plants could result in adverse impacts on the environment and water quality, which were not discussed in this research. There are strong relationships in the food-water and energy-water Nexus, and water was found as a central resource that connects food and energy sectors in the FEW Nexus in MRD. Further, climate change and socio-economic development both affect regional sustainability through Nexus significantly. SSP5-8.5 had a severe impact due to its high energy and water demand and low crop yield among the five scenarios. SSP1-2.6 and SSP3-7.0 had a relatively low impact with high sustainability index, and SSP2-4.5 and SSP4-6.0 were between the high and low impact levels.

A few suggestions were concluded based on the analysis. First, agricultural technology should be highlighted to maintain the growth of crop yield and achieve food security in the MRD. Agricultural techniques such as improved sowing method and short duration rice varieties played a key role in improving the rice yield in the MRD (FAO, 2000). However, future rice yield was found to be vulnerable to extreme climate events, and the rice planting area can be threatened by crop diversification, shrimp farming, and urban development (Bong et al., 2018). Thus, future rice cultivation should continue to rely on technologies to increase unit yield and reduce resources requirement and conflicts with other sectors. Second, cooling towers or non-surface water are suggested for the new coal-fired plant since these two methods withdraw and return less amount of surface clean water than the once-through method, and thus can mitigate potential water conflicts with agriculture and reduce the adverse impact on the environment, especially under the water shortage conditions. However, the adoption of these cooling methods would be expensive and time-consuming (Kablouti, 2015), and access to reclaimed or groundwater could also be limited by the geographic locations of the plant. Third, scenarios that consider both climate change and socio-economic development should be used in future resources management and planning as these two factors are deeply interlinked. Socio-economic activities are the main drivers of climate change which in turn affect future socio-economic development (Van Vuure et al., 2012). Finally, the framework developed in this research help to gain a comprehensive understanding of the climate and socio-economic impact on the regional sustainability through FEW Nexus and thus can be used in other river basins that face similar issues.

There were also limitations and assumptions adopted in this research. The impact of technology improvement on crop yield was assumed unchanged during the whole simulation as the national government has made several plans to maintain the yield growth trend such as Agriculture 4.0, which focuses on incentives and policies for agriculture R&D (MOET, 2017). Cooling water use efficiency was constant during the simulated period as changing of cooling method is expensive and time-consuming. Cooling water sources were assumed as surface water instead of seawater to explore the worst scenario impact on Nexus. The adoption of SI can only enable ranking among scenarios instead of comparison among different years. However, the integration of water, energy, and food resources using weighting factors provide a clear and comprehensive understanding of climate change and socio-economic development on regional sustainability. Thus, the results can be further used as an introductory phase to support policy prioritization for regional resources management and planning.

Acknowledgement

This study has been supported by the National Natural Science Foundation of China (grant no. 51711520317), the Strategic Priority Research Program of the Chinese Academy of Sciences (grant no. XDA20060402), the National Natural Science Foundation of China (grant no. 41625001), the Pengcheng Scholar Program of Shenzhen, the National High-level Talents Special Support Plan (“Ten Thousand Talents Plan”), and the Leading Innovative Talent Program for young and middle-aged scholars by the Ministry of Science and Technology. It was also partly supported by the State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control, and the High-level Special Funding of the Southern University of Science and Technology (Grant No. G02296302, G02296402).

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Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of Mekong River Delta

Appendix A

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Description of Model Structures

The structure of the modified IWRM-based model for MRD is shown in Figure S1. A detailed description of each sector in terms of key variables and equations, interactions, and assumptions are discussed below.

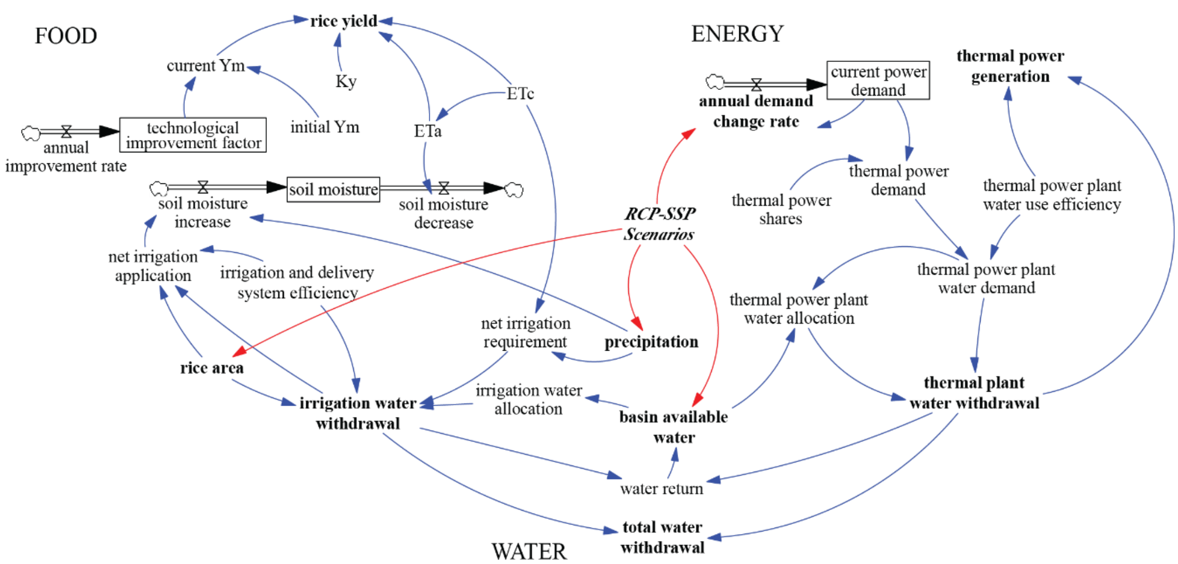

Figure S1. The modified basic structure of the integrated water management model used for MRD with bolded key variables and scenarios impact in red arrows.

The food sector simulates rice yield and irrigation water withdrawal. Rice yield is calculated based on Equation (1, Doorenbos and Kassam, 1979) which is adopted by several crop models such as CROPWAT (Steduto et al., 2012) and CliCrop (Fant et al., 2012). Soil moisture is the main factor that affects yield in this research, and it increases with irrigation and precipitation while decreases through actual evapotranspiration. Irrigation withdrawal is the minimum of irrigation water allocation and demand, which is determined from irrigation efficiency, net irrigation requirement, and rice area. Net irrigation requirement is the difference between potential evapotranspiration and precipitation, which is affected by RCP-SSP scenarios. Rice area is assumed to expand with the changing rate of population from RCP-SSP scenarios.

$$1 - \frac{Y_a}{Y_m} = ky(1 - \frac{ET_a}{ET_c}) \qquad \text{(S1)}$$

Where Y_a and Y_m are simulated and maximum yield, ET_a and ET_c are actual and potential evapotranspiration, *ky* is a crop-specific yield response factor.

The energy sector simulates thermal power generation based on water use efficiency and thermal plant water withdrawal, which is the minimum of plant water demand and allocation. Water demand for the thermal power plants is calculated based on water use efficiency and thermal power demand that is driven by total power demand and thermal power shares. The power demand increases over time represented by the "annual demand change rate", which is assumed to equal to the GDP change rate of RCP-SSP scenarios after 2020.

The water sector simulates total water withdrawal by integrating irrigation and thermal plant withdrawals. Further, basin available water, which is affected by RCP-SSP scenarios, is allocated to food and energy sectors based on their water demands. The water competition between food and energy sectors happens when their demands cannot be fully satisfied with available water.

Extreme-condition Tests and Sensitivity Analysis

Extreme-conditions tests evaluated model response to significant input changes. For example, future precipitation was set as only 50% of historical values as a low input to the model. As expected, irrigation withdrawal increased sharply from an average of 4000 MCM in 1995-2020 to 13000 MCM in 2020-2050. Further, a sensitivity analysis was also used to investigate model responsiveness to important uncertainties of model equations and parameters. For example, irrigation efficiency and thermal plant water use efficiency were varied both within a range of -20% to 20% from a base value of 0.6 and 150 respectively (Figure S2a and S2b). The total water withdrawal ranges resulted from these two test ranges are shown in Figure S2c and S2d with four confidence ranges from 50% to 100%, and reveal that the total water withdrawal is more sensitive to thermal plant water use efficiency than to irrigation efficiency. The reason is the future thermal plant water withdrawal will be much higher than the irrigation water withdrawal due to the 14 new coal-fired plants in the MRD.

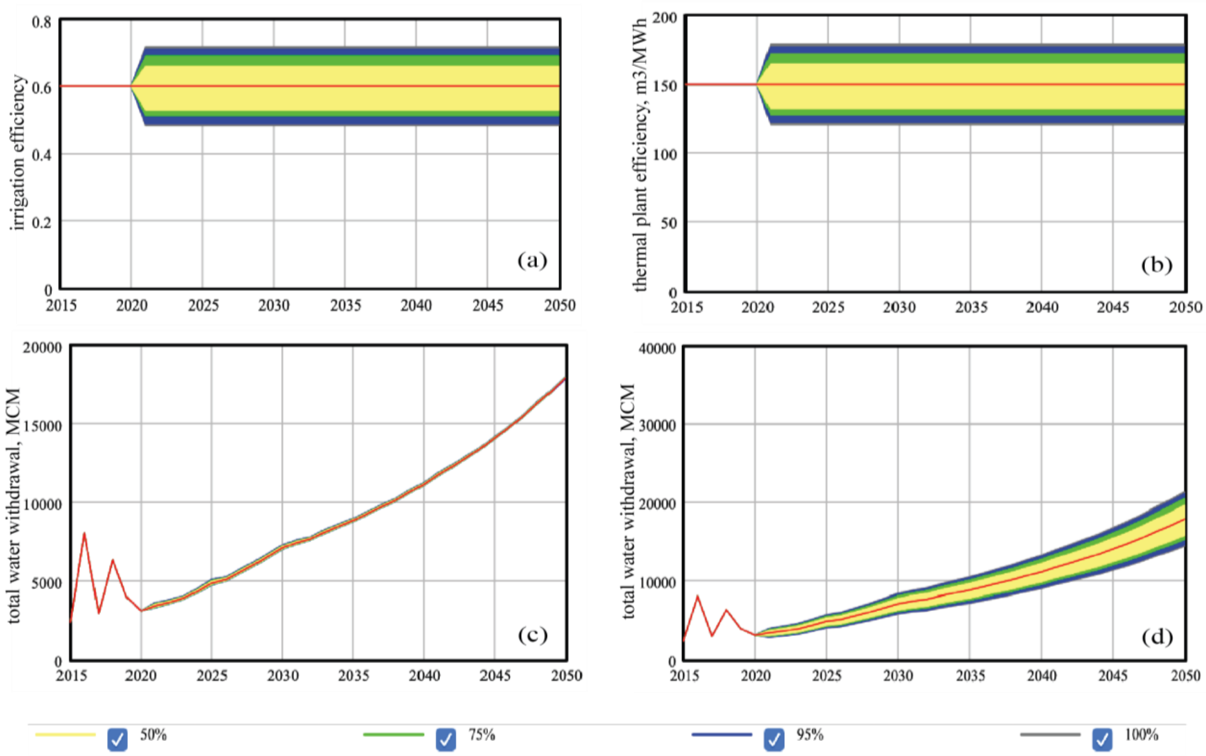

Figure S2. Model Sensitivity Analysis

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Kai Wang: Data collection; Modelling; Results analysis and investigation.

Junguo Liu: Supervision; Review and editing.

Jun Xia: Supervision; Review and editing.

Zifeng Wang: Data collection; Figure making.

Ying Meng: Figure making and editing.

He Chen: Data collection.

Ganquan Mao: Review and editing

Bin Ye: Review and editing

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: