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Assessing Climate-Driven Salinity Intrusion through Water Accounting: A Case Study in Ben Tre Province for More Sustainable Water Management Plans

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Abstract: This scientific paper delves into sustainable water management strategies for Ben Tre Province of the Vietnamese Mekong Delta (VMD) in light of water-infrastructure plans that have been impacted by climate change-induced salinity intrusion. Specifically, we aim to mitigate the effects of salinity intrusion for the province while promoting long-term environmental sustainability. In doing so, a water accounting framework was applied, mostly based on the MIKE11 hydrodynamic modeling and water balance calculations, to determine current and future water stress issues based on two main scenarios of extreme drought year 2016 (baseline) and the future year 2030 under climate change for a medium-low emission scenario (RCP4.5). The study found that salinity intrusion significantly causes severe water stress in the future year 2030 compared to the baseline year 2016, while the existing water management methods are relatively inadequate to control salinity intrusion, leading to over 57% of the area affected by medium to critical water stress levels, although it will go along with planned water infrastructures. Additionally, a system of triple rice cropping converted two rice cropping and upland cropping with 40% water demand cutoff was found to be the most suitable measure for 2030. Particularly, water-saving and water demand reduction should be incorporated into infrastructural planning for sustainable water management. Our study provides valuable insights for policymakers and stakeholders, not only for the province and the VMD, but also other regions facing similar challenges.

Keywords: Mekong; water stress; salinity; climate; sluice gates; sustainability

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1. Introduction

Climate resilience refers to the ability of a community or region to withstand and recover from the impacts of climate change [1,2]. This includes adapting to changes in temperature, precipitation, and sea level rise, as well as mitigating the causes of climate change. Sustainability, on the other hand, refers to the ability of a community or region to meet its present needs without compromising the ability of future generations to meet their own needs [3,4]. This includes balancing economic, social, and environmental factors in decision-making [5].

Salinity intrusion (SI) driven by climate change-induced sea-level rise is a global issue that affects many regions around the world, including coastal areas and river deltas [6–10]. The intrusion of saltwater into freshwater systems is caused by a range of factors, including sea-level rise, reduced freshwater flows, and human activities such as the development of water infrastructure [11–13]. SI can have significant impacts on freshwater resources, including reduced water quality, damage to crops and ecosystems, and threats to human health [13–15]. Therefore, there is a pressing need for sustainable water management strategies that can mitigate the impacts of SI while promoting sustainable development in affected areas [16,17]. This requires a collaborative effort between policymakers, researchers, and practitioners to identify effective approaches for managing freshwater resources, reducing water demand, and promoting sustainable agricultural practices. By adopting a comprehensive and integrated approach to water management, it is possible to ensure the long-term sustainability of freshwater resources in affected areas and promote the well-being of local communities [9,18].

The Vietnamese Mekong Delta (VMD) is currently experiencing SI, which is the infiltration of saltwater into freshwater sources due to rising sea levels and reduced freshwater flow from upstream [19]. This has significant impacts on the region's agriculture, economy, and social well-being. Located in the coastal VMD, Ben Tre Province has growing concerns about SI's impacts [20–22]. In the province, SI has resulted in decreased rice yields and damage to fruit trees, affecting the income and food security of local farmers [23–25]. Moreover, SI is also having significant impacts on the environment, including the loss of freshwater biodiversity and damage to agricultural ecosystems. For instance, SI was the worst in 2016 and 2020, and approximately 40,000 households lacked freshwater, and 57,000 ha of paddy, fruit trees, and vegetables were damaged in Ca Mau and Ben Tre Provinces [19]. Addressing the SI in Ben Tre Province within the VMD context is a critical issue that requires urgent attention from policymakers, researchers, and practitioners to develop effective strategies for managing freshwater resources and promoting sustainable development in affected areas to cope with environmental changes [2]. Sustainable water management is thus essential due to the increasing salinity intrusion and water infrastructure development in the region [24,26].

Several studies have identified the need for sustainable water management strategies that can mitigate the impacts of SI while promoting sustainable development in affected areas [22,27,28]. These studies highlight the importance of adopting an integrated and collaborative approach to water management that involves policymakers, researchers, and practitioners working together to develop effective strategies for managing freshwater resources, reducing water demand, and promoting sustainable agricultural practices. Additionally, the literature review highlights the need for further research to better understand the impacts of SI and water infrastructure development on freshwater resources and to identify effective strategies for mitigating these impacts [10,29,30]. Overall, the literature review underscores the importance of sustainable water management in Ben Tre Province and beyond the delta and the need for continued research and policy interventions to promote the long-term sustainability of freshwater resources in affected areas [24,25,31].

Our study aims to investigate appropriate measures for sustainable water management of the freshwater area of Ben Tre Province under the conditions of climate change and anthropogenic influences, including water infrastructures in 2020 and until 2030, based on the application of water accounting. In doing so, we applied a water accounting framework coupled with the water demand methods of the Food and Agriculture Organization of the United Nations (FAO) and a numerical modeling approach (MIKE11 model). This study sheds light on the need of seeking sustainable water management strategies for coastal provinces of the VMD in coping with the changes of climate and anthropogenic pressures to provide a lesson learnt for similar coastal regions worldwide.

2. Study Area

Ben Tre Province is located in coastal regions of the Vietnamese Mekong Delta (VMD) (see Figure 1), which is one of the five deltas most affected by climate change worldwide [32]. It covers an area of 2394 km^2 and comprises nine administrative units, including Ben Tre city and eight districts, with a population of more than 1.2 million in 2020 [33]. The province is characterized by flat and low-lying ground, with a typical range from 0.5 m to 1.5 m, which accounts for about 70% of the natural area, combined with a dense river network [34]. The surface water source is served by four main tributaries of the Tien River, including Co Chien, Dai, Ba Lai, and Ham Luong Rivers. The fresh surface water flowing in these rivers and the dense canal network maintain the stability of three dominant crop patterns in Ben Tre Province, including paddy, orchard, and aquaculture.

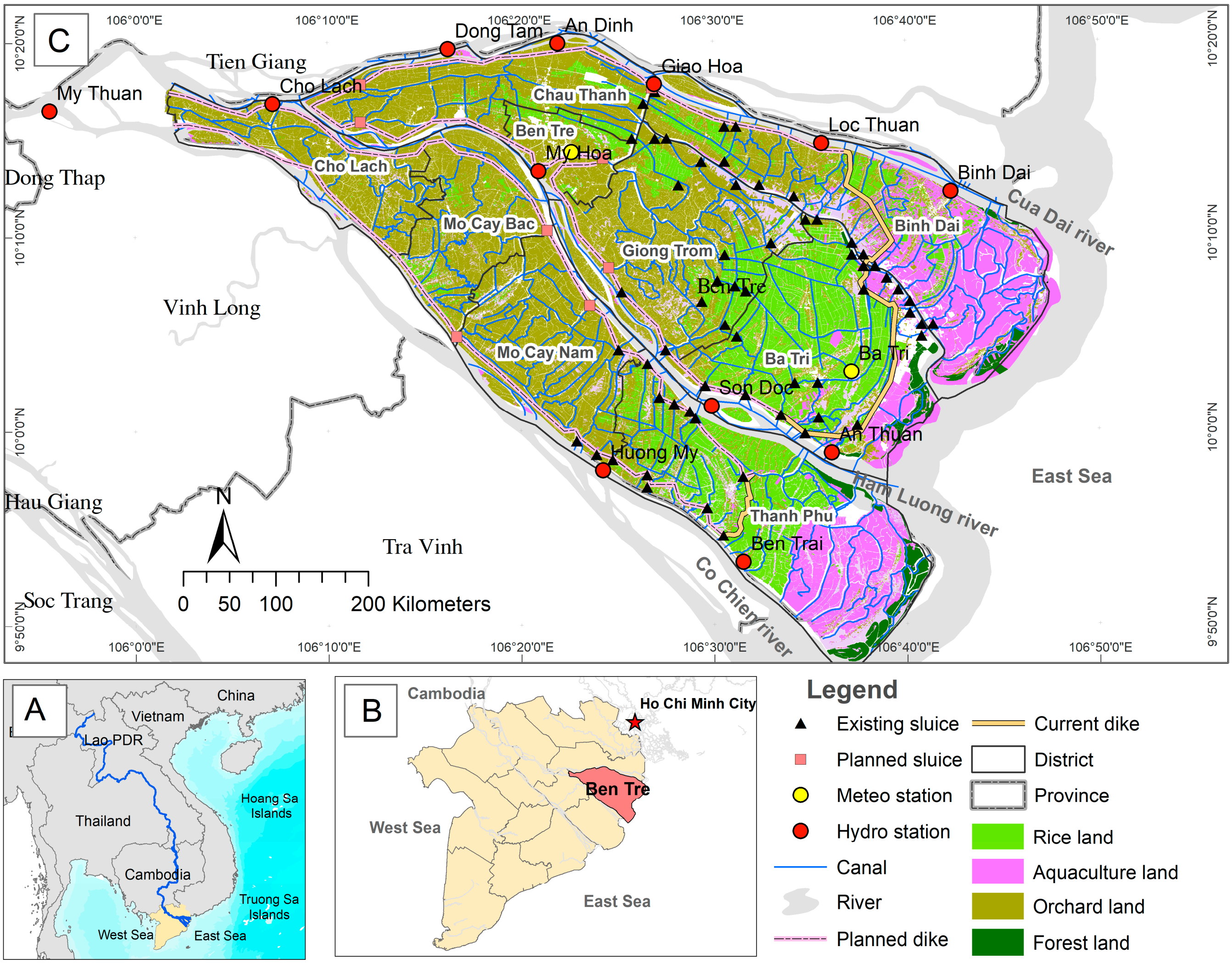

Figure 1. Vietnamese Mekong Delta (VMD) in Mekong River Basin (**A**), Ben Tre Province in the VMD (**B**), and hydro-meteorological stations, land use, and water infrastructure as sluice gates within the river network of Ben Tre Province (**C**).

Ben Tre Province was severely affected by the most severe droughts and saline intrusions over the last three decades in the VMD in 2016 and 2020 [26,35]. In these years, farmers faced damages caused by salinity intrusion impacts since intrusions were further inland and remained longer than usual. It was reported that about 40,000 households lacked freshwater, and 57,000 ha of paddy, fruit trees, and vegetables were damaged across the province. The increase in salinity intrusion in the VMD is mainly from anthropogenic activities, such as upstream hydropower dams, sand mining, land subsidence, water demand increases, and climate change impacts which have caused significant changes in the hydrologic regime [36–38]. Salinity intrusion has threatened the sustainable water management of Ben Tre Province [8].

Existing water management in Ben Tre is dominated by numerous water infrastructure systems that maintain and develop agricultural production. However, several systems have not been completely enclosed, causing severe drought and saline damage in agriculture.

To deal with these issues, farmers have implemented measures such as water storage in ponds, floating reservoirs in the field, or using plastic bags to store water for the orchard. For example, Kenh Lap water reservoir was built from an existing canal to store more than 800,000 m^3 and supply water for 20,000 people in Ba Tri district [39].

3. Data Availability and Methodology

3.1. Data Availability

To address the study's objective and research questions, three types of data were collected. The first type is ground-measured data that focuses on hydro-meteorology and agricultural water demand. The second type is open-source data of population distribution, which was used to calculate spatial household water demand. The third type includes other data types such as land use, cropping calendars, data from statistical books, and climate change that were used to set up a hydrodynamic model.

(i) Ground-measure data

We collected the data of nineteen stations, including four meteorological stations that measured rainfall, humidity, air temperature, and sunshine, twelve hydrological stations that measured water level and/or salinity concentration, and three stations that measured rainfall only. The location of each station is presented in Figure 1, and detailed characteristics of the stations are presented in Table A1 in the Appendix A. All stations are managed by the Southern Regional Hydro-meteorological Center of Vietnam.

(ii) Open-source data

To calculate household water demand spatially, the population distribution map was retrieved from WorldPop Hub (www.worldpop.org, accessed on 10 October 2022). The map was created based on the UN population data in 2015 and has a grid format with a resolution of 100 m. To adjust the population distribution map extracted from the WorldPop Hub, statistical population data in 2020 were retrieved from the Vietnam national census, which is called the Ben Tre Provincial Statistical Book 2020 [40].

(iii) Other data types

The Department of Agriculture and Rural Development (DARD) and Department of Natural Resources and Environment of Ben Tre Province have provided the land use map and attributes, while the cropping patterns were updated from annual reports of the DARD.

Overall, four types of land uses dominate in Ben Tre, namely orchards, rice cultivation, brackish aquaculture, and upland crops covering five key cropping patterns (see Figure A1 in the Appendix A). First, triple paddy rice crops (20,350 ha) are cultivated in the middle and low parts of the province, except for the coast. Each crop requires about four growing months, starting with the Winter–Spring season (WS), the Summer–Autumn season (SA), and ending with the Autumn–Winter season (AW). Second, double paddy rice crops are combined with fresh aquaculture (35,077 ha) in the dry season using water storage in the wet season [34]. The third is one paddy crop and one brackish aquaculture, in which the rice crop takes place at the end of the wet season, and the brackish crop starts at the end of the rainy season, as found in the lower Thanh Phu and Binh Dai districts. The fourth cropping pattern is brackish aquaculture that is cultured only outside the dike and in the coastal regions of Binh Dai, Ba Tri, and Thanh Phu districts [41]. Finally, orchards, as the largest area (101,344 ha), including coconut and fruit trees, are popularly grown throughout the year in upstream areas of Ben Tre Province.

3.2. Methodology

3.2.1. Overall Methods

This study applied a flexible water accounting framework that considers both water quantity and water quality (saltwater concentration) to assess the availability of water resources compared to the water demands of various users (agriculture, domestic, and environment) under current and future climatic conditions. The concept of pixel water balances was used (with a resolution or pixel size of 1 ha) to make more sense of water sources, needs, and consumption over time and space (Figure 2A). Water inflow in a pixel element includes surface water sources and precipitation, while water losses comprise water demand for agriculture, households, and ecosystems. Surface freshwater resources for each pixel element were determined by eliminating water containing salinity concentrations exceeding 2 g/L to define the total renewable freshwater resources.

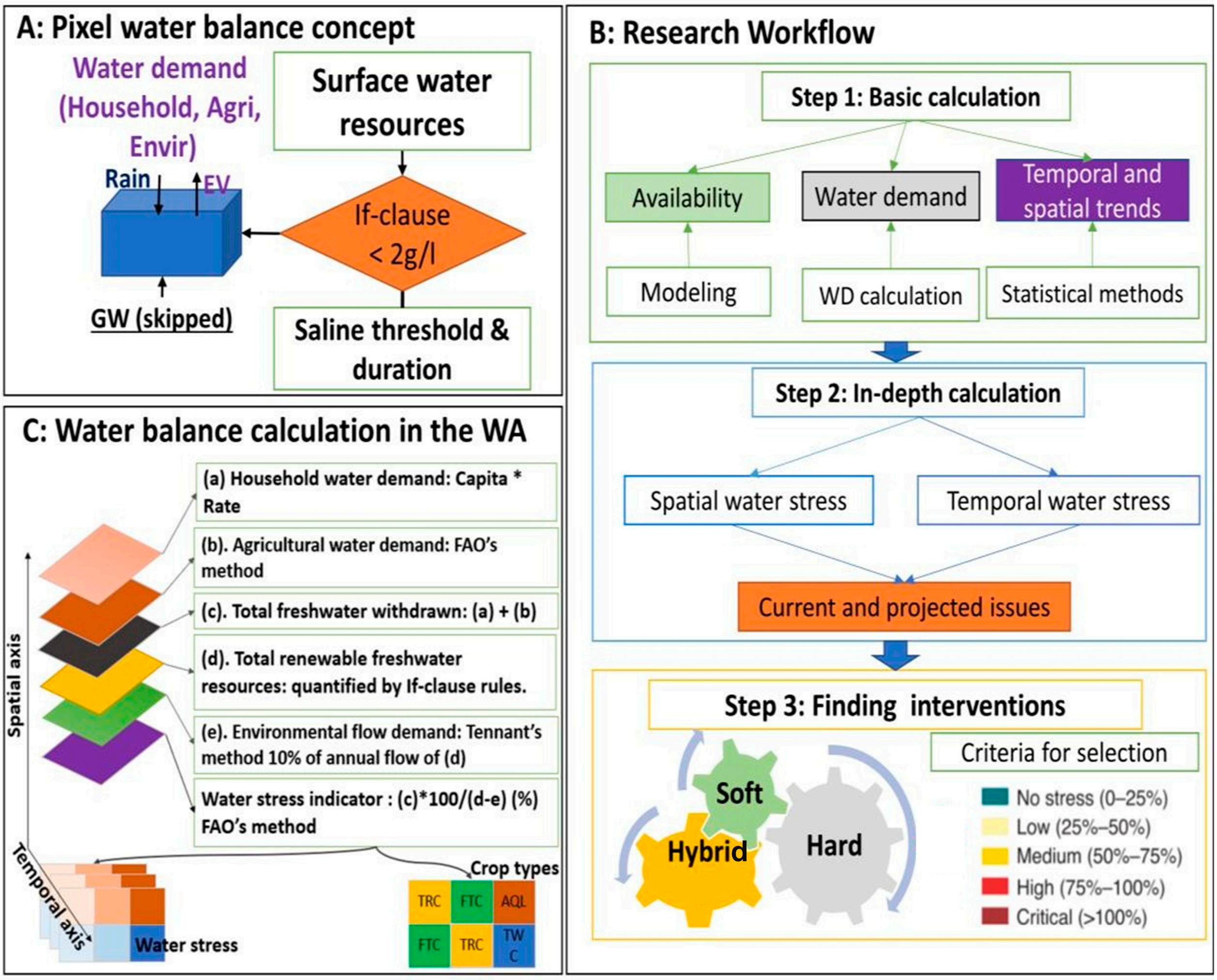

Figure 2. Research workflow of the study including the pixel water concept for the water balance calculation (**A**); research steps in the analysis, which comprise three main steps (i) basic calculation, (ii) in-depth calculation, and (iii) investigations of the interventions (**B**); and detailed water balance calculation method, with * means multiplication sign (**C**).

The three-step research workflow is shown in Figure 2B. In the first step, water availability in time and space was determined based on upstream surface and precipitation water sources. Since groundwater resources is not exploited due to poor quality for water use in the study area, it was disregarded in our calculations [42]. Meanwhile, the spatial and temporal variation of water demands of users was determined using numerical modeling methods based on MIKE11 model's simulations [43] and FAO's water demand procedures [44–46]. In the second step, the efficiency of the existing irrigation system and the planned irrigation system by 2030 was assessed based on planning of local authorities. To evaluate the current and planned solutions regarding water management status, the water stress indicator was employed to indicate how much freshwater is being fitted to demands for all water users in the study area in temporal and spatial aspects [47].

The current and projected issues of water management were shown through the water stress degree in the existing irrigation and planning irrigation systems. If the planned solution does not secure the water needs of all water users, interventions are investigated by combining soft and structural measures in water management in step three. Similarly, the water stress indicator was also used to assess the effectiveness of the proposed measures in the third step based on criteria of the water stress status of crops and areas affected by the water stress.

We used five layers for spatial water balance computations, with outputs represented by the water stress indicator (Figure 2C). For affected areas, including different cropping areas, water stress levels were determined for each scenario. Domestic water demand was calculated as the product of population per area and criteria on water use, while agricultural water needs were quantified using FAO's methods [48]. The total freshwater withdrawn was the sum of the household and agricultural water needs. Moreover, the total renewable freshwater was determined by the amount of water with saline concentration not exceeding 2 g/L. The environmental flow was estimated to be 10% of the annual freshwater flow obtained by the MIKE11 simulation. As a result, the water stress was spatially quantified as the total freshwater withdrawn by households and agriculture divided by the difference between the total renewable freshwater resources and the environmental flow demand multiplied by 100 [49].

3.2.2. Water Accounting Framework

Water accounting is an essential tool for effective water resource management and governance [44,46,50]. It involves a systematic quantitative evaluation of the current status and trends in water supply, demand, accessibility, and use in specific domains, taking into account temporal and spatial variations [51]. Water accounting provides reliable and accurate information that serves as the foundation for good water governance. It is also a useful tool for monitoring and achieving the 17 Sustainable Development Goals (SDGs) related to economic development, poverty eradication, and environmental protection [44,52]. It is noted that our study has applied the water accounting framework but not in detail involving socio-economic achievements from SDGs such as previous studies [53,54].

To achieve sustainable water management, water accounting employs quantitative methods to produce basic information on the supply and demand for water [55]. This information is used to develop suitable ways of water allocation that meet social, economic, and natural needs without compromising future needs. Moreover, governmental planners and corporations can use water accounting to determine the "hydrological costs" of their plans to avoid risks of water scarcity, such as using water from current local users or causing water shortages in other areas.

The water accounting framework consists of several water fact sheets that communicate crucial information on the water resources status, water consumption patterns, water use productivity, and water flows between various water users in specific domains such as river basins, sub-basins, irrigation systems, or agricultural fields. These fact sheets include the Resource base sheet, Evapotranspiration sheet, Productivity sheet, and Withdrawal sheet. Each fact sheet serves a different purpose. For example, the Resource base sheet provides information on water volume regarding over-exploitation, manageable and unmanageable flows, reserved flows, utilized flows, and utilizable flows at the study domains. It also presents landscape evapotranspiration (ET) by precipitation and incremental ET sourced from natural and man-made withdrawals.

3.2.3. Numerical Modeling Approach and Simulation Scenarios

Numerical Modeling Approach

The MIKE11 model was developed by the Danish Hydraulic Institute (DHI) and is a modeling package used for hydraulic phenomena in rivers, lakes, canals, and other inland water systems [56]. It includes various functions to model hydraulic work operations such as sluices, dams, pumps, and embankments in irrigation schemes. The model is widely used for simulating water flow and quality in river basins and other water systems.

The MIKE11 package includes several modules, such as the hydrodynamic, rainfall-runoff, advection–dispersion (AD), sediment transport, and Ecolab modules. In our present study, the hydrodynamic, advection–dispersion, and rainfall–runoff modules were used to simulate water flow and quality in the study area. The hydrodynamic module solves the Saint–Venant equations using fully dynamic descriptions that integrate equations of conservation of volume and momentum. The AD module simulates dissolved or suspended material movements, such as saline intrusion and sediment transport, while salinity concentration is defined as the mass of inorganic salts per volume of water in the model. This module requires outputs from the hydrodynamic modules, including flow and water level, cross-sectional area, and hydraulic radius in temporal and spatial variations. In the package, a lumped, conceptual rainfall–runoff model, the so-called MIKE11 NAM, was used to model several components of runoff generation, including overland-flow, inter-flow, and base-flow as a function of the moisture contents in four vertical storages [56].

We used the SIWRP's MIKE11 network for the whole VMD to update on details of primary and secondary canals and sluice gates within Ben Tre Province (Figure 3A,B). This model has been developed by Southern Institute for Water Resources Planning (SIWRP) since the 2000s, as its model network at the delta-wide level is applied to numerous projects, including water resources planning, flood forecast, and water quality projection [57–59].

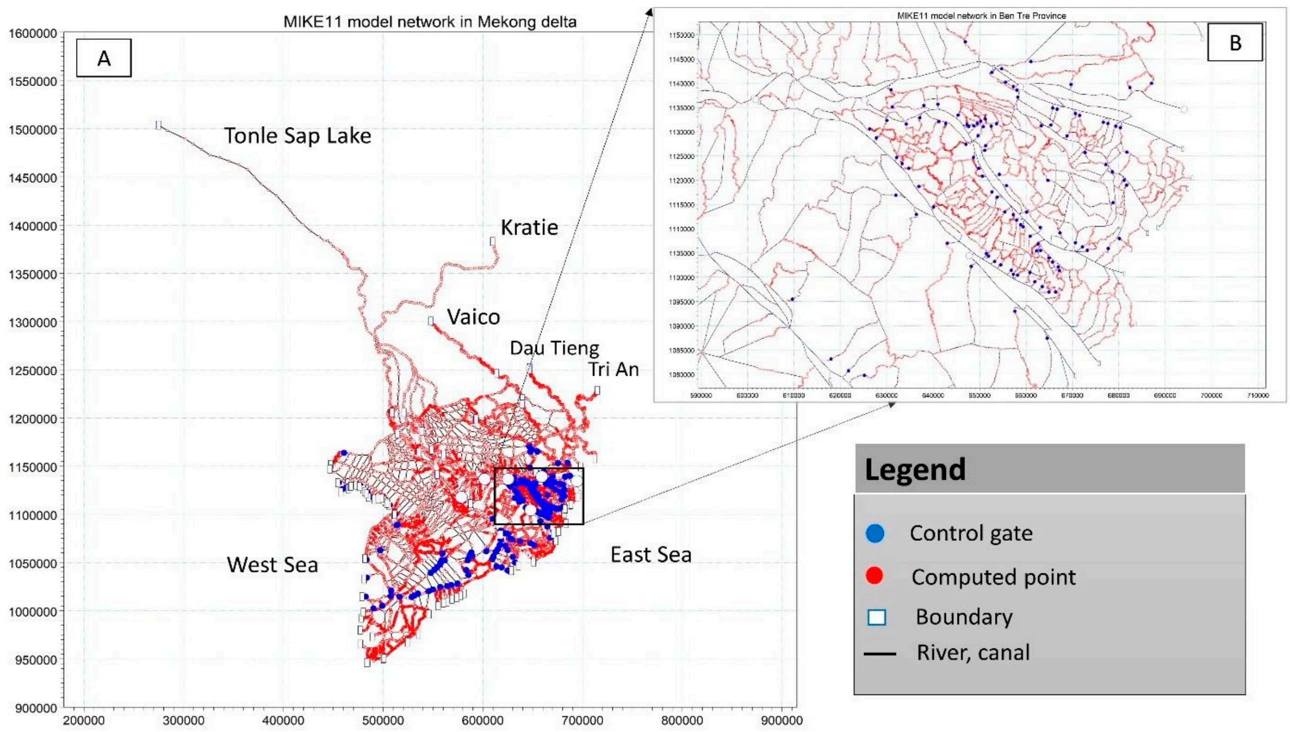

Figure 3. MIKE11 model network of the VMD (**A**) and zooming in Ben Tre Province (**B**).

To ensure the accuracy of the MIKE11 model, calibration and validation simulations were conducted for the two extreme dry seasons of 2016 and 2020, respectively. The goodness-of-fit checks between simulated data and observed data were performed using the Nash–Sutcliffe efficiency (NSE) and correlation coefficient (R^2), which are common criteria used to evaluate model performance [37,60,61]. The NSE values ranged from 0.9 to 1, with values close to 1 indicating optimal performance, while negative values indicate inadequate performance. The correlation coefficient indicates a linear relationship between two variables, ranging from -1.0 to 1.0, with a value of 0 indicating no significant relationship.

The results of the model performance assessments showed good agreement with value and time variations of calibrated and validated simulation. The NSE values were higher than 0.9, and R^2 values ranged from 0.98 to 0.99 at selected stations in the calibration simulation, as shown in Table 1. The highest values of NSE and R^2 were found at My Hoa station in Ham Luong River and My Tho station in Tien River compared to other stations in the calibration, with NSE values of 0.97 and R^2 values of 0.99.

Table 1. Calculated NSE and R^2 of the calibrated simulation in 2016 and the validated simulation in 2020.

Station	**Parameter**	**Dry Season 2016**		**Dry Season 2020**	
		NSE	**R^2**	**NSE**	**R^2**
My Thuan	Q	0.95	0.98	0.93	0.97
My Thuan	H	0.94	0.98	0.92	0.97
My Hoa	H	0.97	0.99	0.96	0.99
My Tho	H	0.97	0.99	0.96	0.99
Tra Vinh	H	0.96	0.98	0.94	0.98
Cho Lach	H	0.96	0.98	0.94	0.97

Note: Q is discharge while H is water level.

Simulation Scenarios

Our study includes three scenarios to evaluate the effectiveness of different water management measures (Table 2). The first scenario is the baseline scenario, the so-called Year 2016, which aims to assess the adequacy of the current irrigation system. The year 2016 was selected as it is the historical extreme drought and saline intrusion event over the previous three decades [35,62], making it suitable for the current assessment of water management in Ben Tre Province. The second scenario evaluates the planned measures by 2030, which enclose a part of the province to protect the freshwater environment and mitigate high tide and sea level rises. Finally, hydraulic simulation was carried out for the entire year to determine the incoming flow that is input on the environmental flow calculation.

Table 2. Scenarios applied for the study.

Scenarios	**Boundary Conditions**	**Water Infrastructure Measure**
Year 2016	Upstream flow in 2016 Downstream water level in 2016 Averaged agricultural water demand 2005–2020 Household water demand in 2020	Existing irrigation system in 2016
Year 2030	Projected upstream flow by 2030 Projected downstream water level by 2030 Averaged agricultural water demand by 2030 Household water demand by 2030	Planned irrigation system by 2030

In scenario 2016, historical datasets were used for the upstream and downstream boundaries in the simulation. The agricultural water demand was calculated as the average value between 2005 and 2020, while the household water demand was calculated based on data from 2020. To assess the impact of climate change on agricultural water demand, the past long-term period of 16 years from 2005 to 2020 was selected for comparison with the agricultural water demand under the scenario in 2030 RCP4.5. For domestic water demand calculation in the current condition, the last available population data in 2020 were chosen.

In the scenario of Year 2030, the projected sea level rise RCP4.5 was added to the water level boundaries, while climate change scenario RCP4.5 (air temperature, precipitation) was used to calculate the agricultural water demand. For the RCP4.5 scenario, a moderate greenhouse emission was selected for our study according to recommendations on selection for climate change scenarios for planning and management [63]. The upstream flow boundary used a 95th percentile flow of the projected flow sequence between 2025 and 2030, which was sourced in a study conducted by Whitehead et al. [64]. The climate change scenarios were referred from Ministry of Natural Resources and Environment of Vietnam (MONRE) in 2020 for the calculations [65]. Under MONRE, six climate models, including CLWRF, PRESIC, CCAM, RegCM, AGCM/RMI, and RCA3, were used to calculate 26 climate scenarios for Vietnam; hence, the climate parameters of RCP4.5 were used for our study. Specifically, the air temperature was projected to increase by 0.7 °C on average, while the rainfall was projected to increase by 17%, and the sea level was projected to rise by 12 cm in the period 2016–2035.

Table 3 shows three possible measures based on the literature. Of those, the Alternate Wetting and Drying (AWD) IRRIGATION measure focuses on reductions of about 40% in water demands by changing the traditional continuous flooded irrigation method to the AWD method [66]. TRC TO FTC measure transforms the triple rice cropping areas into fruit trees. In contrast, TRC TO TWC&AWD IRRIGATION measure combines the agricultural transformation and changes in the irrigation methods. In these measures, interventions are needed to integrate the planned irrigation system to reduce water stress while agricultural sector with triple paddy crop has the largest water consumption among the agricultural water users (e.g., fruit tree, vegetables). Thus, reductions in the water demands for agriculture could minimize the water stress.

Table 3. Proposed three measures incorporated into the planned solution by 2030.

Measures	Recommendations
AWD IRRIGATION	The traditional continuous flooded irrigation method was replaced by the Alternate Wetting and Drying (AWD) irrigation method (40% water demand cutoff) [66,67]
TRC TO FTC	Agricultural transformation: triple rice cropping (TRC) was replaced by fruit trees (FTC) [68]
TRC TO TWC&AWD IRRIGATION	Triple rice cropping (TRC) was replaced by two rice cropping and upland cropping (TWC), with AWD uses (40% water demand cutoff)

4. Results and Discussion

4.1. Water Demand in Comparison with Total Surface Water Availability in 2016 and 2030

Table 4 presents the comparisons of total water demands and water resources for the two scenarios of the years 2016 and 2030, including agriculture, household, and environment, with total freshwater availability in the current and future conditions. In the dry season (December to May), total freshwater availability in the year 2016 was recorded at about 25.5 km^3, while it was found to be 23.37 km^3 for the year 2030. It means the total water demand of all water users in the dry season was approximately 20% and 22% in the year 2016 and the year 2030, respectively. These results indicate that there is an abundance of freshwater sources for water demand, as found by previous publications such as [10,69].

Table 4. Total water demand and total surface water resources in the scenarios of Y2016 and Y2030 (unit: km^3).

Month	Surface Water Resources in Y2016	Total Water Demand in Y2016	Surface Water Resources in Y2030	Total Water Demand in Y2030
Jan	4.03	0.861	3.50	0.864
Feb	2.86	0.895	3.15	0.898
Mar	3.64	0.921	3.48	0.925
Apr	5.07	0.891	4.63	0.894
May	4.91	0.802	4.52	0.805
Jun	6.78	0.777	6.10	0.781
Jul	15.86	0.779	13.93	0.782
Aug	21.37	0.771	18.70	0.774
Sep	28.64	0.752	24.99	0.754
Oct	27.81	0.766	24.17	0.769
Nov	18.59	0.833	15.78	0.836
Dec	4.99	0.845	4.10	0.848
Dry season	25.50	5.215 *(20%)* *	23.37	5.234 *(22%)* *
Year	144.55	9.893	127.04	9.929

* Compared with the surface water resources availability in the same year.

4.2. Water Management Effeciency of Water Infrastructures

To evaluate the water management efficiency of the irrigation system and the planned irrigation system by 2030, salinity concentrations, duration, and water stress indicators were mapped and compared to evaluate the efficiency of the irrigation system in 2016 and 2030 using five levels of water stress degree (Figures 4 and 5). These indicators based on maps, which are simulated by the MIKE11 model, provide valuable insights into the effectiveness of different management measures for water resources in Ben Tre Province, as recommended by previous studies [9,19].

Maximum saline intrusion in the Year 2016 and Year 2030 scenarios in Figure 4A shows that over 85% of Ben Tre Province is affected by saline intrusion due to the incomplete installation of sluice gates. These results are consistent with a study conducted by the UN in 2020 [70] that salinity intruded extensively in that year in the coastal province in the VMD. In contrast, the planned irrigation system in 2030 effectively protects freshwater areas from saline intrusion, although it is costly in operation and maintenance. However, due to the impacts of climate change, saline intrusion in the mainstream extends further upstream than the baseline scenario, limiting the time for water intake from sluice gates [8,14].

Duration of saline intrusion computed for Year 2016 and Year 2030 scenarios indicates that available days for taking freshwater are reduced in the upper part of the study area in 2030 (Figure 4B). These results could be explained due to increased saline intrusion duration caused by climate change impacts concluded by Tran et al. [9]. These results highlight the importance of effective water management measures to increase the days of freshwater exploitation for agriculture and aquaculture [5,13].

Figure 5 and Table 5 present the water stress status of the Year 2016 and Year 2030 scenarios during the dry season. Most of the freshwater areas are affected by medium water stress, while the water stress of medium to critical accounts for approximately 81,760 ha in 2016 (57.7% of the study area) and 16,220 ha (11.4%) in 2030. It means the planned irrigation system is unable to protect about 11.4% of the study area in 2030 under changing climate. Notably, the “No stress” area increased in the Year 2030 compared to the Year 2016 from the conversion of critical and high water stress, thanks to the effectiveness of the completed water infrastructures to reduce impacts of salinity intrusion driven by climate change (Figure 5). Therefore, additional measures are required to be incorporated into the planned solution to reduce water stress areas [2,11].

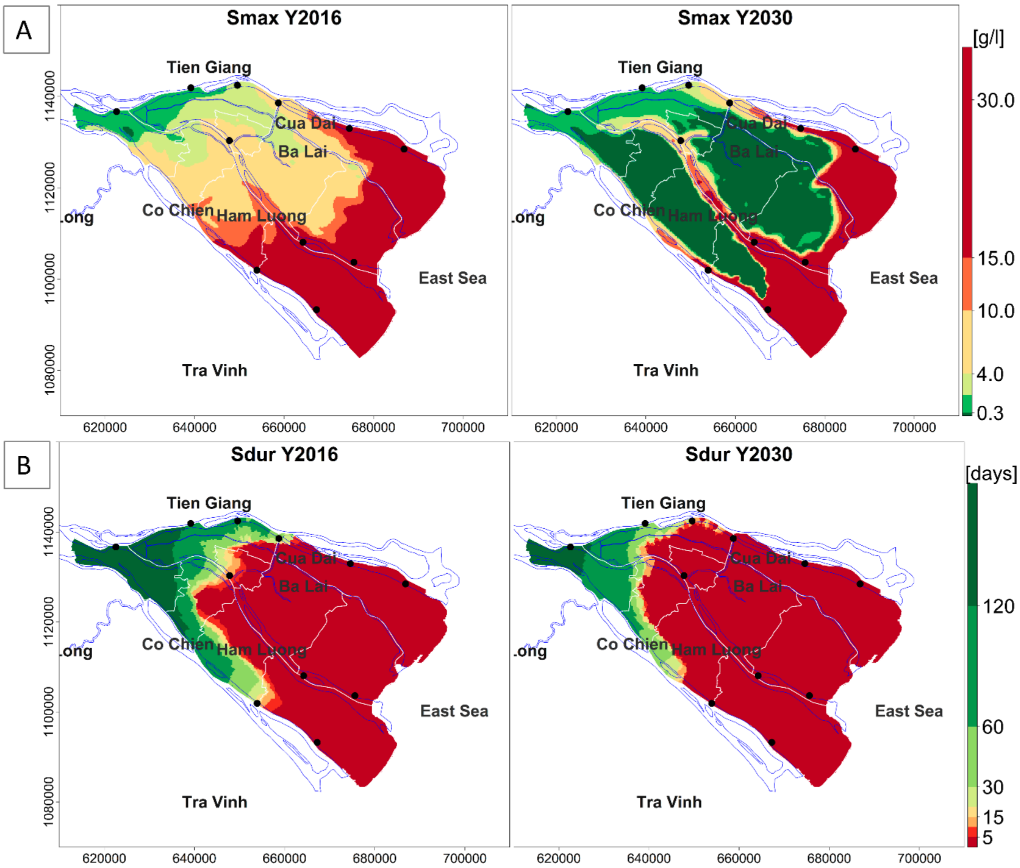

Figure 4. Maximum salinity intrusion (S_{max}) with the planned irrigation system in scenarios of Year 2016 and Year 2030 (**A**) and duration of salinity concentration (S_{dur}) exceeding 2 g/L in the existing irrigation system (**B**).

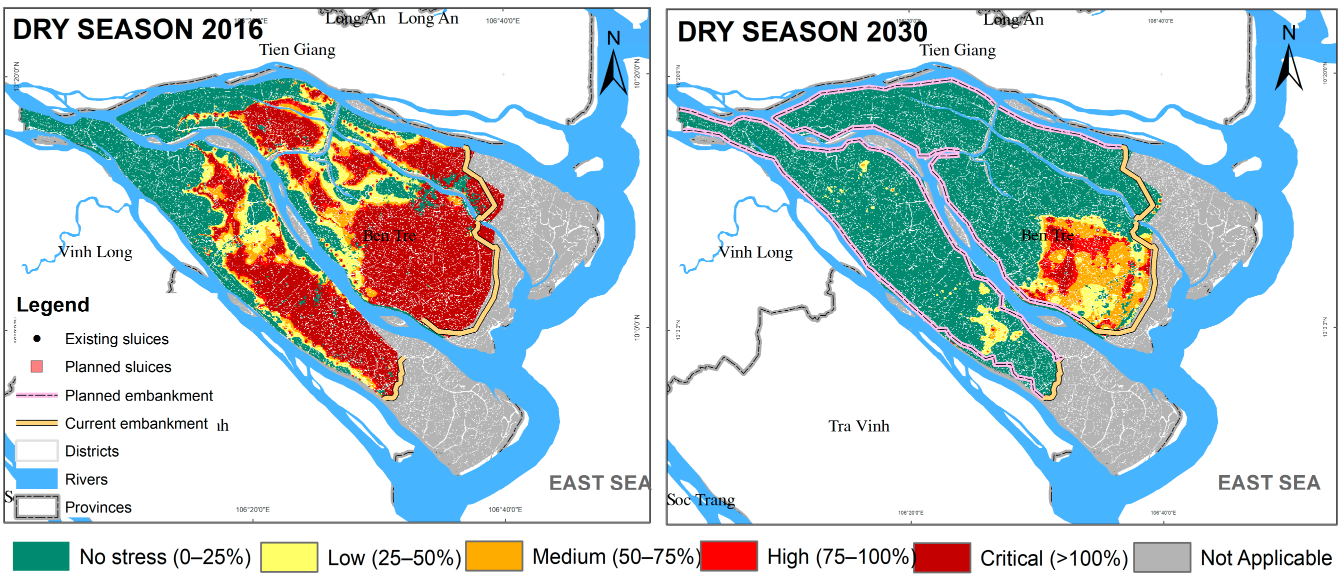

Figure 5. Water stress status in the dry season of the scenarios of 2016 and 2030.

Table 5. Areas affected by water stress under existing and planned irrigation systems (unit: ha).

Water Stress Category	Year 2016	Year 2030
Critical	65,547	2532
High	6189	4259
Medium	10,024	9429
Low	14,329	7233
No stress	45,572	118,208
Total area	141,661	141,661
Percent of the sum of areas from Medium to Critical levels/Total area	57.7%	11.4%

4.3. Measure Assessment for Sustainable Water Management

Table 6 compares the agricultural water demand between the Year 2030 scenario and recommended measures. The TRC TO TWC&AWD IRRIGATION measure achieves the most significant water demand reduction, with a reduction of approximately 168.62 million m^3 (about 24% of total water demand) compared to the Year 2030 scenario. The AWD IRRIGATION measure reduces water demand by about 102.52 million m^3, which is about 13% of the total water demand, while the TRC TO FTC measure cuts off demand by about 29.42 million m^3, which is around 3% of the total water demand.

Table 6. Agricultural water demand of proposed measures compared to Year 2030 (unit: million m^3).

Month	Year 2030	AWD IRRIGATION	TRC TO FTC	TRC TO TWC&AWD IRRIGATION
Jan	136.88	122.28	126.28	103.46
Feb	171.50	149.05	157.23	130.63
Mar	197.51	169.62	183.61	152.88
Apr	167.17	155.29	181.53	154.27
May	78.07	67.97	69.08	58.07
Jun	53.75	43.87	42.97	36.67
Jul	54.80	44.73	50.16	42.27
Aug	46.46	41.59	50.77	42.66
Sep	26.89	22.81	22.01	18.13
Oct	41.93	33.86	34.09	28.69
Nov	109.02	91.64	103.69	85.54
Dec	120.40	104.78	124.37	103.59
Dry season *(Dec–May)*	871.52	769.00 **102.52 *** ***(13%) ****	842.10 **29.42 *** ***(3%) ****	702.89 **168.62 *** ***(24%) ****
Year	1204.37	1047.50	1145.78	956.85

* ***Water demand in the dry season*** *of three proposed measures compared to those in Year 2030.*

Water demand mapping for the three proposed measures was compared to the Year 2030 scenario (Figure 6). The triple rice paddy area in Ba Tri district is significantly reduced, which demands less than 3 thousand m^3 in the TRC TO TWC&AWD IRRIGATION measure. These results demonstrate the effectiveness of management measures for the conversion from triple rice crop to wetting and drying irrigation methods for reducing agricultural water demand and ensuring sustainable water resources [8,9].

In Figure 7, the results show a significant reduction in water stress-affected areas in the TRC TO TWC&AWD IRRIGATION measure and IRRIGATION measure. In contrast, there are small changes in comparison between the TRC TO FTC measure and the Year 2030 scenario. Hence, TRC TO TWC&AWD IRRIGATION and IRRIGATION measures are promising in mitigating water stress and ensuring sustainable water resources.

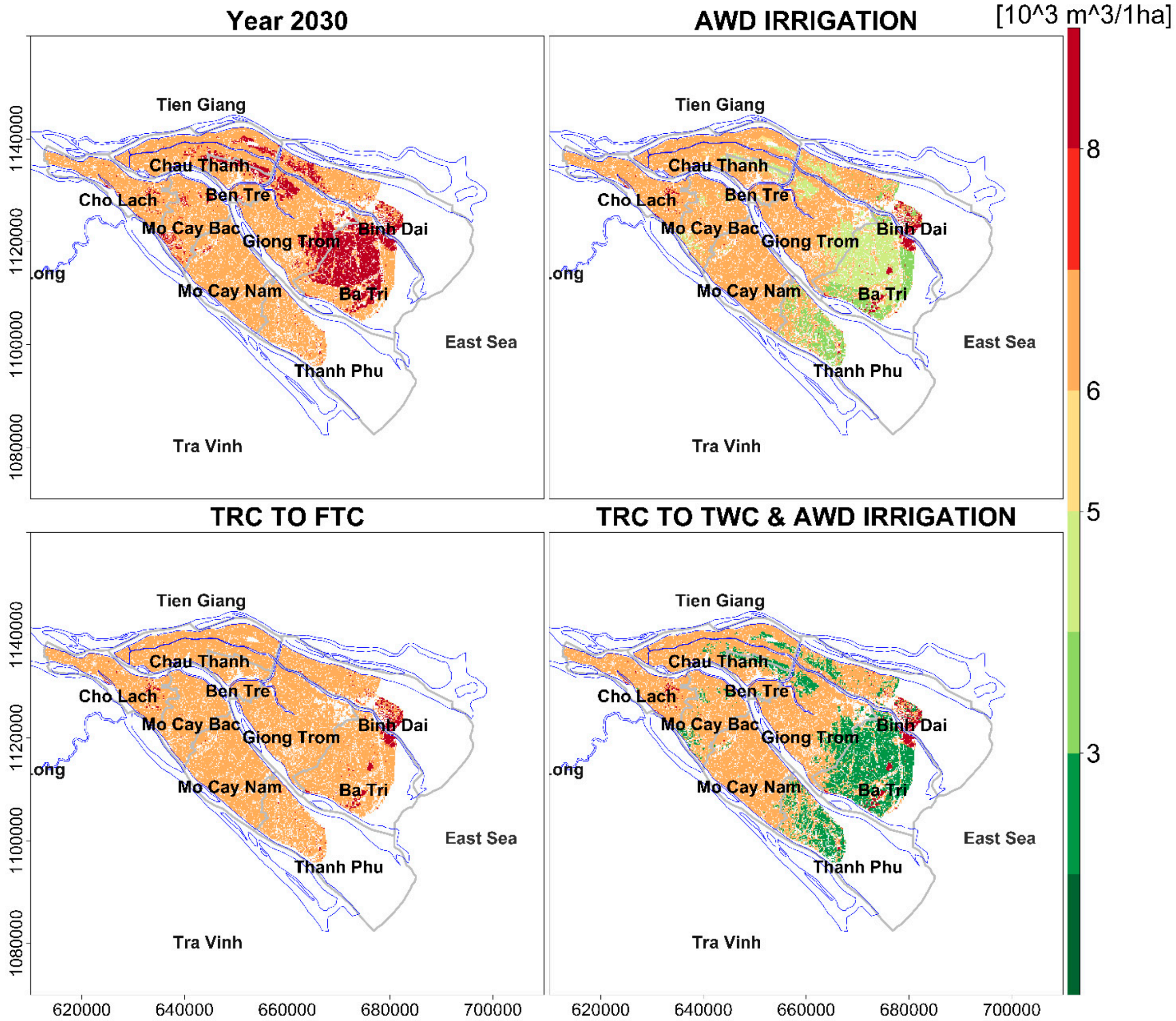

Figure 6. Agricultural water demands in the Year 2030 scenario and the proposed measures.

Table 7 compares in detail the affected areas by water stress shown in Figure 7. The TRC TO TWC&AWD IRRIGATION measure significantly reduces the water stress areas to 4568 ha, which is approximately 3.2% of the total study area, while the AWD IRRIGATION measure decreases the water stress areas to 6558 ha, which is about 4.6% of the entire study area. In contrast, the TRC TO FTC measure decreases the water stress areas to 15,848 ha, which is approximately 11.2% of the total study area. Overall, TRC TO TWC&AWD IRRIGATION is the most effective measure.

Table 7. Comparison of areas affected by water stress between the proposed measures (unit: ha).

Water Stress Category	Year 2030	AWD IRRIGATION	TRC TO FTC	TRC TO TWC&AWD IRRIGATION
Critical	2532	978	2460	869
High	4259	1171	3586	835
Medium	9429	4409	9802	2864
Low	7233	14,626	7481	13,790
No stress	118,208	120,477	118,332	123,303
Total area	141,661	141,661	141,661	141,661
Area of medium to critical levels/Total area *(In percentage)*	**16,220** ***(11.4%)***	**6558** ***(4.6%)***	**15,858** ***(11.2%)***	**4568** ***(3.2%)***

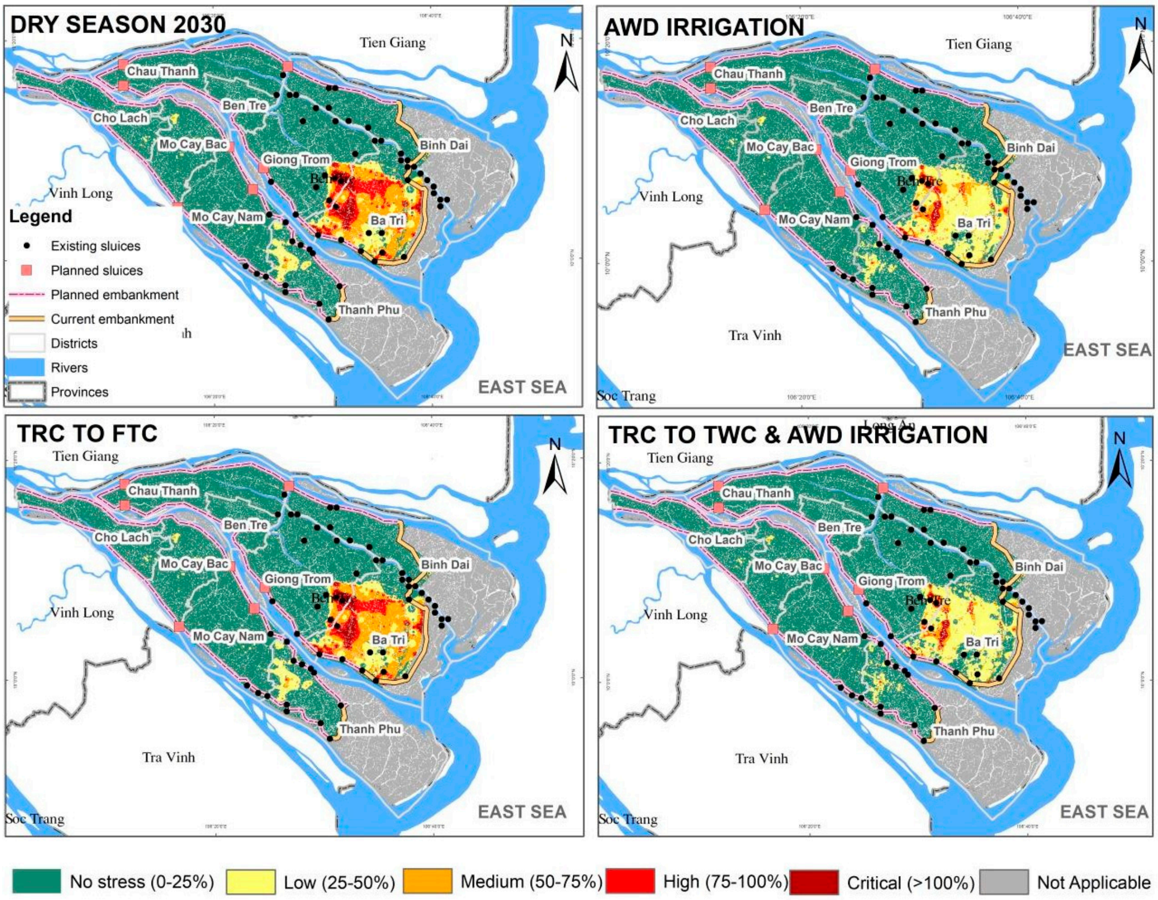

Figure 7. Water stress status in the proposed measures compared with the planned solution.

5. Conclusions

The aim of our study is to identify suitable solutions to improve water management in Ben Tre Province of the Vietnamese Mekong Delta (VMD) during the dry season, considering the impacts of climate change and anthropogenic (water infrastructure development) factors for the scenarios of 2016 and 2030. To achieve this, we applied a water accounting framework based on the MIKE11 hydrodynamic model and water balance calculations to determine current and future water stress issues and improve water management sustainability. Our study provides valuable insights into effective water management measures to ensure sustainable water resources in Ben Tre Province. Three primary water users were identified in the study, involving agriculture, household, and ecosystems, which are implied by three pillars of sustainable development: economic development, social well-being, and environmental protection in the study area dominated by agricultural productions. Our findings help draw three conclusions.

- The province has abundant amounts of surface water resources of about 25.5 km^3 and 23.3 km^3 of water available in the dry season for the scenarios of the extreme drought year 2016 and the future year 2030, which is much higher than the total water demand of 5.215 km^3 and 5.234 km^3. However, these water resources are unevenly distributed temporally and spatially in the study area. Moreover, saline water intrusion significantly causes severe water stress in the study area, highlighting the importance of effective water management measures to mitigate the impacts of saline intrusion and ensure sustainable water resources, especially in the future under increasing climate change impacts.
- The existing water management methods are inadequate for controlling saline intrusion, leading to over 57% of areas being affected by the medium to critical water stress

level. The planned solution by 2030 significantly improves water management but still leaves around 11.4% of areas affected by the medium water stress level, despite that structural measures fully enclose the study area. Our study concludes that the governments at multiple levels should invest in long-term, more sustainable measures (structural and non-structural measures) for not only Ben Tre but also other coastal provinces in a master plan in the VMD. These measures should be completed in different systems to maximize the effectiveness.

- Three measures are proposed to be incorporated into the planned irrigation system, focusing on water-saving and water demand reduction in the study area. The results showed that regions affected by water stress from medium to critical levels were reduced to 11.2%, 4.6%, and 3.2% of the total study area in the TRC TO FTC, AWD IRRIGATION, and TRC TO TWC & AWD IRRIGATION measures, respectively. Among these measures, the TRC TO TWC & AWD IRRIGATION measure is the most suitable measure to be added to the planned irrigation system towards more sustainable water management by 2030.

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

Appendix A

Table A1. Hydro-meteorological stations and parameters in the study. The hourly data in 2016 and 2020 were used for the model performance assessments, while daily and monthly data were collected from 2005 to 2020 and from 2000 to 2020, respectively.

Station Name	Parameters	Data Frequency		
		Hourly	Daily	Monthly
Ben Trai	Water level; Salt	2016, 2020		
An Thuan		2016, 2020		
Binh Dai		2016, 2020		
My Hoa		2016, 2020		
Cho Lach	Water level	2016, 2020		
My Thuan	Water level; Flow	2016, 2020		
Huong My	Salt	2016, 2020		2000–2020
Dong Tam	Salt	2016, 2020		2000–2020
Son Doc	Salt	2016, 2020		2000–2020
An Dinh	Salt	2016, 2020		2000–2020
Giao Hoa	Salt	2016, 2020		2000–2020

Table A1. *Cont.*

Station Name	Parameters	Data Frequency		
		Hourly	Daily	Monthly
Loc Thuan	Salt	2016, 2020		2000–2020
Ba Tri	Rainfall; Air Temperature; Wind; Humidity; Sunshine		2005–2020	2005–2020
Ben Tre			2005–2020	2005–2020
My Tho			2005–2020	2005–2020
Cang Long			2005–2020	2005–2020
Tra Vinh	Rainfall		2005–2020	
Cai Lay			2005–2020	
Go Cong Dong			2005–2020	

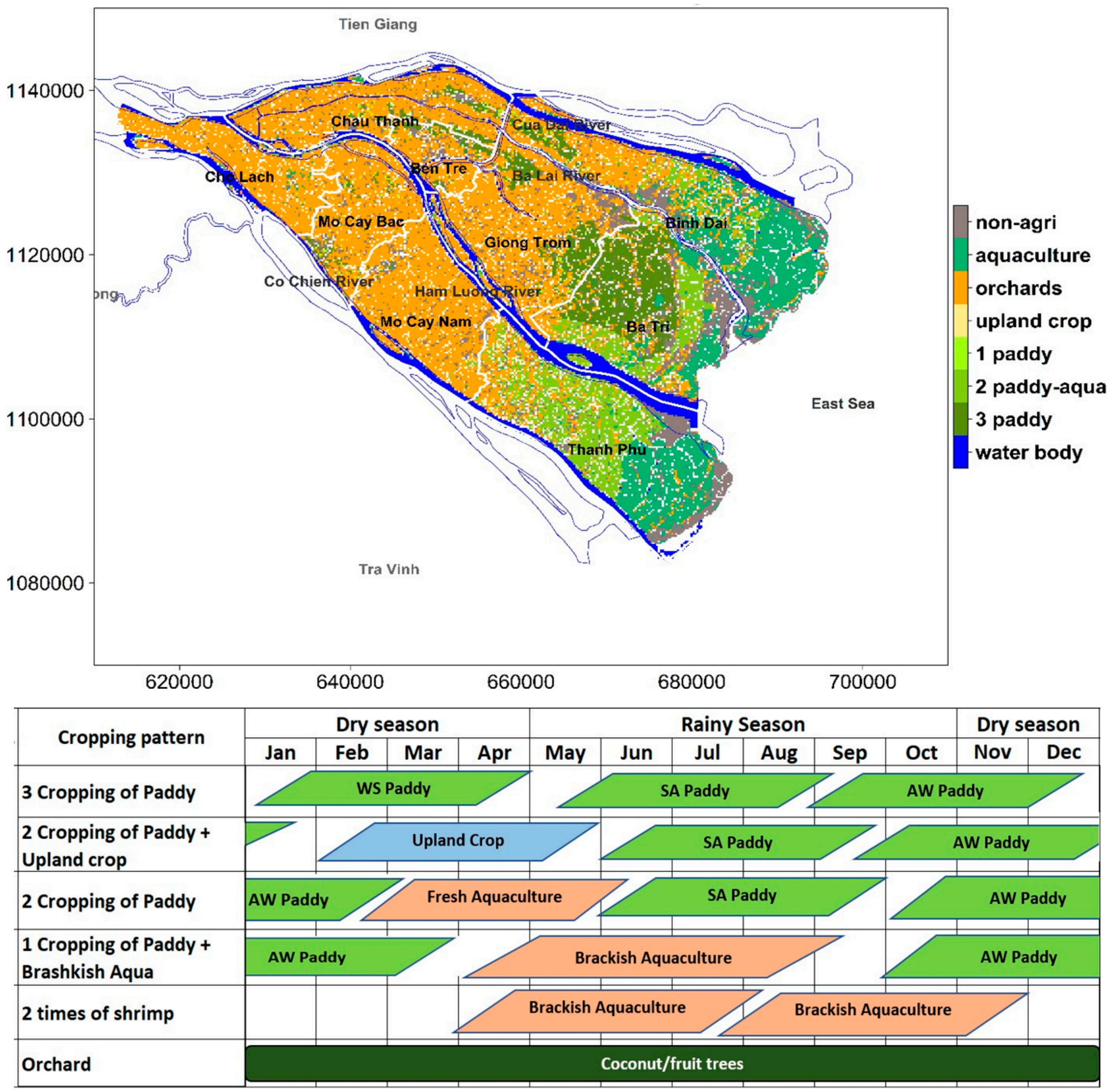

Figure A1. Existing land use of the Ben Tre Province (2020) and main cropping patterns and the calendars in the study area (source: [34] modified by the authors).

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