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**APPLICATION OF A WATER ACCOUNTING FRAMEWORK
FOR SUSTAINABLE WATER MANAGEMENT IN THE BEN
TRE PROVINCE IN THE VIETNAMESE MEKONG DELTA
UNDER THE PRESSURES OF CLIMATE CHANGE AND
ANTHROPOGENIC STRESSES.**

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ABSTRACT

The overall objective of the investigation was to determine suitable measures for improving water management sustainability in Ben Tre Province under climate change and anthropogenic impacts in the present and by 2030. The study focused on a part of Ben Tre (60% of provincial areas), which is planned to be a freshwater area by completing constructions of embankments and sluice gates by 2030.

To achieve the study objectives, the research workflow was carried out through the following three steps. Step 1 investigated the trends in climatic and hydrological stressors on the water management of the study area. Step 2 assessed the efficiency of the existing irrigation system and the planned irrigation system by 2030 regarding the water supply to all the water users. Step 3 investigated additional measures incorporated into the planned irrigation system to improve the sustainable water management.

Fundamentally, the water accounting framework was flexibly employed to carry out the water balance calculations in different scenarios in the three mentioned steps. As a result, the status of water management was represented by the water stress indicators that were used for evaluating and selecting suitable measures in the study. Particularly, the water balance calculation was conducted under a pixel concept, with a resolution of 1 ha. The freshwater source of a pixel element was quantified by using the MIKE11 model, while water demand for agriculture was calculated by using FAO's method. The environmental flow was determined by using Tennant's method, with a threshold of 10 % of the annual freshwater flow, while the household water demand was quantified by population and water rationing.

The study results found that (i) there were increasing trends in climatic and hydrological parameters in the period from 2005-2020 in the study area. Consequently, the water demand in agriculture is forecasted to increase by 3% in 2030 compared to the average water demand in the period 2005-2020. Although the upstream flow to research area was increasing, the salt boundary intruded further inland and longer duration in the mainstream. (ii) abundant amounts of surface water resources flow into the study area, about 25,5 km³ and 23,3 km³, more significant than the total water demand of 5.215 km³ and 5.234 km³ in the dry season in the scenarios of the year 2016 and year 2030, respectively. Yet, the water resources are unevenly distributed temporal and spatially in the study area. Saline water intrusions significantly cause severe water stress in the study area. Particularly, the existing water management solution was inadequate for controlling saline intrusion, leading to over 57% of areas being affected by the medium to critical water stress level. Similarly, the planned solution was not secure for around 11.4 % of areas that were affected by the medium to critical water stress level, although the structural measures fully enclose the research area by 2030.

Three proposed measures were incorporated into the planned irrigation system to address these issues: focusing on demand-oriented solution, including the application of the Alternate Wetting and Drying Irrigation method (AWD IRRIGATION), with a proposed 40% water demand cutoff, replacing triple rice crops by fruit tree (TRC TO FTC) and replacing triple rice crops by two rice crops in combining with AWD irrigation method (TRC TO TWC & AWD Irrigation).

The results revealed that affected areas by the water stress from medium to critical level are reduced to 11.2 %, 4.6%, and 3.2 % of the total study area in TRC TO FTC, AWD IRRIGATION, and TRC TO TWC & AWD Irrigation measures, respectively. In short, the TRC TO TWC & AWD Irrigation measure exhibited the highest reduction efficiency in water stress, demonstrating the measure to be most suitable for incorporation in the planned irrigation system to improve the appropriate water management in the study area by 2030.

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AFFIDAVIT

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LIST OF ABBREVIATIONS AND ACRONYMS

Agri.	Agriculture
AQL	Aquaculture
AW	Autumn-Winter season
BOD ₅	Five-day biochemical oxygen demand
COD	Chemical oxygen demand
ET	Evapotranspiration
ET _o	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FTC	Fruit trees
ICEM	International Centre for Environmental Management
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
K _c	Crop coefficient
me/l	Milliequivalent per litre
P	Precipitation
Pe	Effective precipitation
PERC	Amount of water losses
PSU	Practical Salinity Unit
S	Cultured areas
SA	Summer-Autumn season
SAT	Amount of water needed for land preparation
sd	Standard deviation
SIWRP	Southern Institute of Water Resources Planning
TCVN	Technical guidelines in Vietnamese conditions
TRC	Triple paddy crops
TWC	Two paddy-upland crop
UN	United Nations
UNEP	United Nations Environment Programme
VMD	Vietnamese Mekong Delta
WA	Water Accounting
WA+	Water Accounting Plus
WB	World Bank
Wlaq	Water depth in the aquacultural ponds in the beginning crops
WS	Winter-Spring season
WTE	Water Technology, Reuse and Management

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CHAPTER 1. INTRODUCTION

Ben Tre province is located in coastal regions of the Vietnamese Mekong Delta (VMD) (see Fig.1A), which is one of the five deltas most affected by climate change worldwide (Royal HaskoningDHV, 2013). It covers an area of 2,394 km² and comprises nine administrative units, including Ben Tre city and eight districts, with a population of more than 1.2 million in 2020 (BenTrePortal, 2019). It is characterized by flat and low-lying ground level, with a typical range from 0.5 m to 1.5 m, accounting for about 70% of the natural area, combined with a high dense river network (JICA, 2016). The surface water source is served through 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: Paddy, Orchard, and aquaculture, as shown in Fig.1B.

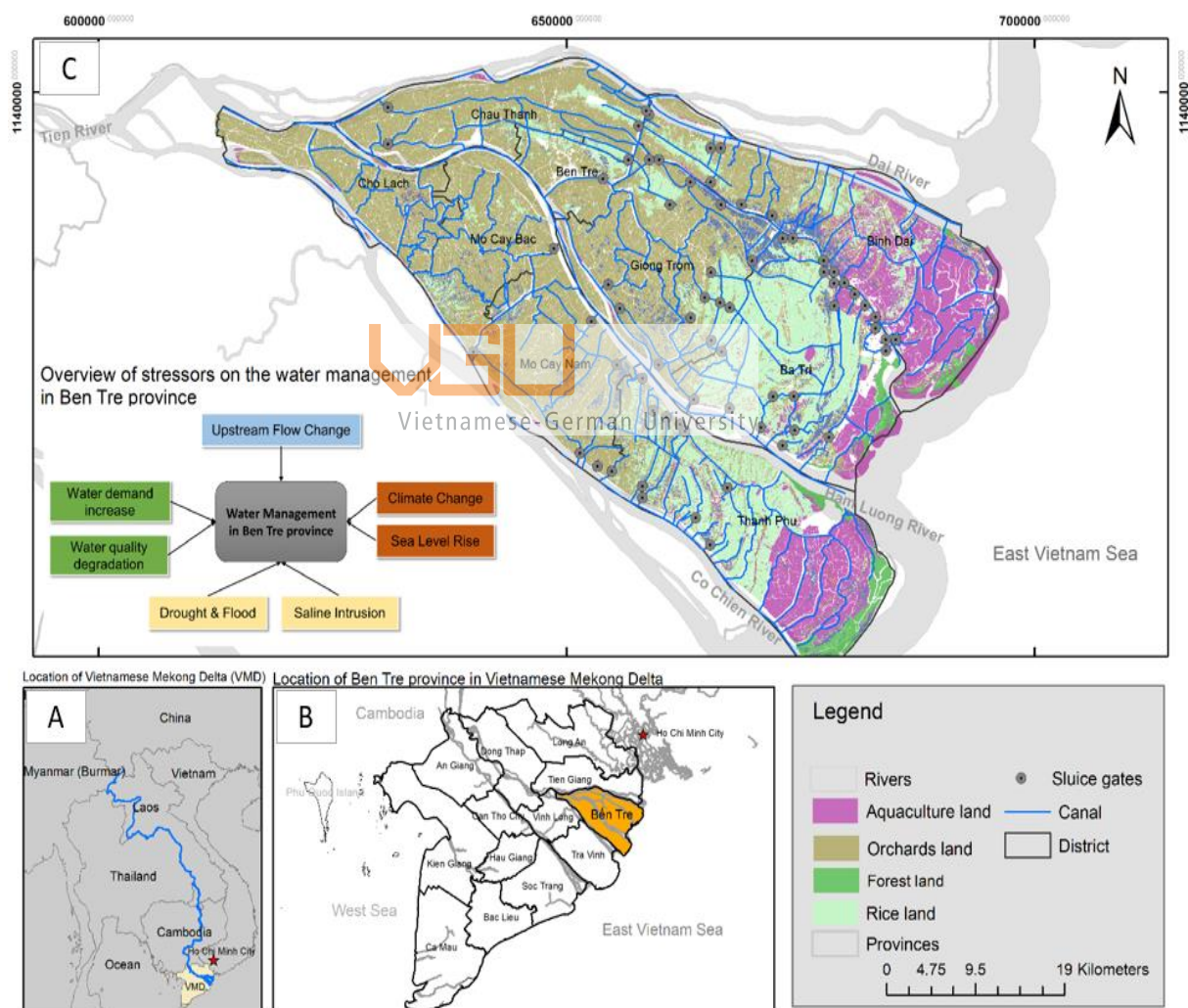


Fig.1. Vietnamese Mekong Delta location in Mekong Basin (A), Ben Tre Province location in VMD (B), Land use and river network of Ben Tre Province (C)

In addition, a considerable amount of upstream water flows into Ben Tre province via the main tributaries of the Mekong River, including Ham Luong, Co Chien, and Cua Dai rivers. At My Thuan

station, on the Tien River, is upstream of the study area. The flow at this station is shared into three main tributaries before flowing out to the East Sea; the yearly water flow at this station is around 17 km³, and the lowest water flow on April is around 4.76 km³. [see Table 17]. Significantly, the low flow in the dry season causes saline intrusion in the coastal region of the VMD (Royal HaskoningDHV, 2013)

Due to its proximity to the East Vietnam Sea, the hydrology of Ben Tre is mainly affected by the mixed diurnal and semi-diurnal tidal regime of the sea in interaction with the upstream flow from the Mekong River. As a consequence, it is dominantly influenced by saline intrusion in the dry season, with the seasonal iso line with a salinity of 1 g/l covering almost 90 % of Ben Tre Province (Minh, 2017).

Ben Tre was one of the most severely damaged provinces in recent droughts and saline intrusions in the VMD in 2016 and 2020 (Nguyen et al., 2021; VDMA, 2020). Additionally, it has been reported that significant changes in the hydrologic regime of the VMD are caused by anthropogenic activities, such as upstream hydropower dams, sand mining, land subsidence, water demand increases, and climate change impacts (Binh et al., 2020; Eslami et al., 2019; MRC, 2021). Consequently, saline intrusions are becoming more intense now and will become more intense in the future in the VMD, especially in the coastal region within the next decades (Loc et al., 2021), threatening sustainable water management of the Ben Tre Province.

As an agricultural area, current water management in Ben Tre is dominated by numerous irrigation systems that maintain and develop agricultural production in the Province. For example, the Ba Lai irrigation system in the north of the study area was one of the salt control projects constructed in the early 2000s in the VMD. Yet, the whole irrigation system has not been wholly enclosed (Loc et al., 2021), causing severe drought and saline damage in agriculture (VDMA, 2016).

For domestic water supply, approx. 95% area of the interest area is covered by water supply systems, with a total supply capacity of about 109,100 m³/day through six water treatment plants that abstract raw water from the Ham Luong and Tien rivers. Saline intrusions are a major issue for all the water treatment plant, coupled with degraded water quality; for example, maximum values of pollutants BOD₅ and COD were measured to be 137 mg/l and 279 mg/l, respectively in the Master Plan for the VDM in 2013 (WB, 2018).

For groundwater resources, there are seven aquifers located from 0 to 700 m beneath the ground surface in Ben Tre Province. The fresh groundwater potential exploitation reserves are estimated at about 213,727m³/day, and about 5,511,282 m³/day of brackish groundwater (MONRE, 2016b). Due to the high sulphate concentration, the groundwater in Ben Tre is unsuitable for use, which is why the government has banned groundwater extraction in various regions of the VMD as of 2020 (WB, 2018). In short, surface water and rainwater sources play critical roles in water security in Ben Tre Province's water management.

To deal with the saline intrusions and droughts, several measures were carried out in the past. At the farming scale, farmers implemented measures to deal with the shortage of water during the dry season, such as storage for water in ponds, floating reservoirs in the field or using plastic bags to store the water for the orchard, as shown in Fig.39 in the appendix. At the system scale, individual solutions (e.g., off-river water reservoir, temporal dams) have been built during the dry season, e.g., Kenh Lap water reservoir has been built from an existing canal to store more than 800,000 m³ and supply the water for 20,000 people in Ba Tri district (VNS, 2020).

To secure water supply to all water users in the dry season in the climate change and upstream development impacts, local authorities have planned to complete the irrigation system by 2030, protecting about 1.410 km² (60% of the provincial area) (JICA, 2016; VDMA, 2020). The planned solution mainly comprises structural measures, such as sluice gates, pumping stations, and embankments. Specifically, the protected area will be a freshwater environment by enclosing using embankment routes that are connected to the existing embankment, as shown in Fig.2. Moreover, eight big sluice gates will be built to regulate water in the protected area. A pumping station will be installed to intake the water from upstream into the freshwater area. Details on the sluice's parameters is shown in Table 21 in the appendix. Thus, this study aimed to investigate solutions for the water management issues in the freshwater area of the Ben Tre Province, disregarding the outer regions of the investigation.

The research objective was 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 in 2020 and until 2030, based on the application of water accounting.

To achieve the study objective, the following three research questions were addressed by applying the 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:

- i. Do the currently available water resources meet the water needs of the people, the agriculture and the environment, given climate change and anthropogenic influences in the Ben Tre province?
- ii. How adequately do current solutions (soft & structural measures) solve issues in the water management of Ben Tre province?
- iii. What are appropriate measures for sustainable water management in Ben Tre province in the context of climate change and anthropogenic pressures?

The thesis is composed of seven parts. Firstly, Chapter 1 provides an overview of the study area regarding its natural characteristics, current and planned water management, its challenges concerning the water supply taking into account climate change and anthropogenic stresses, research objectives, and a short introduction about the methods applied in the thesis study. Chapter 2 then discusses published information on water resource management, water accounting applications and other topics related to the topic of the thesis. The third chapter illustrates details of the materials and

methodologies employed in the thesis. The results on water availability, water demands, current and planned irrigation system efficiencies, and possible, additional measures are presented and discussed in Chapter 4. The main conclusions were drawn in Chapter 5. Finally, a summary of the thesis is given in Chapter 6.

PLANNED IRRIGATION SYSTEM BY 2030 IN BEN TRE PROVINCE

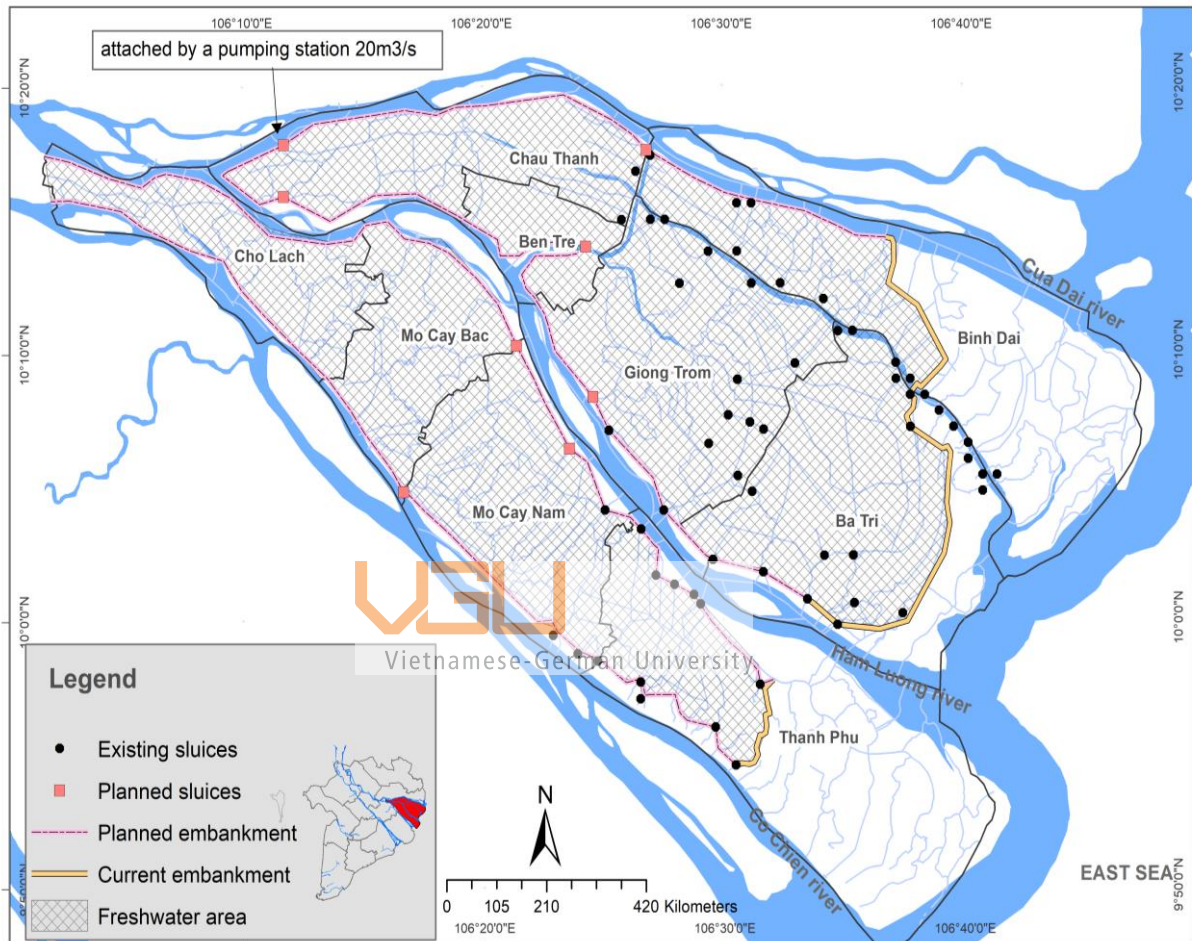


Fig.2. Planned solution for water management by 2030 in Ben Tre province; a gray crosshatch area is the freshwater area protected by structural measures. The existing irrigation system includes the sluice gates indicated by black dots and the current embankment illustrated by yellow lines. In contrast, for the planned irrigation system, new sluice gates, shown by pink rectangular and new embankments represented by the pink lines, will be constructed in combination with the existing irrigation system to enclose the freshwater area by 2030.

CHAPTER 2. LITERATURE REVIEW

Integrated Water Resources Management (IWRM) has been defined by the technical committee of the Global Water Partnership (GWP) as “a process which promotes coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems”. In addition, IWRM is principally formed by three components: social equity, economic efficiency, and environmental sustainability. It has been internationally recognized and widely applied in the world, especially integrated into Sustainable Development Goals (SDGs) of the agenda 2030 (Van Tra, Nguyen, Linh, Bach, & Son, 2022; World Water Council, 2015).

Within the Mekong Region, an IWRM support project has been carried out by the Mekong River Commission, with funding by the world bank since 2013. It aims at supporting IWRM in the lower Mekong countries at regional and national levels. Particularly, the regional objectives have prioritized encouraging transboundary discourse to advance regionally synchronized solutions, creating a regional approach to disaster risk management and environmental protection, increasing stakeholder understanding of regional IWRM concepts, and promoting transboundary cooperation. In contrast, at the national level, the project focused on supporting riparian countries to apply IWRM in their terrestrial areas. For example, Vietnam has implemented river basin management in the Upper Sesan and Srepok rivers (2-S basin)) and developed hydromet networks in the 2-S basin and the VMD (MRC, 2019).

Further, Mekong IWRM phase II, financed by the World Bank, sets out objectives to improve the collection, analysis, and exchange of water resources data to support the implementation of integrated water resources management in Lower Mekong. In addition, it also focused on strengthening the capacity of the Ministry of Natural Resources and Environment, the Vietnam National Mekong Committee (VNMC), and relevant organizations to manage transboundary water resources and climate risks through river basin approaches (WB, 2020).

While Vietnam is actively engaged in the application of IWRM on the regional level, there is a limitation of IWRM applications at the national level in Vietnam. Vietnam has gone from 35th in 2017 to 52nd in 2020 in ranks for IWRM implementation according to a study about the degree of integrated water resources management implementation (indicator 6.5.1) of target 6.5 of SDG6 in the Agenda 2030, carried out by the United Nations Environment Programme (UNEP (2021)). The level of the IWRM implementation is considered to be medium-high.

Indicator 6.5.1 is composed of 4 dimensions of IWRM, including (i) enabling environment, (ii) institutions and participation, (iii) management instruments, and (iv) financing. The current level of IWRM implementation in Vietnam indicates that much more is needed to improve these four dimensions to achieve target 6.5, the implementation of IWRM at all levels by 2030, including appropriate transboundary collaboration. In addition to the IWRM implementation at a regional level, Van Tra et al. (2022) have found that the degree of IWRM in the VMD is at a medium-high level by employing indicator 6.5.1. The study also revealed that despite the enabling environment dimension significantly improving, technical and financial capacity dimensions were still limited in IWRM implementation in the VMD.

Water accounting is a vital tool for water resource management and governance (FAO&WWC, 2018). The term is defined as the systematic quantitative evaluation of the current status and trends in water supply, demand, accessibility, and use in particular domains considering temporal and spatial variations (FAO, 2016). Water accounting provides sound, reliable basic information as the foundation for good water governance. Notably, water accounting is a helpful tool for monitoring and achieving the 17 SDGs¹ on economic development, poverty eradication, and environmental protection (FAO&WWC, 2018). For sustainable water management, water accounting comprises a set of quantitative methods that produce basic information on the supply and demand for water to develop suitable ways of water allocation fitting with social, economic, and natural needs without compromising future needs. In addition, governmental planners and corporations can determine the “hydrological costs” of their plans to avoid risks of water scarcity, using water from current local users, or causing water shortages in other areas.

The significance of reporting on water has prompted the development of standardized water accounting frameworks by several national and international organizations, including the Australian government (Water Accounting Standards Board, 2014), the UN (SEE-Water) (Vardon, Martinez Lagunes, Gan, & Nagy, 2012), FAO (FAO, 2016), and IWMI (Poolad Karimi, 2014). Frameworks have been shown to be effective in persuading decision-makers that water should be considered a valuable good and valued according to its supply and demand (Droogers, Simons, Bastiaanssen, & Hoogeveen, 2010). However, each framework has differences in terminologies, structures, input data, etc., and no framework has been approved as a widely recognized standard (Droogers et al., 2010). Significantly, WA+ is a water accounting system developed by UNESCO-IHE in collaboration with FAO and IWMI and uses fractional analysis for reporting on the water availability and water consumption at the basin level. It primarily relies on open-access satellite observations that make it possible to calculate water consumption, flows, fluxes, and storages by land use class. The method distinguishes between beneficial and unbeneficial uses of water as well as consumptive and non-consumptive uses of water. The system can be accessed through a specific platform at www.wateraccounting.org (Poolad Karimi, Bastiaanssen, Molden, & Cheema, 2012).

The WA+ framework comprises several water fact sheets, which are created to communicate crucial information on the water resources status, water consumption patterns, water use productivity, and water flows between various water users in specific domains (e.g., 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 delivers various purposes; the Resource base sheet provides the water volume information on over-exploitation, manageable and unmanageable, reserved, utilized, 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. Assessments of commitments to environmental legal agreements and water scarcity status could be carried out based on the Resource base sheet. The Evapotranspiration sheet provides water consumption information for various land use categories, anthropogenic influences on ET, and insights into land use planning's impact on consumptive water use. The productivity sheet indicates information about biomass returns, carbon sequestration, and food security, while the Withdrawal

¹ Sustainable Development Goals

sheet provides status on management, regulations, and water allocations (P. Karimi, Pareeth, & Michailovsky, 2019).

The WA+/water accounting framework has been flexibly applied based on the requirements, local characteristics, and data availability. Droogers et al. (2010) used the whole WA+ framework to find solutions for dealing with water scarcity in Okavango basin in Africa. By contrast, for the Nile Basin, just a water resources base fact sheet was applied to report water consumption status and water availability in a study carried out by FAO and IHE Delft (2020).

Although the water accounting framework is a comprehensive tool for water depletion and productivity assessments related to land use, it has its own limitations. The critical limitation is that numerical models (hydrological, hydraulic models) are required in the water accounting framework to provide detailed water flow information in specific domains (Poolad Karimi, 2014). Furthermore, while numerous studies on water accounting/water accounting plus have considered water quantities in the calculations (Elga Salvatore, Claire Micheilovsky, Bert Coerver, & Bastiaanssen, 2017; FAO & IHE Delft, 2020; Poolad Karimi, 2014; Poolad Karimi et al., 2012); nevertheless, water quality (e.g., salinity concentration, BOD, DO) hasn't been integrated into these previous studies.

Although the water accounting framework was introduced more than 20 years ago and has been applied in various projects worldwide (FAO&WWC, 2018; WaterAccounting.org, 2022), only a few studies have applied the water framework in the Mekong River Basin and related areas in Vietnam. One of these was a case study implemented in the Ca River in Vietnam, where a web-based water accounting scenario platform was developed to solve uncertainties in water resources management (Seifollahi-Aghmiuni et al., 2017). Within the Mekong region, another application of the WA+ system in Cambodia is based on remote sensing open data sources associated with free Geographic Information System (GIS) data and hydrological models. The results recommended solutions for water management and possible water savings for Cambodia (Elga Salvatore et al., 2017).

While water accounting considers the supply and demand of water for various water uses, a variety of essential services are also provided by fluvial systems in their nature flow regimes for the survival of human society. These are referred to as ecosystem services (Bussetini & Vezza, 2019), including provisioning services (e.g., food and water), regulating services (e.g., flood control), cultural services (e.g., recreational and spiritual), and supporting services (e.g., nutrient cycling, self-purification). Thus, there must be an appropriate threshold for fluvial process functionality in terms of flow quantity, sediment regime, and flow quality in order to guarantee these services. A key constraint of sustaining riverine ecosystems and its services is the establishment and maintenance of such flow and sediment regimes, namely environmental flows. The term “environmental flows” was originally introduced in the Brisbane Declaration in the 10th International River Symposium's endorsement. It is defined as “Environmental flows describes the quantity, quality and timing of water flows required to sustain freshwater ecosystems and the human livelihoods and well-being that depend on these ecosystems.” Additionally, the meaning of the environmental flow concept has changed over time, moving away from the conventional view of minimum water flows and toward a more thorough and holistic knowledge of a riverine system and its behaviors, such as a deeper understanding of interactions between ecological dynamics and flow regime (Anderson et al., 2006).

In practice, due to river management gathering together from multi-disciplines, the environmental flow is referred to by various names in different areas over the world, such as instream flow needs (Anderson et al., 2006), ecological reserve, ecological demand of water (Tan et al., 2011),

environmental water requirement and ecological flows (European Union, 2015). While there are slight differences in the wording of these definitions; yet, they all imply that certain amounts of water are required under five aspects (Kelly Mott Lacroix & Brittany Choate Xiu, 2003) of water flow: magnitude, duration, frequency, timing, and rate of change in order to secure a healthy ecosystem.

For example, the ecological flow is defined as “the hydrological regime that allows the achievement of the good ecological status of water bodies” in the European legislation implementation on water protection.

Numerous methods have been formulated to quantify flows required to sustain the ecosystem’s services worldwide (Bussetini & Vezza, 2019; Kelly Mott Lacroix & Brittany Choate Xiu, 2003; SWP consortium partners, 2018). Consideration of the physical, biological, sociocultural, and livelihood elements of fluvial ecosystems may all be involved in the assessment of the environmental flows (SWP consortium partners, 2018). These methods are commonly divided into four types: hydrological methods; hydraulic rating methods; biological methods; and holistic methods.

A natural flow pattern is a crucial variable dominating aquatic ecosystem characteristics and functioning in the hydrological method category. In contrast, relationships between flow and river geometry, which are focused on in the hydraulic methods, are frequently employed as proximate for elements that maintain aquatic species and native ecosystems. Extending from the hydraulic methods, the biological approaches link flow requirements to the needs of particular species for their environment. There are links between habitat characteristics and flow that are direct and indirect. Finally, the holistic approaches aim to account for all significant interdependent elements of aquatic ecosystems, which are characterized by their length, timing, amplitude, and frequency (SWP consortium partners, 2018).

For the hydrological method category, a primary assumption used in this category is that environmental flow recommendations derived from the natural flow regime will produce processes and circumstances that preserve native ecosystems and species. According to the desired environmental conservation degree, the ecological recommendations will reflect the natural flow characteristics. Tharme (2003) has found that the hydrological method category accounted for the highest percentage of the environmental flow methodologies documented (30%, closely followed by biological methods). The hydrological methods are the most frequently applied in India, Turkey, China (Xiqin Wang, Zhang, & James, 2009) and are partly used in European Union, the United States (Bussetini & Vezza, 2019). In particular, some specific methods (e.g., Tennant (Tennant, 1976), modified Tennant, and random arbitrary low flow indicators methods) have been widely employed among the hydrological method category for environmental flow determination.

Indicators for measuring water withdrawal intensity as a percentage of the available freshwater resources are also vital considerations in water accounting. These demonstrate the need for efficient supply-and-demand-management policies in water management. The water stress indicator is one such index used in qualitative evaluations of water resources vulnerability in water management (Ding & Ghosh, 2017) and was also employed as an SDG Indicator 6.4.2 by FAO in the UN-Water Integrated Monitoring Initiative for SDG 6 (FAO & UN Water, 2021).

Hui Xu and May Wu (2017) reviewed that a number of methods for water stress determination have been introduced over the last 30 years. These methods are different based on water sources, such as blue water (i.e., water withdrawals to available water resources ratio, net water uses to water resources), green water (i.e., comparing the ratio of long-term average actual evapotranspiration

(AET) to potential evapotranspiration (PET), the proportion of a crop's green water footprint to its available green water). Similarly, D. Wang, Klaus, Shan, Gerbens-Leenes, and Liu (2021) also pointed out several methods have been proposed to quantify physical water stress indexes with differences in input data; for example, Green water scarcity requires the population and green water resources, or Blue water scarcity needs blue water footprint, run-off, and environmental flow requirements.

Moreover, FAO (2019) introduced an approach incorporating environmental flows into the water stress indicator 6.4.2. This approach was used to encourage nations to take part in the evaluation of SDG 6.4.2 on water stress. For applying the water stress indicator in the water accounting framework, Hunink et al. (2019) have carried out a study on the assessment of climate change's impact on water resources for the agricultural sector in different river basins in Europe. The result showed that water stress was used for quantification to various water sources, such as blue water and green water. However, it was basically calculated by using green or blue water over the water availability in total, without consideration of environmental flow, duration, and timing. For the application of water stress in Vietnam, Ngo, Le, Hoang, and Luong (2018) have quantified the water stress indexes for Vietnam under virtual water perspectives. Yet, the environmental water flow was not taken into account in the calculations.

Once environmental flow requirements and water stress indicators have been determined, it is commonly found that there is a need to reduce the demand for water to improve the sustainability of water resources management. Water-saving approaches may be an important element of demand reduction. In the agricultural sector, Siopongco JDLC, Wassmann R, and Sander BO (2013) have found that the Alternate Wetting and Drying Irrigation method reduces up to 30% of the water demand and 40% of the methane emissions in the rice practices. It was considered to be a promising way to deal with water scarcity and climate change. Similarly, Yamaguchi, Tuan, Minamikawa, and Yokoyama (2016) have revealed that the water consumption in the rice paddy field was cut by about 15%-40% compared to continuous flooded irrigation in a study on the utilization of Alternative Wetting and Drying Irrigation technology in rice paddies in the Vietnamese Mekong Delta.

Another example of the application of AWD Irrigation in VMD, five years of an experiment was carried out at an alluvial paddy owned by a typical triple-cropping farmer in the delta's center (Hironori, 2021). The results showed that AWD reduced irrigation water consumption by 43% on average between 2013 and 2016. The water-saving approaches, such as AWD Irrigation, are aligned with transforming technology in an agricultural transformation model adapting to climate change in the VMD, with four model cores, including changing vision, production model transformation, institutional transformation, and science and technology transformation (VCCI & UNDP, 2022). In addition to the water-saving approaches, rice-based farming system diversification (Van Kien, Hoang Han, & Cramb, 2020) and transforming triple rice crops to two rice crops and other crop types (Bui BB et al., 2019) were recommended as promising measures adapting the water scarcity in the climate change and anthropogenic impacts.

To quantify the water needs of new crops, FAO's methods are available (FAO (1986)). These provide different approaches to calculating water demand for a variety of crops, such as paddy, banana, sugarcane, and cacao. The FAO's method was incorporated into technical guidance (TCVN 8641:2011 & TCVN9168:2012) for calculations on crop water needs in Vietnam. In addition, local characteristics were determined by adjusting some parameters, for example K_c , ET_0 , in using FAO's methods (Nam et al., 2022).

CHAPTER 3. MATERIALS AND METHODOLOGY

3.1 DATA COLLECTION

Several data types were collected to carry out the study, including (i) ground-measured data, especially on hydro-meteorology and agricultural water demand data, (ii) open-source data of population distribution that was used to calculate spatially household water demand, and (iii) other data types, such as land use, cropping calendars, data from the statistical books, and information on climate change scenarios.

3.1.1 Ground-measured data collection

The collected data includes climatic and hydrological data that were used for simulating exercises, analyzing trends in the hydrometer patterns, and calculating agricultural water demand. Fig.3 shows hydrometeorological stations that are located inside and surrounding the study area.

There are 19 stations that collected the data, including four meteorological stations measuring rainfall, humidity, air temperature, and sunshine, 12 hydrological stations measuring water level and/or salinity concentration, and three stations measuring rainfall only, as shown in Table 1. These stations are all managed by the Southern Regional Hydrometeorological Center.

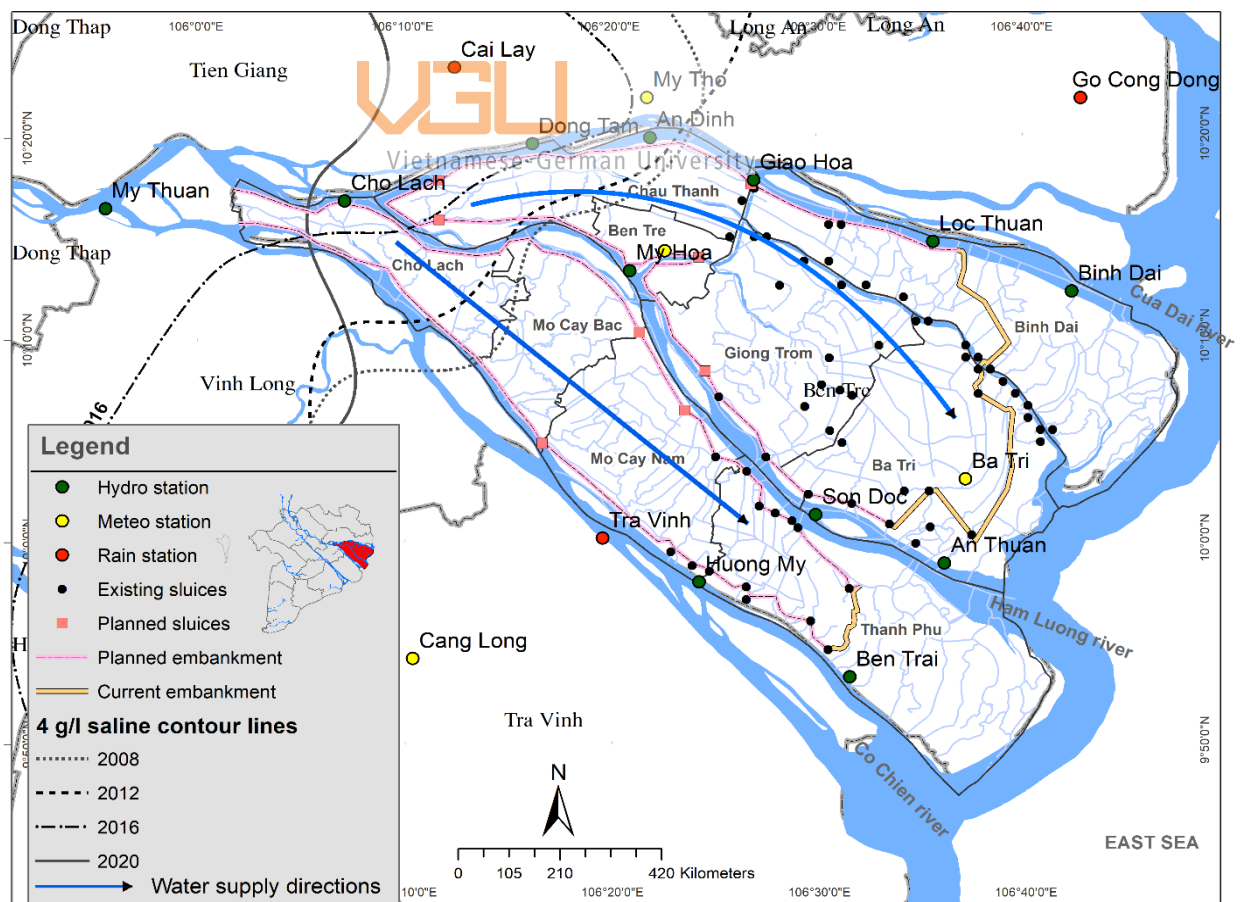


Fig.3. Hydrometeorological stations, the irrigation system, and historical salinity iso-line and averaged max saline intrusion 1996-2020 in Ben Tre Province

Table 1. Hydrometeorological 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	Station type	Parameters	Data frequency		
			Hourly	Daily	Monthly
Ben Trai	Hydrology	Water level; Salt	2016, 2020		
An Thuan	Hydrology		2016, 2020		
Binh Dai	Hydrology		2016, 2020		
My Hoa	Hydrology		2016, 2020		
Cho Lach	Hydrology	Water level	2016, 2020		
My Thuan	Hydrology	Water level; Flow	2016, 2020		
Huong My	Hydrology	Salt	2016, 2020		2000-2020
Dong Tam	Hydrology	Salt	2016, 2020		2000-2020
Son Doc	Hydrology	Salt	2016, 2020		2000-2020
An Dinh	Hydrology	Salt	2016, 2020		2000-2020
Giao Hoa	Hydrology	Salt	2016, 2020		2000-2020
Loc Thuan	Hydrology	Salt	2016, 2020		2000-2020
Ba Tri	Meteorology	Rainfall; Air Temperature; Wind; Humidity; Sunshine		2005-2020	2005-2020
Ben Tre	Meteorology			2005-2020	2005-2020
My Tho	Meteorology			2005-2020	2005-2020
Cang Long	Meteorology			2005-2020	2005-2020
Tra Vinh	Rainfall station	Rainfall		2005-2020	
Cai Lay	Rainfall station			2005-2020	
Go Cong Dong	Rainfall station			2005-2020	

3.1.2 Open-source data

To calculate household water demand spatially, the population distribution map was retrieved from WorldPop Hub (www.worldpop.org). It was created based on the UN population data in 2015 and is in a grid format with a resolution of 100 m (WorldPop (www.worldpop.org) - School of Geography and Environmental Science, 2013).

Statistical population data for 2020 was also retrieved from the Vietnam national census and was used to adjust the population distribution map extracted from the WorldPop Hub. Several parameters from 2005 to 2020 were also retrieved from the Ben Tre province statistical book 2020.

Based on the above, the adjusted population distribution was then used to calculate the household water demand. This data was used to determine water demand amounts and trends.

3.1.3 Other materials

- Land uses

There are four types of land uses that dominate in Ben Tre: orchards, rice cultivation, brackish aquaculture, and upland crops, as shown in Fig.4. Overall, the perennial plants (e.g., coconut, fruit, ornamental trees) are widely distributed in the upper parts of Ben Tre Province that are characterized by prevalent alluvial soil. These account for the largest area of about 101,344 ha compared to other land use categories. By contrast, aquaculture is popular in the coastal region, with an area of approximately 28,150 ha.

Rice cultivation is predominant in the downstream parts of Ba Tri and Thanh Phu districts, where the major soil types are saline alluvial and saline soil (JICA, 2016). Triple rice cropping is cultivated on about 20,350 ha, as shown in Table 2. Additionally, upland crops (e.g., vegetables, corn) are scattered in the paddy and orchard areas, and rotational cultivated systems of the paddy and aquaculture can be found in some coastal districts, such as Binh Dai, Ba Tri, and Thanh Phu districts.

- Cropping patterns

In general, five major cropping patterns and corresponding cropping schedules are used in Ben Tre Province, as shown in Table 3. The first cropping pattern is triple rice crops which is popular in the middle and low parts of the study area, except for the coast. Each crop requires about four months, starting with the Winter-Spring season (WS), the Summer-Autumn season (SA), and ending up with the Autumn-Winter season (AW) crop. A variation of the first cropping pattern is double rice cropping, where rice is cultivated in combination with one crop of vegetables. This pattern is suitable for areas with inadequate water supply during the dry season.

The second cropping pattern is the double paddy crops combined with fresh aquaculture in the dry season using water storage in the wet season (JICA, 2016).

The third cropping pattern 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. This pattern can be 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. Here shrimp are cultured twice per year with a relatively short practicing period of about 3-4 months.

Finally, orchards, including coconut and fruit trees, are popularly grown in upstream areas of Ben Tre Province, such as Chau Thanh, Cho Lach, and Giong Trom districts throughout the year.

Current land use of Ben Tre province

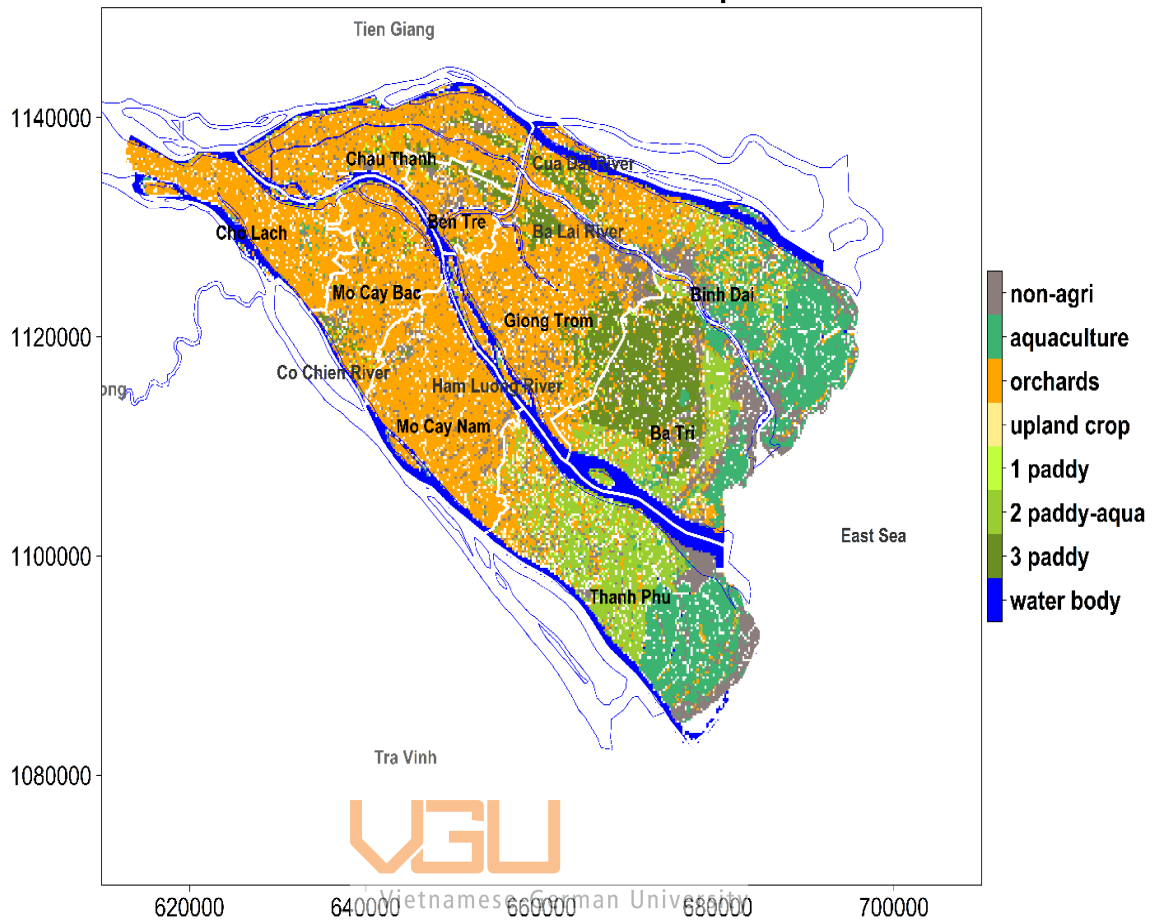


Fig.4. Current land use of the Ben Tre Province

Table 2. Areas of predominate land use categories in Ben Tre Province

Categories	Area [ha]
Triple Paddy Land	20,350
Double Paddy - Aquaculture/Upland crop Land	35,077
Orchard Land	101,344
Aquaculture Land	28,150
Non-agricultural land	26,292
Waterbody	26,756
Total	237,970

Table 3. Main cropping patterns and its calendars in the study area (source: (JICA, 2016) modified by the author)

Cropping pattern	Dry season				Rainy Season						Dry season		
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
3 Cropping of Paddy	WS Paddy				SA Paddy						AW Paddy		
2 Cropping of Paddy + Upland crop	Upland Crop				SA Paddy						AW Paddy		
2 Cropping of Paddy	AW Paddy		Fresh Aquaculture			SA Paddy						AW Paddy	
1 Cropping of Paddy + Brackish Aqua	AW Paddy				Brackish Aquaculture						AW Paddy		
2 times of shrimp					Brackish Aquaculture								
Orchard	Coconut/fruit trees												

- Crop coefficient (K_c)

The crop coefficient is a dimensionless factor, basically the proportion of the crop's evapotranspiration (ET_c) to a reference evapotranspiration (ET_o) for grass.

K_c indicates the effects of four key attributes that differentiate the crop apart from grass in general. The four main characteristics include the crop height, which influences the crop's aerodynamic resistance, the crop-soil surface's adobe, the crop canopy resistance and evaporation from the soil. K_c varies by stages of plant cycles and climatic conditions (Allan, Pereira, & Smith, 1998). A standard table of single K_c of various crops in conditions for non-stress and well-practices in subhumid climates is provided by Allan et al. (1998). Overall, three typical values for K_c are applied throughout the crop cycle, $K_{c\text{ ini}}$, $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ for different agricultural plants, such as vegetables, fruit trees, sugar cane, etc.

For Vietnam conditions, reference values of K_c for several crops (e.g., paddy, vegetables) are provided in the national technical guidance (TCVN 9168:2012) based on local experiments. Table 4 shows the K_c of seven growth stages of paddy in three cropping seasons in the VMD, with a period of 10 days for each stage. Overall, the highest K_c values occur at the reproductive stages (panicle initiation to flowering) in the SA season compared to other stages and in different seasons.

In the land preparation stage, it is advisable to secure 30 - 50 mm water depth on fields. This takes about 20-30 days before the sowing stage (MOST, 2012).

For upland crops, maize was selected as a representative plant in the study, according to crop areas in the statistical book 2020 of Ben Tre province. Maize's K_c is divided into five stages, including (i) initial stage (K_c : 0.4), (ii) crop development stage (K_c : 0.57), (iii) middle season (K_c : 1.1), (iv) maturity stage (K_c : 1.15) and (v) harvest (K_c : 1.0) (MOST, 2012).

Limited studies have focused on the K_c of fruit trees in Vietnam. According to Allan et al. (1998), K_c of the tropical fruit and trees depends on tree heights and coverages of canopies. For example, K_c values of palm trees of 8 m height are recommended as 0.95, 1.0, and 1.0 for the initial, middle, and

end stages, respectively, while for cacao trees of 3 m height, K_c values are recommended as 1, 1.05 and 1.05 for the initial, middle and end stages respectively.

As mentioned in the introduction, most orchards in Ben Tre Province are coconuts. K_c values of coconuts were not directly available, therefore the K_c values for palm trees were selected to use for the water demand of the fruit trees in this study as palms and coconuts are closely related species.

Table 4. Crop coefficient (K_c) of paddy in different crops in the VMD (source (MOST, 2012) modified by the author)

Growth stages	Winter-Spring (WS)	Summer-Autumn (SA)	Autumn-Winter (AW)
Sowing	1.04	0.91	0.93
Start tillering	1.08	1.05	0.99
Stem elongation	1.08	1.15	1.06
Panicle initiation	1.04	1.21	1.17
Flowering	1.02	1.21	1.16
Milk stage	1.02	1.19	1.08
Mature stage	1.03	1.13	0.96

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3.2 METHODOLOGY

3.2.1 Overall research workflow

The study methodology involved applying a water accounting framework flexibly to fit with local conditions, considering both water quantity and water quality (salt concentration) to assess the status of the water sources compared with water demands of various water users (agriculture, domestic, and environment) under current and future climatic conditions. Specifically, the concept of pixel water balances in WA+ was applied to make more sense of the water sources, water needs, and status of water consumption over time and space.

The water balance calculation was performed with a resolution or pixel size of 1 ha. The water inflow in a pixel element includes surface water sources and precipitation, while water losses comprise water demand of the agriculture, households, and ecosystems, as shown in Fig.5A. Surface freshwater sources for each pixel element were determined by eliminating water containing salinity concentrations exceeding 2 g/l to define the total renewable freshwater resources.

The research workflow is shown in Fig.5 B. Overall, there were three main steps, in which the first step aims to determine the water availability in time and space based on upstream surface and precipitation water sources. The quality of groundwater resources quality is not suitable for the water uses in the research area (WB, 2018). Thus, it was disregarded in considering water sources in the

study. Meanwhile, the spatial and temporal variation of water demands of users was determined. Numerical modeling methods and FAO's water demand procedures were applied to balance the water availability and the water demand, respectively.

Details on the method are presented in the below sections. Additionally, a trend analysis was carried out in temporal and spatial aspects for water availability, water demand, and stressors such as climate change, sea-level rise, and saline intrusion on the water management of Ben Tre province. The R programming language was employed to carry out the trend analysis, water demand calculations and water balance calculations.

In short, the first step revealed general trends in climatic, hydrological drivers, water sources, and water demand in the study area. It also provided inputs for calculations in the second step.

Step 2 aimed to assess the efficiency of the existing irrigation system and the planned irrigation system by 2030 that was used based on the planning prepared by the local authorities. To evaluate the current and planned solutions regarding the 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.

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 did not secure the water needs of all water users, interventions were investigated by combining soft and structural measures in water management in step 3.

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. As a result, a suitable measure will be found for the study area to improve water management sustainability.

The spatial water balance calculation, Fig.5C, shows five layers were used for the water balance computation, with outputs represented by the water stress indicator. For affected areas, including different cropping areas were determined by their water stress levels for each scenario. Domestic water demand was of particular concern. This was calculated as the product of population per area and criterion on water use, while the agricultural water need was quantified by FAO's methods. Consequently, the total freshwater withdrawn is a 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 2g/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 is 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 (FAO, 2019).

Connections between input data and calculated steps and outputs in the research workflow are shown in Fig.6. Overall, six input groups were used for four calculation tasks in step 1. The result of step 1 was used for inputs in step 2, which comprises three tasks of the calculations, including Total

freshwater withdrawn, Environmental flow requirements, and Total renewable freshwater estimates. Consequently, the output was obtained, including trend assessments, mapping of water demand, water sources, and water stress results of scenarios. In particular, trend analysis was carried out for the climate and hydrological data. At the same time, FAO's method was employed to calculate the agricultural water demand, with inputs including crop parameters (i.e., crop patterns, crop coefficients) and climatic data.

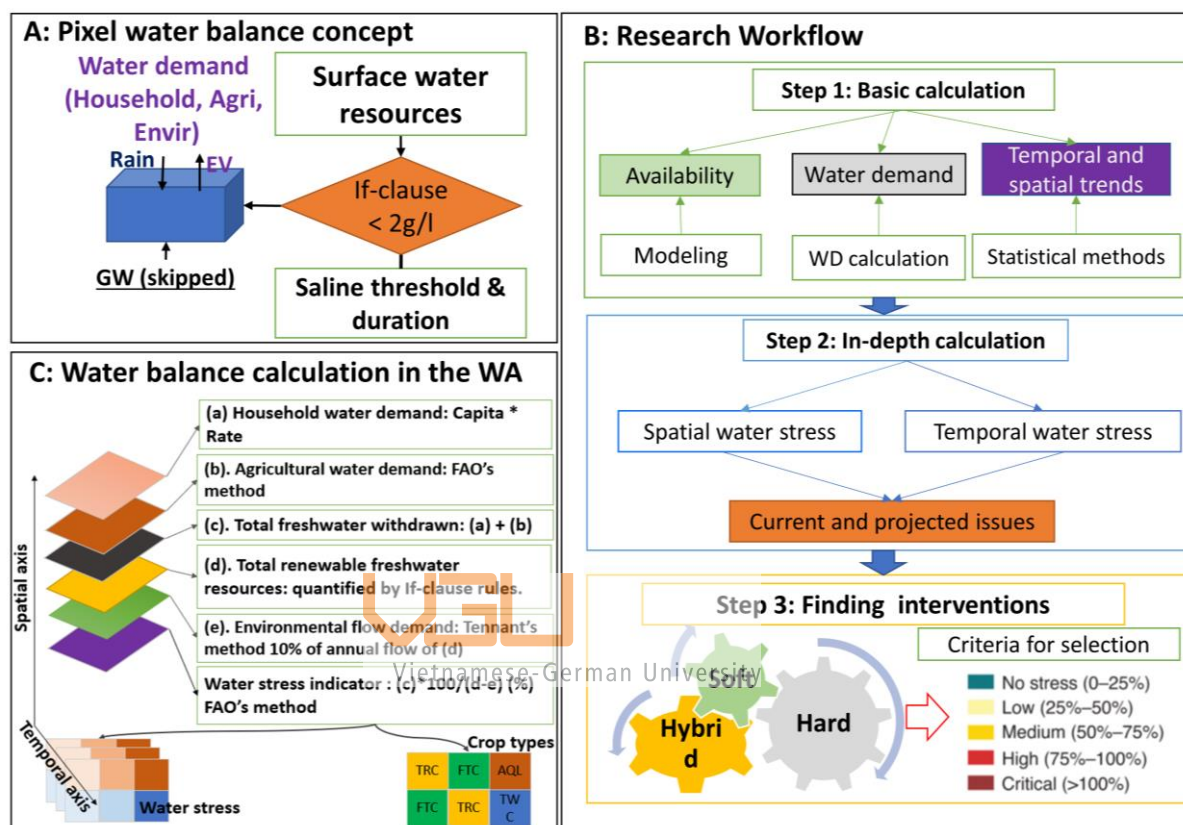


Fig.5. Research workflow of the study; Panel A indicates the pixel water concept for the water balance calculation; Panel B shows research steps in the analysis, which comprises three main steps (i) basic calculation, (ii) in-depth calculation, and (iii) investigations of the interventions.

Climate change scenario RCP 4.5 was used for the agricultural water demand calculation, projecting the water demand in agriculture by 2030. The population data were used as input for the household water demand calculation. In contrast, other input data, such as hydrological data, sea level rises, and projected upstream flow, were used for simulating scenarios by using the MIKE11 model. Additionally, in the second step, the total freshwater withdrawn was quantified by the sum of the agricultural water demand and the domestic water demand, while the environmental flow requirement was quantified by using Tennant's method. The total renewable water resources were quantified from the MIKE11 result, with salinity concentration non-exceeding 2g/l.

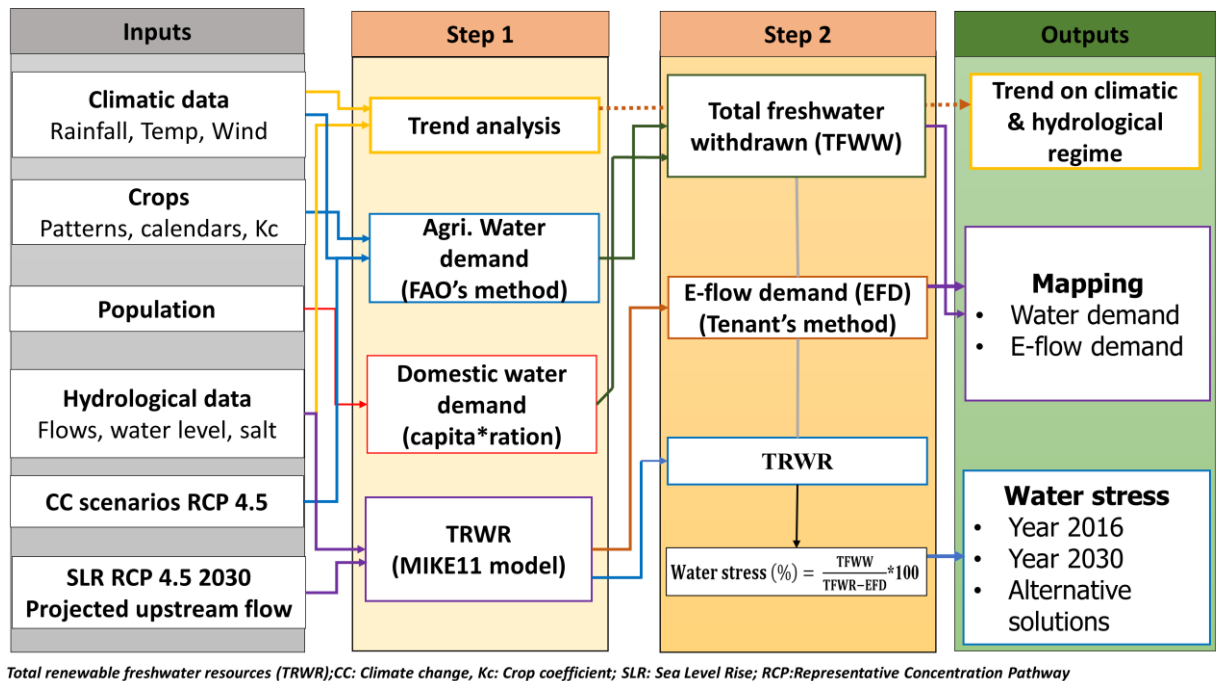


Fig.6. Interlinkages between inputs and processing stages and outputs of the research

3.2.2 Numerical modeling approach

Numerical modeling has become a crucial tool in water management, with three common models based on the number of spatial dimensions (D) simulated as 1D, 2D, and 3D (Herrera-Granados, 2010). Despite rapid developments in computing power that have been recorded (Middleton, Scheitlin, & Wilhelmson, 2005), the 1D numerical model is still widely employed in water management studies due to its flexibility in establishing scenarios and fast computational speeds. Several 1D models have been widely employed to quantify the water quantity and quality in the VMD, including MIKE11 (Nguyen Khoi, Ha, Trang, & Nguyễn, 2016; Thi Nhung, Le Vo, Van Nghi, & Quoc Bang, 2019), ISIS (ADB, 2013) and VRSA (Hoanh et al., 2009; Kam et al., 2001). In this study, the MIKE11 model was selected to simulate the water quantity and saline intrusion and evaluate the irrigation scheme in the study area.

• Model description

The MIKE11 model, developed by the Danish Hydraulic Institute (DHI) (DHI, 2014a), is a modeling package for hydraulic phenomena in rivers, lakes, canals, and other inland water systems. It also contains numerous functions to model hydraulic work operations (e.g., sluices, dams, pumps, embankments) in irrigation schemes.

There are several modules of the MIKE11 package, known as the hydrodynamic module, rainfall-runoff module, advection-dispersion module, sediment transport module, and Ecolab modules. The hydrodynamic module used fully dynamic descriptions to solve the Saint Venant equations that comprise vertically integrated equations of conservation of volume and momentum. The advection-dispersion (AD) module simulates dissolved or suspended material movements (e.g., saline intrusion, sediment transports). Salinity concentration is defined as a 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 addition, the rainfall-runoff module, MIKE11 NAM, is a lumped, conceptual rainfall-runoff model, modeling several components of runoff generation, including the overland-flow, inter-flow, and base-flow as a function of the moisture contents in four vertical storages (DHI, 2014b). In this study, the hydrodynamic, advection-dispersion, and rainfall runoff modules were used.

The MIKE11 model of the VMD has been developed by Southern Institute for Water Resources Planning (SIWRP) since the 2000s. It has been applied to numerous projects, including water resources planning, flood forecast, and water quality projection (SIWRP, 2014-2021, 2016-2012, 2016-2021). In this study, the SIWRP's MIKE11 network was used with updates on details of primary and secondary canals and sluice gates inside Ben Tre Province. Fig.7 shows the MIKE11 model network at the delta-wide level in Panel A and zooms into the model domain in Ben Tre Province in Panel B.

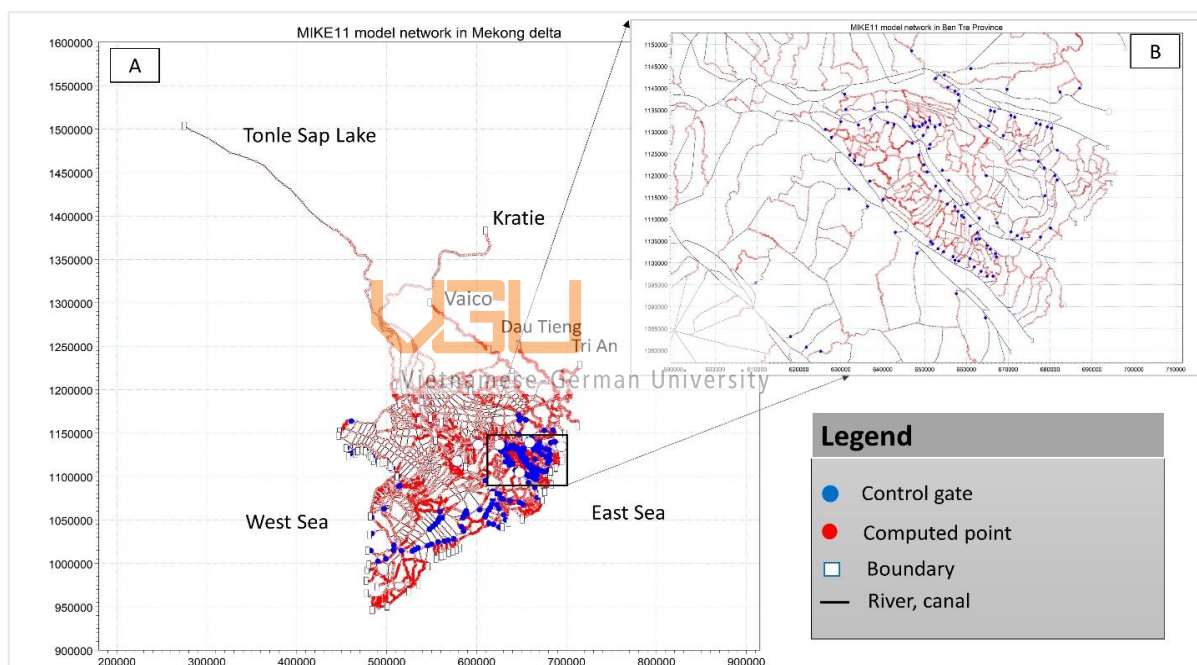


Fig.7. MIKE11 model network of the VMD (A) and zooming in Ben Tre Province (B)

The MIKE11 model network covers most of the rivers and primary canals of the Mekong flood plain in Cambodia and the Vietnamese Mekong delta. It comprises five upstream boundaries, three in Cambodia, including Kratie station, which observes water from the upstream part of the Mekong river basin, the Tonle Sap Lake, and the Vaico river as closed boundaries; and two boundaries in Vietnam at Dau Tieng reservoir and Tri An reservoir. There are 99 downstream boundaries at the mouths of rivers and canals in the West Sea coast and East Vietnam Sea coast of the VMD, as shown in Fig.7 Panel A.

For the model domain in Ben Tre province, there are a total of 250 branches (including rivers and canals), of which 50 are existing branches and 200 branches were newly added [see Fig.28 in the appendices], 13 main sluice gates (width ≥ 10 m) and 25 medium sluice gates (width < 10 m and ≥ 5 m) in the model [see Table 21.]. Most cross-sections of the updated branches in the model were sourced from a recent Ben Tre Water Management Project (JICA3) as well as various other relevant water projects in the Vietnamese Mekong Delta. For many secondary canals, there is missing data on

cross-sections, so cross-sections were created based on the canal width measured on Google Earth, and bed levels were estimated at -1 to -1.5 m, as shown in Fig.29 in the appendix.

• Model performance assessment

To evaluate the model's performance before simulating scenarios in the study, calibration and validation simulations were carried out in dry seasons (from January to June) in 2016 and 2020, respectively. Goodness-of-fit checks between simulated data and observed data were carried out by employing two common criteria, the Nash-Sutcliffe efficiency (**NSE**) in the equation (3-1) and correlation coefficient (**R²**) in the equation (3-2) (Eslami et al., 2019; Tran et al., 2018; Triet et al., 2017). The Nash-Sutcliffe efficiency varies from $-\infty$ to 1, with values close by 1 being the most optimal performance; otherwise, negative values signify inadequate performance (SASTRY, 2021). Additionally, the correlation coefficient indicates a linear relationship between two variables, ranging from -1.0 and 1.0, implying a perfect inverse relationship and a perfect relationship, respectively, while a value of 0 reflects no significant relationship. Comparison graphs between simulated and observed datasets were also created to evaluate the modeling fit to the observed data.

$$NSE = 1 - \frac{\sum_1^n (X_i - Y_i)^2}{\sum_1^n (X_i - \bar{X})^2} \quad (3-1)$$

$$R^2 = \frac{[\sum_1^n (X_i - \bar{X})(Y_i - \bar{Y})]^2}{[\sum_1^n (X_i - \bar{X})^2 \sum_1^n (Y_i - \bar{Y})^2]} \quad (3-2)$$

Where:



Y_i : Simulated value at the time i ; \bar{Y} : Average simulated value

X_i : Measured value at the time i ; \bar{X} : Average measured value

Results of the model performance assessments showed that the **NSE** values are more significant than 0.9, and **R²** values range from 0.98 to 0.99 at selected stations in the calibration simulation, as shown in Table 5. The highest values of **NSE** and **R²** were found at 0.97 and 0.99, respectively, at both My Hoa station in Ham Luong River and My Tho station in Tien River [station's location in Fig.3] compared to other stations in the calibration.

For the validation simulation, the **NSE** values approximate the **NSE** of the calibration, with most NSE exceeding 0.9. Similarly, the **R²** of the validated simulation is less than the calibration's **R²**, yet, these values are more significant than 0.95 in all stations. Compared to modeling performance categories of the **NSE** and **R²**, a very good category of **NSE** exceeds 0.85, while the **R²** of a very good category is larger than 0.85 (Moriassi, Gitau, Pai, & Daggupati, 2015); as a result, the model performance was considered to be very good for both **NSE** and **R²** of the water level and flow at the calibrated stations.

Comparisons between simulated and measured flow and water level at the calibrated stations were plotted and are presented in the appendix. For example, Fig.8 shows a linear relationship between simulated and observed discharge on the left-side graph; meanwhile, flow variations in March are compared between the simulation and observation on the right-hand chart.

For salinity comparisons between simulated and measured results, Fig.9 shows a good agreement between the simulated salt and the observed salt at measured data periods at My Hoa station in Ham

Luong river in the validated results. Similarly, acceptable results of the calibration and validation for salinity concentration were found at other stations, such as Tra Vinh, Son Doc, My Tho stations, which are shown in Fig.31 to Fig.33, Fig.35 to Fig.37 in the appendix.

Overall, good agreements on value and time variations of the validated simulation were revealed in these graphs. Conclusively, the model performance assessment results reflected that the MIKE11 was well calibrated and adopted high accuracies in simulating the hydrodynamic and salinity phenomenon in the study area.

Table 5. Calculated NSE and R² 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

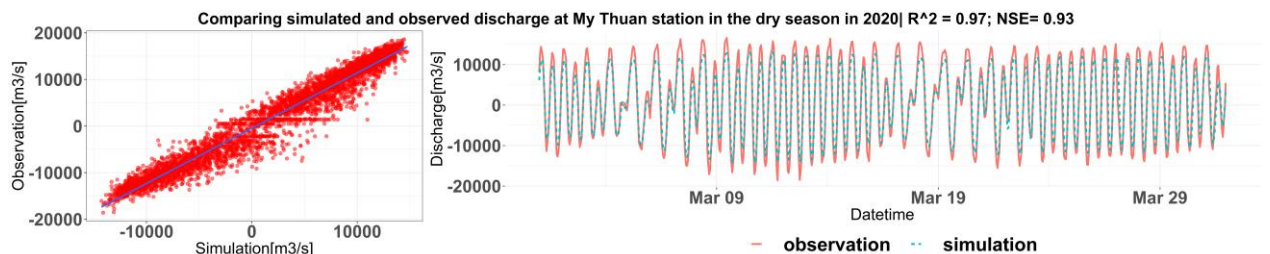


Fig.8. Comparison of simulated discharge against observed discharge at My Thuan station in the validated simulation

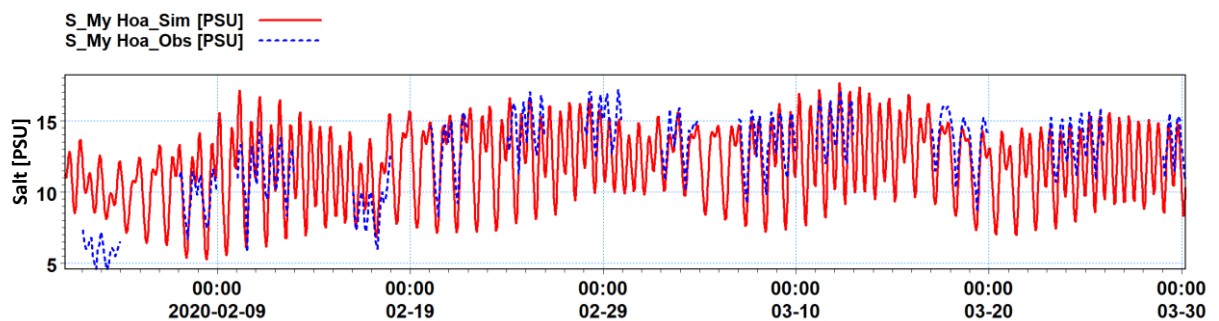


Fig.9. Comparison of simulated saline concentration against observed saline concentration at My Hoa station in the validated simulation

3.2.4 Water demand assessments

• Agricultural water demand

As mentioned above, the FAO irrigated water need calculation procedure (Allan et al., 1998) was applied to determine the agricultural sector's water demand in the study. Fig.10 shows a workflow to calculate the irrigated water needed for several crops, such as paddy, vegetable (maize), fruit trees, and aquaculture. Overall, agricultural land use was prepared in the grid with a pixel area of 1 ha. As mentioned in the land use and crop pattern descriptions, there are four major crops (i.e., triple paddy (TRC), double crops (TWC), orchard (FTC), and aquaculture (AQL)). Firstly, meteorological parameters (e.g., wind, sunshine, temperatures) were determined for each pixel using the Thiessen Polygon Method (Thiessen, 1911), weighting the meteorological station according to areas. Then, ET_o at each pixel was calculated by using the Penman-Monteith equation (FAO, (N.D)) using these climatic parameters at the pixel. Finally, the water demand of different agricultural crops was estimated by pixel, then aggregated over time and space, and used for the water balance calculations. The time window used for the water demand calculation is a 10-day period.

The data inputs of the water demand calculation were also prepared for each land use pixel, including crop schedules, ET_o , precipitation, K_c , required threshold for water layer in the paddy field, land preparation, water losses caused by percolation, and seepage. Major data inputs for the water demand calculations were determined before the water demand calculations, as follows:

- P_e is the effective rainfall, $P_e = P * \alpha$, where P is rainfall, α : Coefficient of precipitation, $\alpha = 0$ if $P < 5$ mm; $\alpha = 1$ if $(5 \text{ mm} < P < 50 \text{ mm})$, and $\alpha = 0.8$ if $P > 50$ mm (Phi, 2014). For aquacultural water demand calculation (P_{eq}), precipitation directly contributes to the water amount of the aquacultural ponds without losses.
- $PERC$, the amount of water loss caused by percolation and seepage. It was recommended to be 2 mm/day in Vietnam (MOST, 2012), leading to about 20 mm per timestep in the water calculation.
- K_c , crop coefficients were used for the calculation, as discussed in the section on materials, based on the standard table for paddy and maize (MOST, 2012). For fruit trees's K_c was taken as the K_c value of palm trees in the FAO recommendations.
- ET_o , the reference evapotranspiration, was determined by applying the Penman-Monteith equation (Allan et al., 1998), as presented below.
- SAT , the amount of water needed for land preparation, is used for the paddy water demand calculation. It is advisable to be from about 30 to 50 mm water depth in the rice fields before sowing (MOST, 2012).
- W_{Laq} , the water depth needed for the ponds at the beginning time of the aquaculture. It was found to be between 1.4 and 1.6 m water depth, according to a study carried out by Nguyen Phu Quynh, Do Dac Hai, and Vu Hoang Hoa (2015).
- S , cultured area of the paddy fields, orchard, and aquaculture. The cultivated area typically accounts for about 80% to 90% of one ha, while the cultured aquaculture area accounts for about 50% of one ha (Nguyen Phu Quynh et al., 2015).

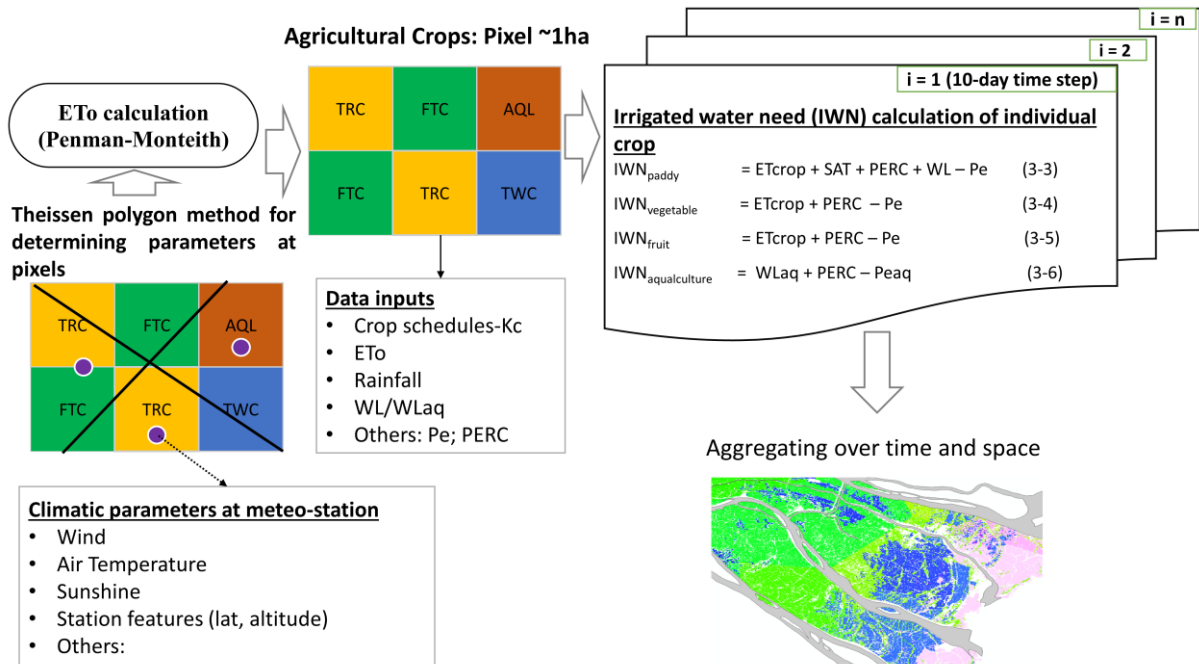


Fig.10. FAO water demand calculations for the individual crop in the study

The Penman-Monteith equation (FAO, (N.D)) is shown below.

$$ET_o = \frac{0,408 \Delta (R_n - G) + \gamma \frac{900}{273 + t} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0,34 u_2)} \quad (3-7)$$

Where:

- ET_o: reference evapotranspiration [mm day⁻¹],
- R_n: net radiation at the crop surface [MJ m⁻² day⁻¹],
- G: soil heat flux density [MJ m⁻² day⁻¹],
- T: air temperature at 2 m height [°C],
- u₂: wind speed at 2 m height [m s⁻¹],
- e_s: saturation vapour pressure [kPa],
- e_a: actual vapour pressure [kPa],
- e_s - e_a: saturation vapour pressure deficit [kPa],
- D: slope vapour pressure curve [kPa °C⁻¹],
- g: psychrometric constant [kPa °C⁻¹].

• Household water demand

To calculate domestic water demand, daily water use is estimated according to rations of the water supply imposed in Vietnam Building Code (QCXDVN 01: 2008/BXD), depending on the grades of urban areas; for higher grades, higher water supply rations. Table 6 shows the water supply ration corresponding to the urban categories in current and long-term planning in Vietnam (MOC, 2008).

Currently, three types of urban areas were adopted, including Ben Tre city, which was set as an urban category II, while other administrative units (town, districts, and rural areas) were set as urban categories III and IV.

By 2030, Ben Tre city will upgrade the town supply to grade I according to the master plan of Ben Tre Province to 2020, vision to 2050 (VDMA, 2020). In this study, the domestic water demand was calculated for the years 2020 and year 2030, corresponding to the water supply allowance rates of 120 liters/person/day for Ben Tre city and 80 liters/person/day for the rest of the areas in 2020, while 150 liters/person/day for Ben Tre city, and 100 liters/person/day for the remaining areas by 2030.

The current household water demand is determined by the equation (3-8), while the planned household water demand in 2030 is calculated by using the equation (3-9) as shown in Fig.11. Overall, the daily domestic water demand is obtained by multiplying the population with the water supply ratio corresponding to the urban grade categories.

The water demand result was then aggregated over time and space in the study in order to incorporate it into the water balance calculation.

Table 6. Water supply ratio based on urban grade categories in the next 10 years and next 20 years

Urban grade category	Water supply ration in the next 10 years [liters/person/day]	Water supply ration in the next 20 years [liters/person/day]
Special	≥180	≥200
I	≥150	≥180
II	≥120	≥150
III,IV, V	≥80	≥100

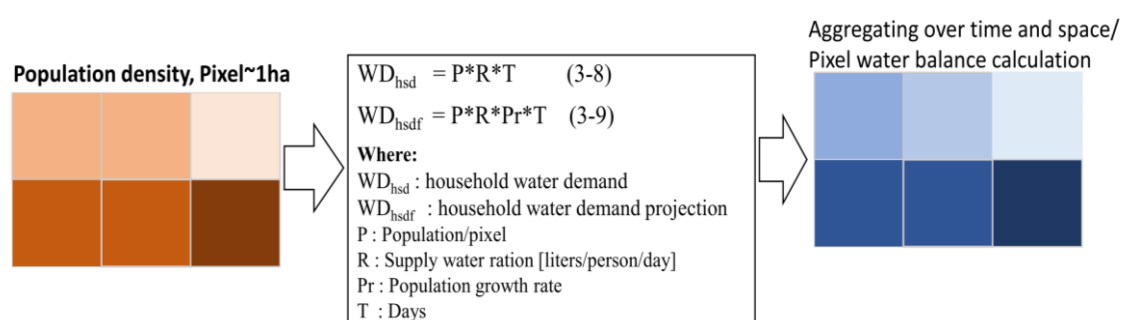


Fig.11. Method for domestic water demand calculations in current and planned conditions

3.2.5 Environmental water demand and water stress index calculations

• Environmental water demand calculation

In this study, the Tennant method, introduced by Tennant (1976), was selected to determine water requirements for the environment based on limitations of ecological inputs that are strictly required for

other ways, such as holistic and habitat methods. Additionally, this method is considered suitable for the planning study and only requires flow data (Bussettini, 2018). A threshold of 10% of the average annual flow was selected as a minimum flow to maintain a majority of aquatic living forms' environment for short-term survival.

• Water stress indicator calculation

To incorporate the environmental flow into the water stress indicator, FAO (2019) recommended the below formula that describes the amount of water that is still left and accessible in the environment. It provides an estimation of the pressure being placed on renewable freshwater resources in basins and nations by all water users.

$$\text{Water stress (\%)} = \frac{\text{TFWW}}{\text{TRWR} - \text{EFD}} * 100 \quad (3-10)$$

Where:

TRWR stands for Total Renewable Water Resources refers to the surface freshwater availability quantified by the MIK11 model considering the saline threshold for usable freshwater.

TFWW is defined as the sum of the relevant withdrawals in two main sectors of agriculture and domestic water supply.

EFD refers to the environmental flow requirements that are quantified by Tenant's method, as 10% of the annual renewable freshwater resources.

According to FAO's recommendation on the usual range for irrigation water, Chloride varies from 0 to 30 me/l (FAO, 1994). To determine a threshold for saline concentration that was used to separate usable and unusable surface water in the assessment of the freshwater sources. A relationship between Chloride and salinity concentration is described by a formula introduced by United Nations Educational Scientific and Cultural Organization (UNESCO) in 1967².

$$S_{\%o} = 1.80655 \text{ Cl (\%o)} \quad (3-11)$$

Where:

S‰: Salinity concentration in the simulation

Cl (‰): Chlorinity concentration

To determine the threshold of saline concentration for usable water in the irrigation, apply the formula above, obtaining the salinity concentration is about 2 g/l.

$$S = 1.80655 * 30 * 35.5 / 1000 = 1,924 \text{ g/l} \sim 2 \text{ g/l.}$$

Where:

35.5: Chloride weight (mg/mol)

30: The upper level of chlorinity concentration of the usual range for the irrigation (me/l)

² [https://www.eps.mcgill.ca/~courses/c542/CHOC_Week%20a\(Seawater&Salinity\)_2020.pdf](https://www.eps.mcgill.ca/~courses/c542/CHOC_Week%20a(Seawater&Salinity)_2020.pdf)

The FAO water stress indicator formula was used, in combination with some adjustments that were made to be suitable for the study. Fig.12 indicates the surface water resources' components in the study. Overall, the total renewable freshwater resources were considered to be the surface freshwater with saline concentrations non-exceeding 2 g/l. Specifically, the salinity concentration exceeding 2 g/l is generally not recommended for use in agriculture and the domestic water supply. To quantify the total renewable freshwater resources, a time window used for calculations is a weekly (~10 days), similar to FAO perspectives on the water demand calculations in agriculture. In detail, a median value of the daily average salt concentration was determined on a weekly basis for the water flow volume at a specific pixel. As a result, the total usable freshwater amount at the pixels is the sum of water flows with weekly salt concentration non-exceeding 2 g/l, as shown in Fig.12 Panel B.

The water stress level is classified into five categories corresponding to different proportions of the total freshwater withdrawn to the total renewable freshwater resources, after taking into account the environmental water demand, including No stress (0-25%), Low (25-50%), Medium (50-75%), High (75-100%) and Critical (>100%). Accordingly, values below 25% can always be deemed safe (no stress); however, levels above 25% should be considered potentially and increasingly hazardous and should be qualified and reduced (FAO & UN Water, 2021).

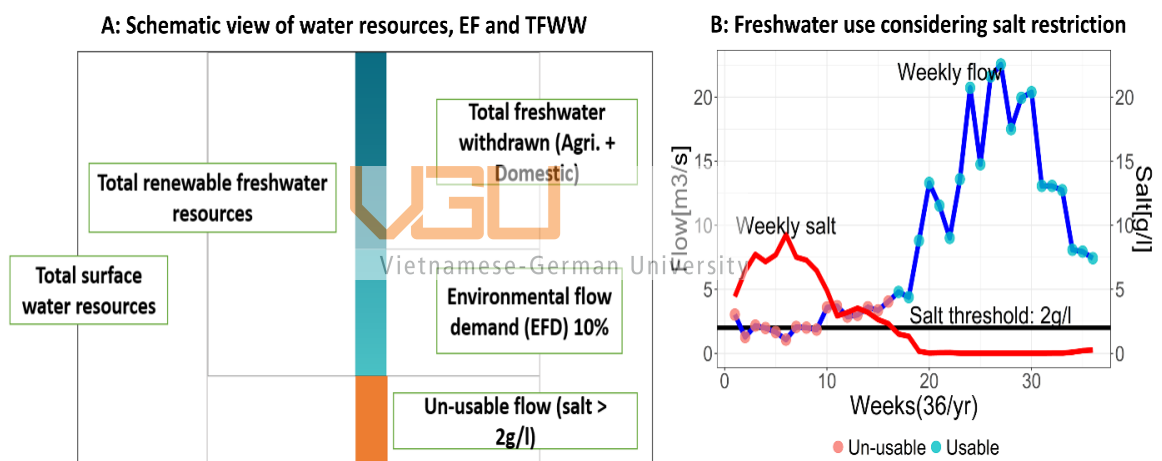


Fig.12. Illustration of the surface water resources, environmental flow demand, and total freshwater withdrawn (Panel A: sourced by (FAO, 2019) modified by the author); Panel B indicates how to quantify the total renewable freshwater considering salt concentration criteria in weekly periods. In particular, the total renewable freshwater was a sum of weeks, with saline concentrations non-exceeding 2g/l.

3.2.6 Correction of the open-source data and trend analyses

- **Correcting and projecting population data**

As mentioned in the data source section, the population density map was retrieved from open-source data, which was generated in 2015. Therefore, the map was corrected to match the population in 2020 based on the statistical book of Ben Tre Province. The total population in 2015 was calculated based on district boundaries. A ratio of the total population by district scale between the year 2015 and the year 2020 was determined. As a result, the population density map in 2020 was produced by the district population ratio multiple with the map in 2015.

For population projections, according to a study carried out by General Statistic Office (GSO) (2020), the total population of Ben Tre Province was forecast to be 1,282,176 by the year 2030, slightly decreased compared to the year 2020 (1,288,463). A ratio of population growth rate between the current and future by 2020 was determined by the total predicted population over the current total population. Consequently, the year 2030 population density map is generated using the population growth ratio multiple with the population density map in 2020. High density populations are found in the Ben Tre city and town centers, with population density ranging from 100-200 people/ha. In contrast, the population density is less than 30 persons/ha in rural areas. Moreover, there are insignificant changes in population density comparisons between the year 2020 and the year 2030

• Trend analyses

The trend analyses were carried out to reveal changes in climatic parameters (e.g., rainfall, air temperature, humidity, sunshine, evaporation, ETo, and wind speed) and hydrological parameters (e.g., flows and saline intrusion) in the study area. The hydrometeorological dataset was used for the trend analysis, collected from 2005 to 2020. Non-parametric Mann-Kendall trend test and Sen slope estimator were used to conduct the monotonic trends. The Mann-Kendall test was introduced by Mann (1945) and further developed by Kendall (1975), while the Sen slope estimator is a simple non-parametric method developed by Sen (Sen, 1968) (Sen, 1968). The monotonic tendency is identified by the Sen slope equation (3-12). For the Mann-Kendall test, the first step is to calculate the difference between values at time j and i by using the indicator function (3-13). Then, the mean and variance of quantity in the first step are computed using equations (3-14) and (3-15), respectively. The Mann-Kendall test statistic was calculated by using the equation (3-16). A positive value of Z_{MK} indicates the data set tend to increase with time. In contrast, a negative Z_{MK} indicates the data set tend to decrease with time.

$$S = \text{Median} \left(\frac{x_j - x_i}{j - i} \right), j > i \quad (3-12)$$

(x_i, x_j) : pairs of time series elements where $i < j$

$S > 0$ indicates the upward trend and versa downward trend.

Equations of the Mann-Kendall test:

$$\text{sgn}(x_j - x_i) = \begin{cases} +1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases} \quad (3-13)$$

$$E[S] = \sum_{i=1}^{n-1} \sum_{j=i+1}^n (x_j - x_i) \quad (3-14)$$

$$\text{VAR}[S] = \frac{1}{18} \left(n(n-1)(2n+5) - \sum_{k=1}^p q_k (q_k - 1)(q_k + 5) \right) \quad (3-15)$$

$$Z_{MK} = \begin{cases} \frac{E[S]-1}{\sqrt{\text{VAR}[S]}}, & E[S] > 0 \\ 0, & E[S] = 0 \\ \frac{E[S]+1}{\sqrt{\text{VAR}[S]}}, & E[S] < 0 \end{cases} \quad (3-16)$$

Where:

$E[S]$: Mean

$VAR[S]$: Variance

p : Total number of tie groups

q_k : Number of elements contained in the k -th tie group

Z_{MK} : The Mann-Kendall test statistic

n : Length of the dataset.

3.2.6 Climate change scenario selection

The climate change scenarios for Vietnam are officially provided by MONRE of Vietnam, with several versions in 2009, 2012, and 2016 and the latest one in 2020. In this study, the projected climatic and sea level rise by 2030 in the climate change scenarios for Vietnam was used for the calculation. The RCP 4.5 scenario, a moderate greenhouse emission was selected according to recommendations on selection for climate change scenarios for planning and management (MONRE, 2020).

Table 7 shows the projection of climate (air temperature, precipitation) and sea level in RCP 4.5 and RCP 8.5 in Ben Tre province. Overall, the air temperature is projected to increase by 0.7 °C on average, while the rainfall is projected to increase by 17 %, and the sea level is projected to rise by 12 cm in the period 2016-2035.

Table 7. The projected climatic and the sea level rise in the climate change scenarios in the interest area (source: (MONRE, 2016a, 2020))

Scenarios	Period	Air temperature [°C]	Rainfall [%]	Sea level rise [cm]
RCP4.5	2016-2035	0.7 (0.4÷1.2)	17.0 (10.1÷23.2)	12 (7÷17)
RCP8.5	2016-2035	0.8 (0.5÷1.2)	14.7 (9.7÷19.8)	14 (10÷18)

The projected upstream flow by 2030 used for hydraulic simulation for determining water inflow into Ben Tre Province in 2030 was sourced from the results of a study carried out by Whitehead et al. (2019).

3.2.7 Scenario formulation & criteria for measure selection

To achieve the study objectives, scenarios were formulated as shown in Fig.13. Overall, a baseline scenario, the year 2016, was carried out to figure out how adequate the current irrigation system is. The year 2016 was recorded as a historic drought and saline intrusion event (CGIAR, 2016; VDMA, 2016), and so it was selected for the current assessment of water management in Ben Tre Province. The second step was to assess the planned measures by 2030 planning to enclose a part of the province to keep the freshwater environment and to protect the high tide, and sea level rises, as shown in Fig.2. If the planned solution does not meet the criteria in the water management, several other measures will be investigated for incorporation into the planned solution. The dry season (including Dec, Jan to May) was selected for analysis in the study. Furthermore, the hydraulic simulation was carried out for the whole year to determine the incoming flow that is input on the environmental flow calculation.

To evaluate the efficiency of the proposed measures, the water stress indicator was used in the study. Particularly, the criteria for selecting the most suitable solution is if the water demand of the water

users is ensured in the protected area and the area affected by water stress is minimal among the proposed measures.

For boundaries for the simulation, in scenario 2016, upstream and downstream boundaries were used as historical datasets, while the agricultural water demand was used as the average value between 2005 and 2020, and the household water demand was calculated in 2020. To highlight the influence of the climate changes on agricultural water demand, the past long-term period of 16 years from 2005 to 2020 was selected for comparison with that of agriculture’s water demand under the RCP.4.5 scenario in 2030. In contrast, the last available population data in 2020 was chosen for the domestic water demand calculation in the current condition.

In the scenarios Year 2030 and Year 2030*, the projected sea level rise RCR4.5 by 2030 was added to the water level boundary, while climate change scenario RCP 4.5 was used to calculate the agricultural water demand. The projected values on climate and sea level rise are shown in Table 7. 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. (2019). The comparison flow in 2016 and the 95th percentile projected flow by 2030 is shown in Fig.27 in the appendix. Detailed information on the simulated scenarios is given in Table 8.



Fig.13. Process for carrying out scenarios to find out the suitable measures improving the water management sustainability

Table 8. Summaries of information on the simulated scenarios in the study

Simulated scenarios	Boundary	Water supply solution
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
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 + additional interventions that are presented in Section 4.5 in Chapter 4

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1 PATTERNS AND TREND ANALYSES OF CLIMATE AND HYDROLOGY

4.1.1 Climatic analysis results

The results of characteristic and trend assessments of climatic and hydrological parameters in Ben Tre province are presented below. For climatic assessments, monthly variations of climatic factors (i.e., precipitation, humidity, temperature, and sunshine) are analyzed from 2005 to 2020, as shown in Table 9. Linear trends of these parameters were obtained, as shown in Fig.14.

The ET_o of Ben Tre province was calculated from 2005 to 2020 and projected to 2030 according to the climate change scenario RCP4.5 as mentioned above. The results of the ET_o projections obtained are summarized as monthly amounts and trend for the period 2005 to 2020, as presented in Fig.15.

The monthly climatic parameters (i.e., rainfall, evaporation, humidity, average temperature, and sunshine) were analyzed from 2005 to 2020. The dry season precipitation was about 288.5 ± 193.4 mm, accounting for about 19% of the annual rainfall of about $1,501.9 \pm 525.1$ mm. The lowest rainfall occurs in February, with an average value of 3.3 ± 7.3 mm. In contrast, the evaporation of the dry season was estimated to be 647.5 ± 102.8 mm, approximately 2.5 times the rainfall in the dry season, and the most significant evaporation peaks in March at about 125.1 ± 16.3 mm. The humidity of the dry season was about 79.8 ± 1.5 %, lower than the average annual value of 82.7 ± 1.5 %. In contrast, the average air temperature was estimated as 27.3 ± 0.5 °C, and 27.4 ± 0.4 °C in the dry season and the yearly, respectively. For the sunshine duration, a figure of the dry season sunshine was about $1,332.1 \pm 129.1$ hours, accounting for about 60 % of the annual sunshine $2,182.8 \pm 232.9$ hours.

Regarding the trends in the climatic drivers, linear trends in the climatic parameters were visualized in Fig.14. Overall, the trends were increasing for the three variables of average temperature, wind speed, and sunshine; however, rainfall and humidity showed declining tendencies from 2005 to 2020. The increasing trend in the temperatures agreed with the result of increasing temperatures recorded at all stations in the Delta, found by Vo Quoc Thanh et al. (2021). However, the rainfall was found to have an inverse trend compared to other studies (MONRE, 2020). It could come from different lengths of datasets that influence the results of trend analysis (Weatherhead et al., 1998). Additionally, the rising trends in climatic parameters could cause increasing the water demand, especially in the agricultural sectors. Similarly, Xiaojun Wang et al. (2014) have revealed that despite the fact that demand will vary greatly depending on geography and climatic factors, climate change will increase the world's need for water. Agriculture will be more negatively impacted than other industries by the need for water. Lee and Truong An (2017) have found that the ET_o and Etc were increased by 2.1 and 2.2 %, respectively, in the RCP4.5 scenario for the 2020s, 2055s, and 2090s-time scales for Long Xuyen Quadrangle area of Vietnam. In this study, ET_o in 2030 was projected to increase by 2% compared to the average ET_o from 2005 and 2020, as shown in Fig.15. The increasing trend in ET_o is similar to the trend in the temperatures in the same period. Further, the ET_o peaks in March and April at approximately 150 mm. Consequently, the water demand by 2030 will be increased in the agricultural sector in this study.

Table 9. Summaries of average and standard deviations in basic climatic parameters in Ben Tre Province from 2005 to 2020

Month	Rainfall±sd [mm]	Evaporation±sd [mm]	Humidity±sd [%]	Temperature±sd [°C]	Sunshine±sd [hours]
Jan	12.3±15.6	104±20.6	79.6±1.6	25.7±0.6	194.6±18.1
Feb	3.3±7.3	111.5±19.9	78.3±1.6	26.3±0.5	240.3±16.9
Mar	10.4±18.5	125.1±16.3	78.2±0.9	27.6±0.3	263.4±22.5
Apr	37.7±33.9	117±11.6	78.3±1.3	28.9±0.4	247.5±21.9
May	180.1±79.6	96.2±16.7	82.6±1.8	28.9±0.6	208.8±19.8
Jun	200.8±38.8	79.1±10.4	85.4±1.8	28±0.2	167.3±17.2
Jul	210.6±42.4	82.5±8.1	85.7±1.6	27.5±0.2	170±19.9
Aug	200.7±55.2	84.4±9.7	85.8±1.6	27.5±0.2	187.3±22.6
Sep	253.3±63.6	71.6±9.2	86.7±1.6	27.2±0.3	151.9±17.6
Oct	253.6±69.4	70.8±7.5	85.7±1.8	27.3±0.3	178.4±25.4
Nov	94.4±62.3	83.5±10.9	83.9±1.3	27.3±0.4	190.4±19.2
Dec	44.7±38.5	93.7±17.7	81.9±1.6	26.3±0.5	177.5±29.9
Dry season	288.5±193.4	647.5±102.8	79.8±1.5	27.3±0.5	1,332.1±129.1
Year	1,501.9±525.1	1,119.4±158.6	82.7±1.5	27.4±0.4	2,182.8±232.9

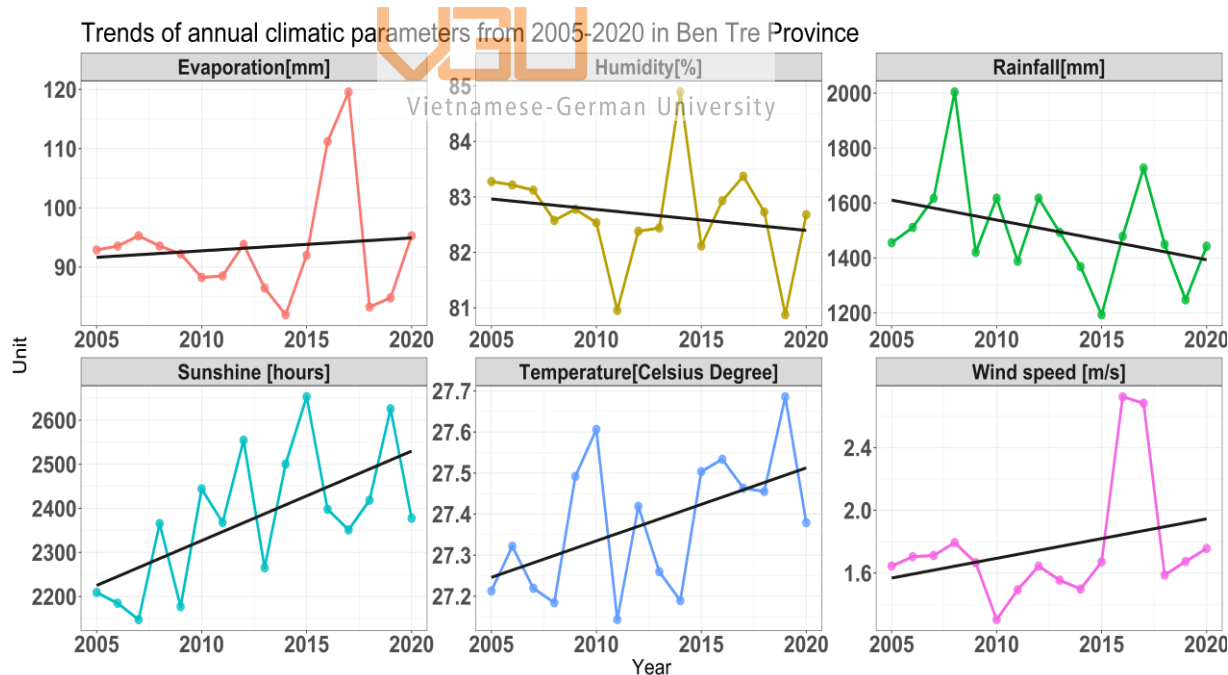


Fig. 14. Trends of the climatic parameters from 2005-2020 in Ben Tre Province



Fig. 15. (A) Variations of monthly average ET_0 from 2005 to 2020, (B) annual ET_0 trends from 2005 to 2020, and (C) comparing the historical monthly averaged ET_0 and projected ET_0 by 2030.

4.1.1 Hydrological analysis results

Regarding the hydrological assessment, several parameters, such as flow, water level, and salinity concentration in stations along main rivers in the study area, were assessed from 2005 to 2020. Flows at the My Thuan station, located upstream Ben Tre province were obtained - monthly summaries and flow trend analysis of the lowest flow month of April are summarised and presented in Table 17. Similarly, for salt data at the Son Doc station, pattern and trend assessments are shown in Fig.16. Trend analyses of water level and salinity concentration from 2005-2020 were carried out at stations along coastal regions and mainstream in Ben Tre province, are shown in Table 10. The locations of these hydrological stations are shown in Table 1 & Fig.3. The trend results of the water level and salt intrusions at stations along main rivers are presented in Table 10. The flow pattern and trend in flow at My Thuan station and salt at Son Doc station in April are shown in Fig.16.

The results of salt trend analysis were carried out at stations along mainstreams, which are shown in Table 10 in Chapter 4. Overall, stations on the Ham Luong river (e.g., Son Doc, An Thuan) and on the Co Chien river (Huong My) were found to have rising trends in the saline concentrations. In contrast, downward trends in the saline concentrations were found at stations on the Tien River. That means the saline intrusions varies in the different river during the estimated over period. The increasing trends in saline intrusions in the Mekong Delta have been revealed in a number study (Eslami et al., 2021; Loc et al., 2021). Similarly, the upward trends in the water level were recorded in all stations in the study area. The results aligned with a study conducted by Binh et al. (2020).

For the upstream flow, annually, the study area receives about 204 km³ in total and a monthly average of 17 km³ from 2005 to 2020. The lowest flow occurs in April, and March is approximately 4,7 km³. By contrast, the highest flow was recorded in October, about 35,5 km³. In recent years, the flow in April was found to be an upward trend, as shown in Fig.16A, agreed with studies (Binh et al., 2020; MRC, 2018). Yet, the saline intrusion trend was recorded to also be increasing; for example, Fig.16D indicates an increasing trend in maximum salt at Son Doc station, Ham Luong River. Consequently, the saline isoline intruded further upstream, although the flow was found to be on an upward trend in recent years and difference in rivers. The signal was found to be aligned with a study conducted by Eslami et al. (2021). It has revealed saline intrusions in the Mekong delta caused by sea level rise can increase salinity-affected areas by 5–19%. Other anthropogenic causes, including extraction-induced subsidence and riverbed level reductions owing to sediment hunger, can raise it by another 10%–27%.

Table 10. Results of water level and salt trend analysis using the Mann-Kendall trend test and Sen slope estimator. The annual values were summarized from the data set in 16 years, from 2005 to 2020, in the trend tests.

Station	Parameters	P-value	Slope	Kendall's Tau	Years	Annual changes [%]	Trend
Son Doc	Salt	0.79	0.08	0.06	16	7.69	upward
Loc Thuan	Salt	0.02	-0.40	-0.43	16	-39.05	downward
Huong My	Salt	0.28	0.22	0.22	15	30.89	upward
An Thuan	Salt	0.06	0.20	0.35	16	11.44	upward
Binh Dai	Salt	0.19	-0.15	-0.25	16	-9.00	downward
Ben Trai	Salt	0.02	-0.24	-0.44	16	-14.58	downward
An Thuan	Water level	0.13	0.00	0.29	16	3.301	upward
Ben Trai	Water level	1.00	0.00	0.00	16	0.000	upward
My Thuan	Water level	0.03	0.02	0.42	16	18.301	upward
My Hoa	Water level	0.09	0.01	0.33	16	8.683	upward
Cho Lach	Water level	0.39	0.01	0.17	16	8.972	upward

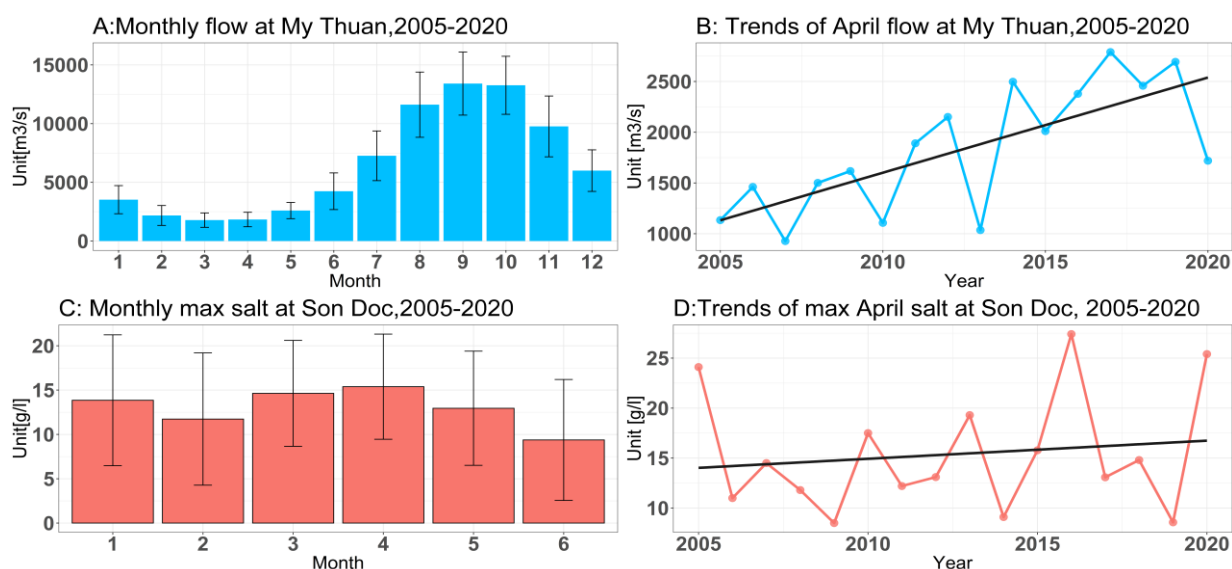


Fig.16. Flow patterns and April flow trend at My Thuan stations and salt patterns and April salt trend at Son Doc station, 2000-2020

4.2 WATER DEMANDS AND SURFACE WATER AVAILABILITY IN THE YEAR 2016 AND YEAR 2030

4.2.1 Water demands in the year 2016 and year 2030

The water demand calculation carried out of the agriculture, domestic, and ecosystems in the protected area are presented as follows. To evaluate the impacts of climate changes on the water demand, the average agricultural water demand for the period from 2005 to 2020 was calculated, compared to the water demand by 2030 under the RCR 4.5 scenario, as shown in Fig.17. The average agricultural water demand in the historical period was determined as the scenario for 2016. The household water demand calculations it was obtained by using the latest population in 2020 and the projected population in 2030 in the study area, as shown in Fig.18. For the environmental flow requirements, both water volume and water flow demand were determined by using the Tennant method. Fig.19 shows the results of the environmental flows by pixel in the study area. In addition, monthly summaries of the water demand of all water users in the study area are shown in Table 11. And detailed sectoral water demand in agriculture is presented in Table 18 & Table 19 in the appendix.

The agricultural water demand results of the scenario Year 2016 and Year 2030 are presented in Fig.17. Overall, higher water demands were found at the rice paddy in lower parts of the study area, with total water demand ranging from 7 to about 9 thousand m^3 per ha, while the fruit tree demand was recorded at less than 7 thousand m^3 per ha in the dry season. As mentioned, due to climate change, the water demand in the year 2030 is higher than in the year 2016; for example, in Mo Cay Nam district, approximately 6 thousand m^3 per ha in the year 2016, and about 7 thousand m^3 per ha in the year 2030. For total water demand in the dry season, the increased value by the Year 2030 was found to be 2% (~14 million m^3) higher than for the Year 2016 [see Table 11].

Similarly, the projected household water demand was found to increase by 26% (4,83 million m^3) by the year 2030 [see Table 11]. This could be explained by increases in water supply rations according to the urban grade. Fig.18 shows the household in the year 2020 and year 2030. Generally, upward trends were found in the urban areas, such as Ben Tre city, or in towns of the districts, ranging from 500 to 1500 m^3 per ha, while other regions have less than 500 m^3 per ha.

Environmental flows were represented in water volume and water flows, as shown in Fig.19. The environmental flow was calculated in the freshwater areas and disregarded the open water, such as big rivers. It was also represented by pixels as other variables, such as water demand. The environmental water demand ranges from less than 100 m^3 to approximately 1000 m^3 , with smaller magnitude in areas with small canals, for example, in the Ba Tri and Mo Cay Nam districts. The upper parts of the freshwater area have more significant environmental water demand ranging 500 to 1000 m^3 . Environmental flows, vary from less than 1 m^3/s to 3 m^3/s in remote areas from the mainstream, while for regions with large canals, the environmental flows range from 5 to 10 m^3/s .

For comparing the water consumption across the different water users, agriculture's water demand of around 857.6 million m^3 was significantly higher than the household demand of approximately 19.3 million m^3 in the dry season in the period of 2005-2020. Likewise, the agricultural water consumption is estimated to be the highest among all water users by 2030. It is aligned with the conclusion that agriculture is the most water-intensive sector, accounting for more than 85% of total human water consumption (D'Odorico et al., 2020).

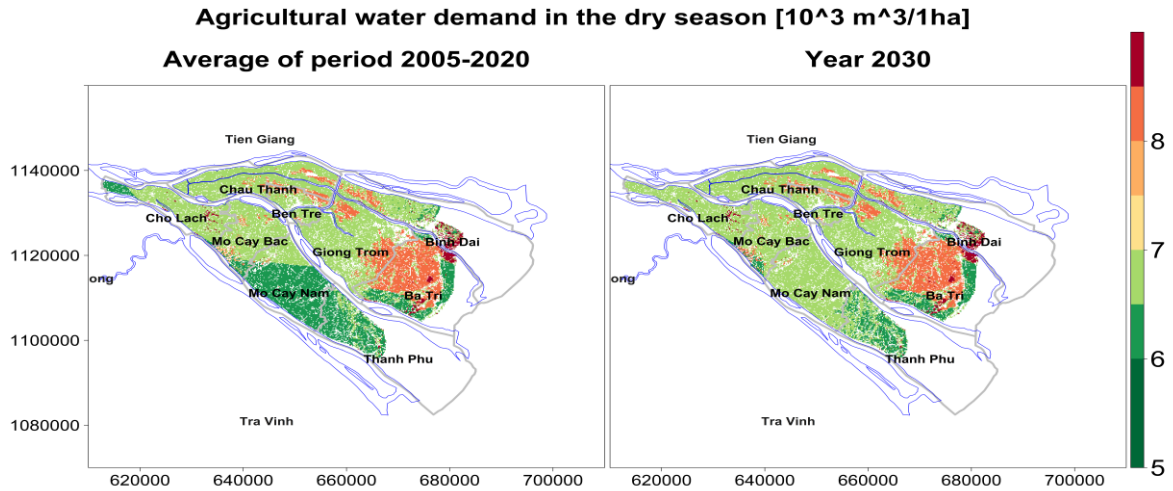


Fig.17. Comparing the average agricultural water demand of the period of 2005-2020 and the agricultural water demand of the Year 2030 in the dry season.

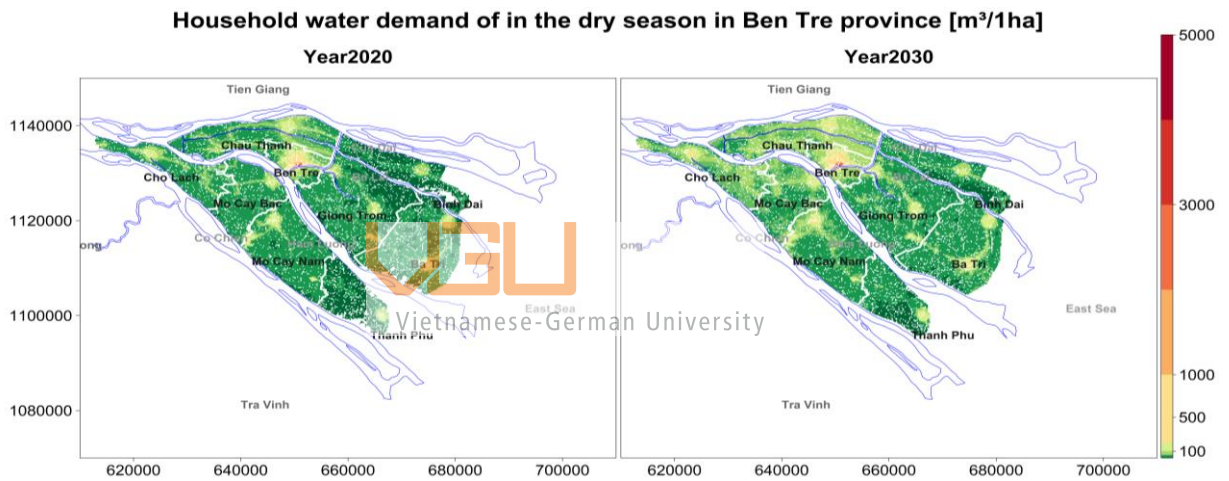


Fig.18. Comparing household water demand in the Year 2020 and Year 2030 in the dry season.

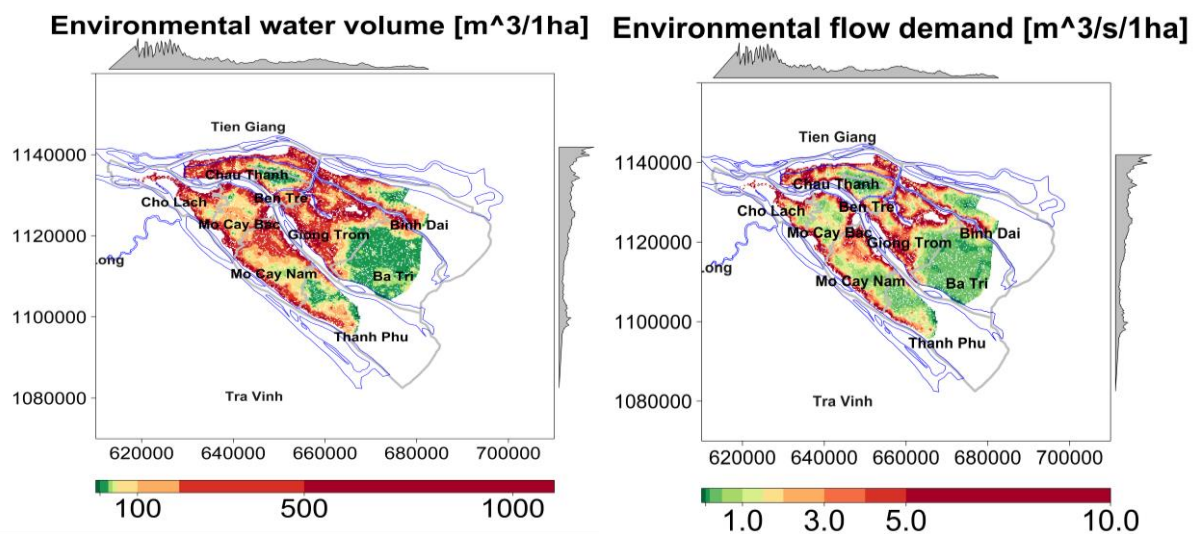


Fig.19. Environmental water volume demand (left) and Environmental flow demand (right)

Table 11. Water demand of all water users in the current and future conditions (Unit: 10⁶ m³)

Month	Agriculture from 2005-2020	Agriculture Year 2030	Household Year 2020	Household Year 2030	E-Flow
Jan	135.2	136.9	3.3	4.1	723
Feb	169.2	171.5	3.0	3.7	723
Mar	194.7	197.5	3.3	4.1	723
Apr	164.8	167.2	3.2	4.0	723
May	75.3	78.1	3.3	4.1	723
Jun	51.2	53.7	3.2	4.0	723
Jul	52.4	54.8	3.3	4.1	723
Aug	44.3	46.5	3.3	4.1	723
Sep	25.6	26.9	3.2	4.0	723
Oct	39.7	41.9	3.3	4.1	723
Nov	107.0	109.0	3.2	4.0	723
Dec	118.4	120.4	3.3	4.1	723
Dry season	857.6	871.5	19.3	24.1	
Year	1,177.9	1,204.4	38.7	48.4	

4.2.2 Total water demands compared with total surface water availability of the year 2016 and year 2030

Comparisons between the total water requirements of all water users to available surface water resources in the present and given climate change and anthropogenic influences in the study area are shown in Table 12.

Comparisons of total water demands including the agriculture, household and environment with total freshwater availability in the current and future conditions are shown in Table 12. Total freshwater availability in the year 2016 was recorded at about 25.5 km³, while it was found to be 23.37 km³ in the dry season for year 2030. The total water demand of all water users was approximately 20% and 22% in the year 2016 and in the year 2030, respectively. It indicates that there is an abundance of freshwater sources for water demand. However, the freshwater source is unevenly distributed in spatial and temporal and saline intrusion, causing limitations of usable water in the study area. Further details are present in the assessment of the current and planned irrigation system efficiency in the next section.

Table 12. Summary of total water demand and total surface water availability in the scenarios of Y2016 and Y2030 in the study area (Unit: km³)

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	23.37	5.234
Year	144.55	9.893	127.04	9.929

4.4 ASSESSMENTS OF THE CURRENT AND PLANNED IRRIGATION SYSTEMS EFFICIENCY



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The water management efficiency of the irrigation system and the planned irrigation system by 2030 were evaluated by considering salinity concentrations and water stress indicators. Particularly, max saline intrusion maps were generated in both scenarios of the Year 2016 and Year 2030, showing the efficiency of the planned solution in terms of saline intrusion control, as shown in Fig.20. By contrast, the impacts of sea level rise on saline intrusion are seen by mapping the duration of salinity concentration exceeding 2g/l in both the current condition and future condition by 2030 with simulations based on the existing irrigation system, as shown in Fig.21.

Additionally, water stress indicator maps were made for scenarios to evaluate the efficiency of the irrigation system in 2016 and 2030 using five levels of the water stress degree, as shown in Fig.22. Areas affected by the different water stress categories were quantified in the scenarios, are presented in Table 13. Crop areas affected by the water stress are compared between the scenarios for 2016 and 2030, as shown in Fig.23.

For saline intrusion, Fig.20 shows the maximum saline intrusion in the scenario Year 2016 and Year 2030. Overall, due to the sluice gates not being completely installed along the study area, the saline intrusion covers over 85% of the Ben Tre province. The results of maximum saline areas in the year 2016 determined here are well aligned with the study conducted by the UN (2020). By contrast, the freshwater area was protected from saline intrusion in 2030 by the planned irrigation system. However, due to climate change impacts, the saline intrusion in the mainstream extends further upstream than for the historical case. Consequently, the time that water intake from sluices can occur is limited. Fig.21 indicates the saline intrusion duration in the scenario year 2016 and year 2030. In general, the available days for taking water in the year 2030 were reduced in the upper part of the study area. For water stress assessments, Fig.22 shows the water stress status of the scenario year 2016 and year 2030 in the dry season. Overall, almost all freshwater areas were affected by the medium

water stress, approximately 81.760 ha (57,7% of the study area), while remote parts of the freshwater area were affected by the water stress, about 16.220 ha (11.4% of the study area) [see Table 13]. In summary, the planned irrigation system could not protect about 11.4% of the study area in the year 2030. Thus, additional measures were recommended to incorporate into the planned solution for reducing the water stress areas.

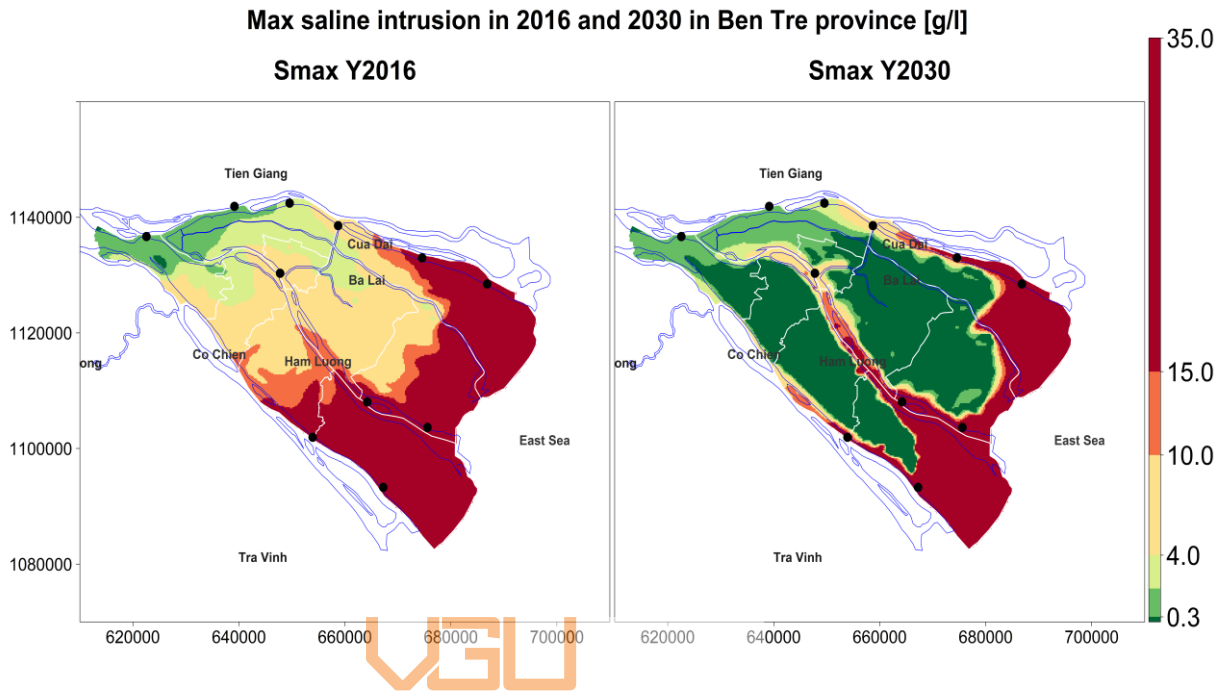


Fig.20. Maximum salinity intrusion (Smax) in scenarios of Year 2016 and Year 2030 with the planned irrigation system

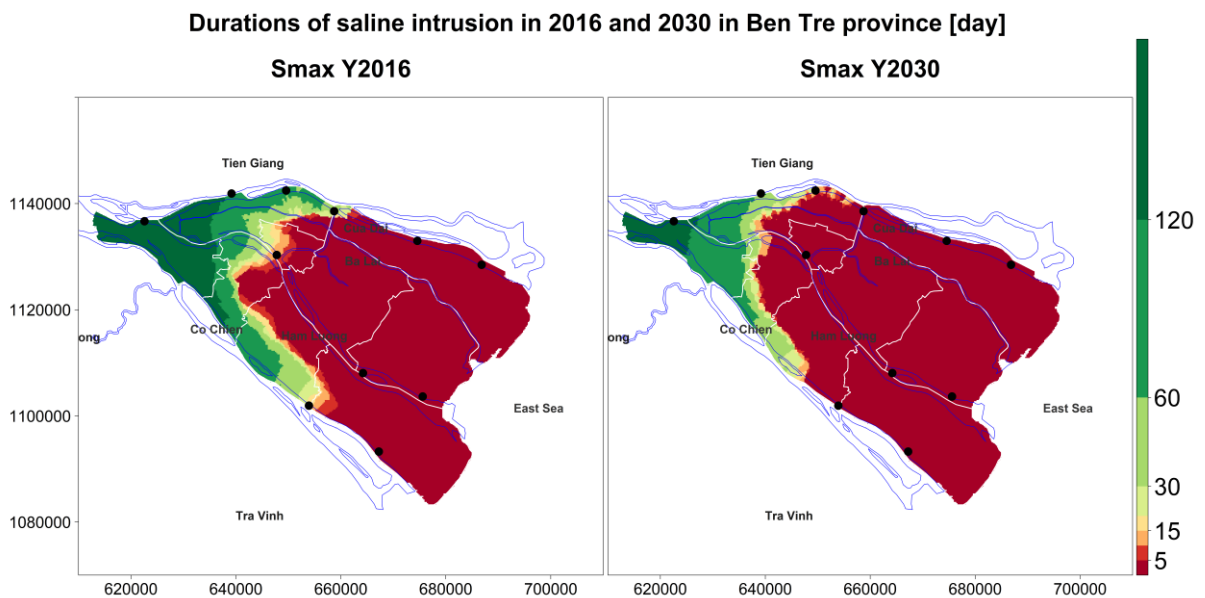


Fig.21. Duration of salinity concentration exceeding 2 g/l in the year 2016 and the year 2030 in the existing irrigation system

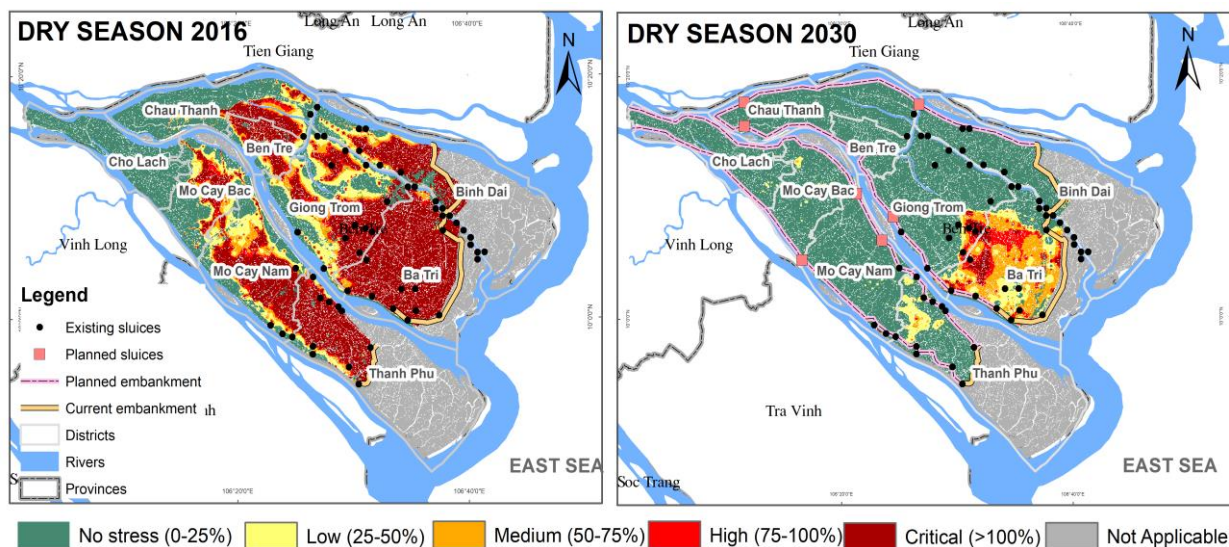


Fig.22. Water stress status of the existing scenario, Year2016, and Year 2030 in the dry season

Table 13. Areas affected by the water stress in the existing and planned irrigation systems (Unit: ha)

Water stress category	Year 2016	Year 2030
Critical	65,547	2,532
High	6,189	4,259
Medium	10,024	9,429
Low	14,329	7,233
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%

4.5 INVESTIGATIONS ON FURTHER INTERVENTIONS

4.5.1. Measure proposals

The assessment of the planned irrigation systems' efficiency showed that although the study area is entirely closed by the sluice gates, 11.4% of areas are estimated to be affected by the water stress from medium to critical levels. It indicates that the structural measures could partly solve the water stress in the study area. Further investigations of possible interventions are needed to integrate the planned irrigation system. Additionally, the largest water user was found to be the agricultural sector, in which the triple paddy crop was the largest water consumption among the agricultural water users (e.g., fruit tree, vegetables), as mentioned in Section 4.2.1. Thus, reductions in the water demands for agriculture could minimize the water stress in the research area. Table 14 shows three possible measures based on the literature. Focusing on a demand-oriented solution, the AWD IRRIGATION measure focuses on reductions of about 40% in water demands by changing the traditional continuous flooded irrigation method to the Alternate Wetting and Drying (AWD) irrigation method. TRC TO FTC measure is to transform 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, as shown in Table 14.

Table 14. Proposed three measures incorporated into the planned solution by 2030

Measure Name	Recommendations
AWD IRRIGATION	The traditional continuous flooded irrigation method was replaced by the Alternate Wetting and Drying (AWD) irrigation method (40% water demand cutoff) (Yamaguchi, Tuan et al. 2016) (Hironori 2021)
TRC TO FTC	Agricultural transformation: Triple rice cropping was replaced by Fruit trees
TRC TO TWC&AWD IRRIGATION	Triple rice cropping was replaced by two rice cropping and upland cropping, with AWD uses (40% cutoff)

4.5.2. Assessment of the suitable measure

To compare the proposed measures, the water demand in agriculture was calculated in each measure to indicate how much water demand was decreased compared to the planned solutions. The results of water demand of the proposed measures are shown in Fig.24 and Table 15. Moreover, the water stress indicators were quantified and mapped in the measures, compared to the result of the planned solution, as shown in Fig.25. Summaries of areas affected by the water stress in the measures were obtained and shown in Table 16. Crop areas that were affected by the water stress in the measures, are also made comparisons, as shown in Fig.23. Summaries of affected crop areas are presented in Table 20 in the appendix.

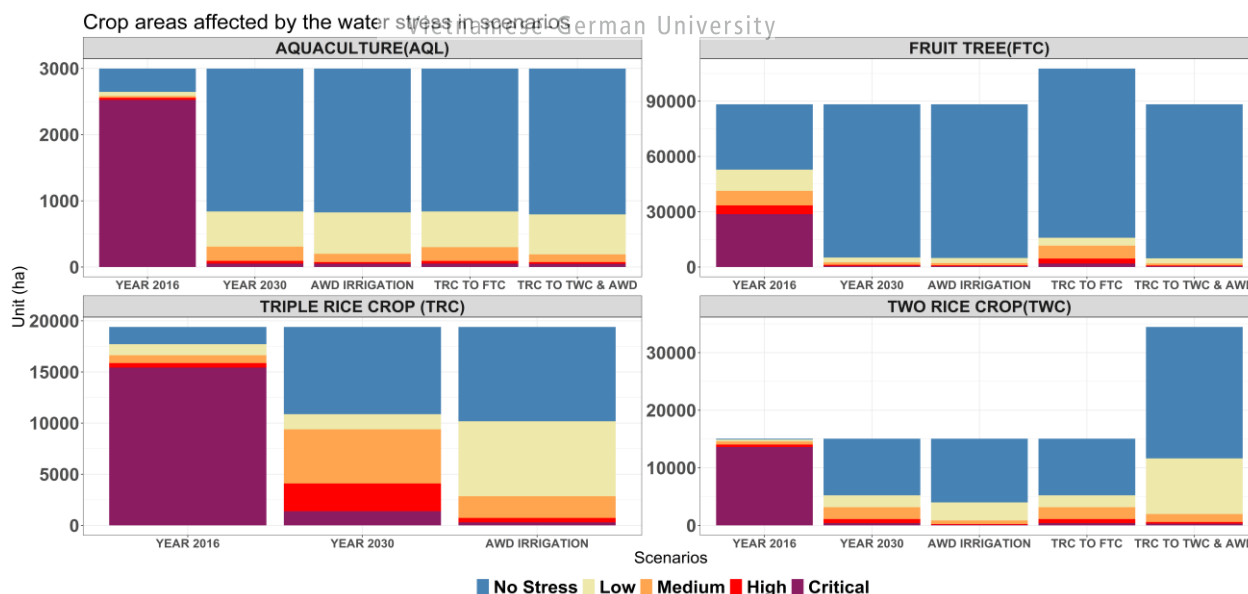


Fig.23. Comparing the crop areas affected by the water stress in all scenarios

For the agricultural water consumption reductions, Table 15 shows comparisons of the agricultural water demand between the year 2030 and recommended measures. Overall, the TRC TO TWC&AWD IRRIGATION achieved the most significant water demand reduction, with approximately 168,62 million m³ (about 24% of total water demand) compared to the year 2030, while AWD IRRIGATION

measure reduced water demand by about 102,32 million m³, about 13% of the total water demand, and the TRC TO FTC measure cut off demand by about 29.42 million m³, around 3% of the total water demand. Fig.24 shows water demand mapping in the recommended measures compared to the year 2030. The triple rice paddy in Ba Tri district significantly decreased to about less than 3 thousand m³ in TRC TO TWC&AWD IRRIGATION measure.

Assessing the recommended measures, Fig.25 shows the water stress results of the recommended measures compared to the scenario Year 2030. Overall, a significant reduction in the water stress-affected areas was found at TRC TO TWC&AWD IRRIGATION measure and IRRIGATION measure. By contrast, there are insignificant changes in comparison between the TRC TOT FTC measure and the scenario year 2030.

Comparing Agri. water demand between Year 2030 & scenarios in the dry season [10³ m³/1ha]

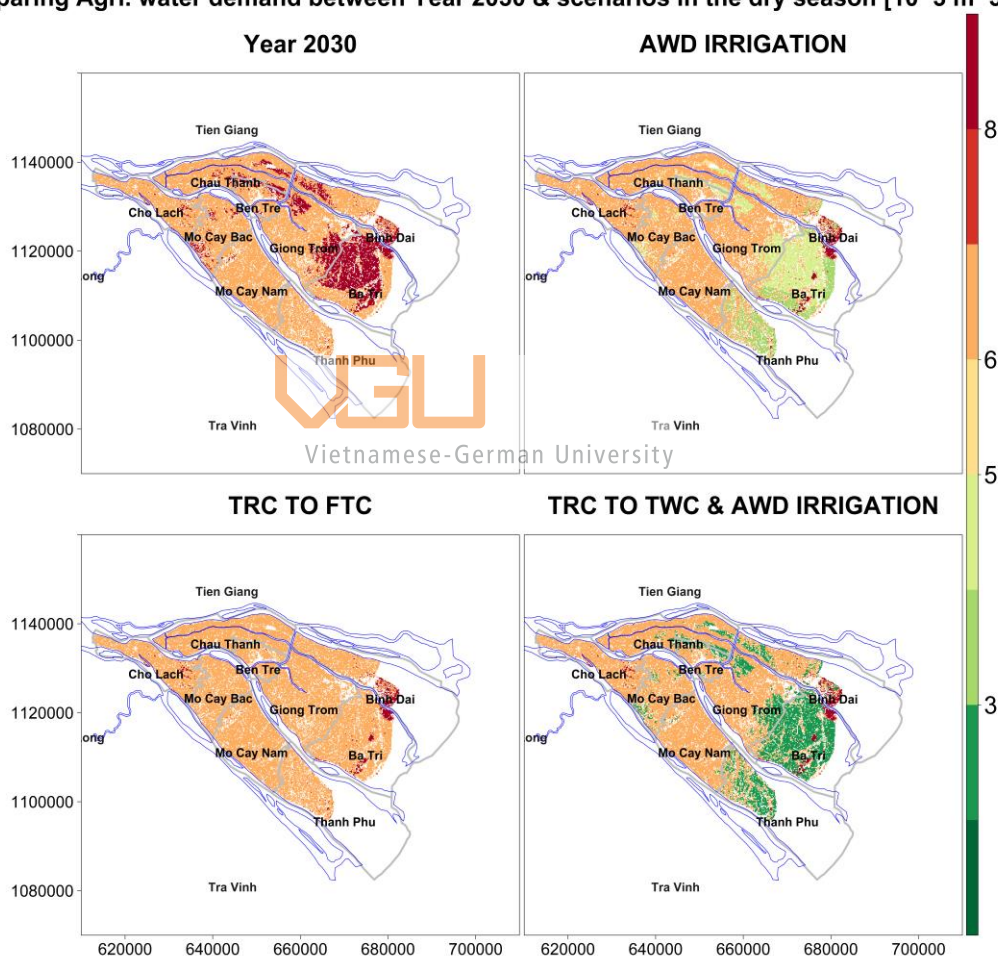


Fig.24. Agricultural water demands in the scenario Year 2030 and the proposed measures

Additionally, comparing affected areas by the water stress area shown in Fig.15. Generally, the TRC TO TWC&AWD IRRIGATION measure significantly reduced the water stress areas to 4.568 ha, approximately 3.2% of the total study area, while the AWD IRRIGATION measure reduced the water stress areas to 6.558 ha, about 4.6% of the entire study area. By contrast, the TRC TO FTC measure decreased the water stress areas to 15.848 ha, approximately 11.2% of the total study area. Moreover, the crop area affected by the water stress in the measures is shown in Fig.23 and Table 20. Overall, the

entire areas affected from medium to critical water stress levels were determined in the measures, including 4.100 ha, 6.003 ha, and 14.999 ha in TRC TO TWC&AWD IRRIGATION measure, IRRIGATION measure, and TRC TOT FTC respectively. As a result, the most effective measure was found to be TRC TO TWC&AWD IRRIGATION measure among the three recommended measures, with a minimum of the areas affected from medium to critical water stress levels.

Table 15. Comparing the agricultural water demand in the Year 2030 and the proposed measure (Unit: 10^6 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	871.52	769.00	842.10	702.89
Year	1204.37	1047.50	1145.78	956.85

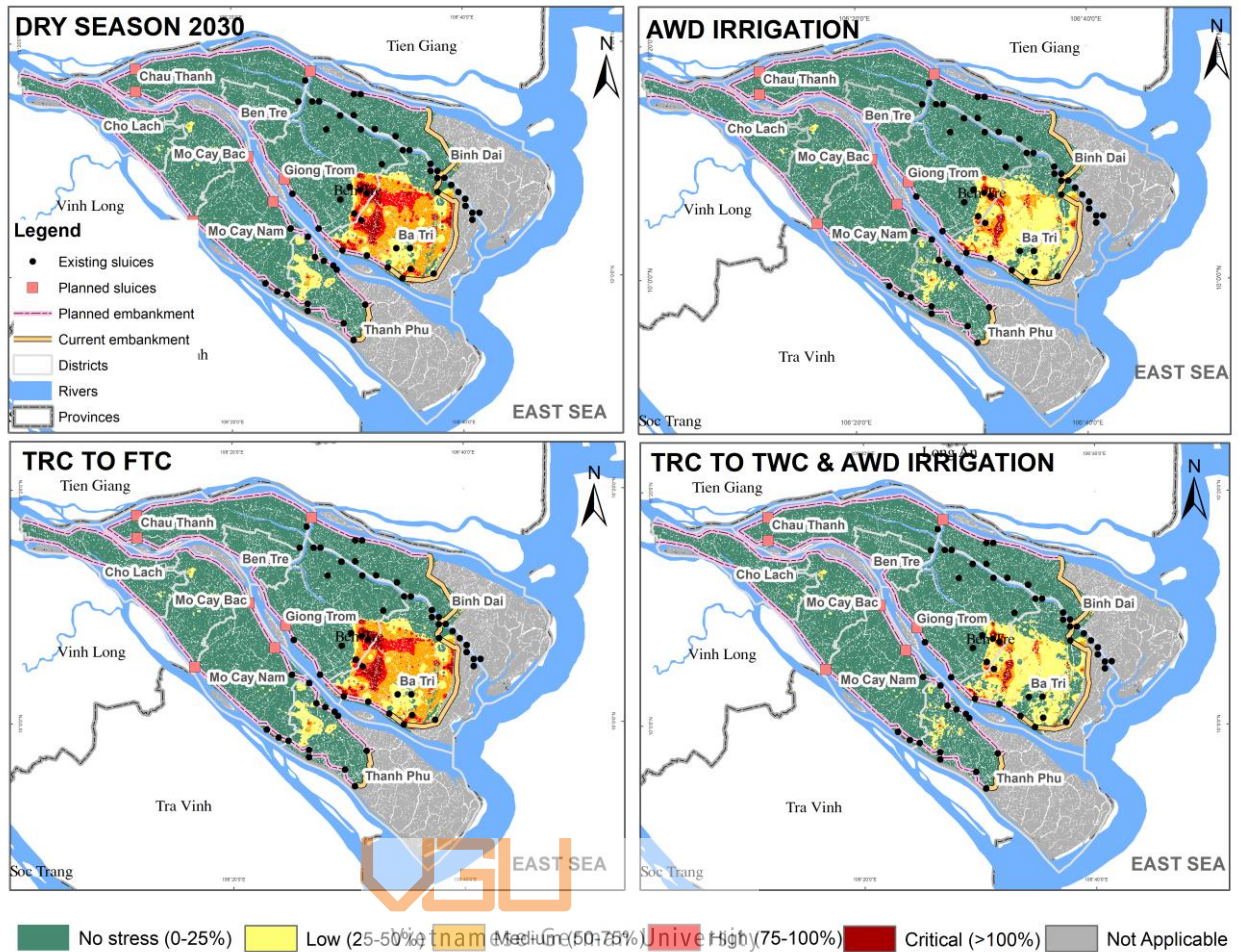


Fig.25. Comparing water stress status in proposed measures with the planned solution

Table 16. Comparison of areas affected by the water stress between the planned solution and the proposed measures (Unit: ha)

Water stress category	Year 2030	AWD IRRIGATION	TRC TO FTC	TRC TO TWC&AWD IRRIGATION
Critical	2,532	978	2,460	869
High	4,259	1,171	3,586	835
Medium	9,429	4,409	9,802	2,864
Low	7,233	14,626	7,481	13,790
No stress	118,208	120,477	118,332	123,303
Total area	141,661	141,661	141,661	141,661
Percent of the sum of areas from Medium to Critical levels/ Total area	11.7	4.6%	11.2%	3.2%

CHAPTER 5. CONCLUSIONS

The major finding was that combining structural solutions and soft measures improved the sustainable water management in the study area in the climate change and anthropogenic impacts by 2030. Particularly, the planned irrigation system incorporated by a measure of transforming triple rice crops to two rice crops, in combination with the use of the alternate wetting and drying irrigation method, ensured 87% of areas without water stress in 2030, compared to 42% of the areas in the current condition.

The results revealed that between 2005 and 2020, there were upward trends in the climatic and hydrological indices. If this trend continues, the average water demand for agriculture will increase by 3% by 2030. Even though the upstream flow to Ben Tre province increases by 2030, the salinity isoline intrudes farther inland and for a more extended period.

Large volumes of surface water resources enter the study area, even during the dry season being about 25,5 km³ and 23,3 km³ for 2016 and 2030, respectively; however, the total water demand in the dry season is 5.215 km³ in the year 2016 scenario and 5.234 km³ in the year 2030 scenario, respectively.

Nevertheless, the study area's water resources are unevenly distributed in time and space. In the studied area, severe water stress is mainly caused by saline water intrusion. Over 57% of regions were affected by the medium to critical water stress level because the existing water management system was insufficient for managing salt intrusion. Similarly, despite the structural measures completely enclosing the study area, the solution anticipated for 2030 was insecure for around 11.4% of the locations that experienced medium to critical water stress levels.

Three measures were recommended to add to the planned irrigation system, focusing on water-saving and lowering water demand in the research area, including the application of the Alternate Wetting and Drying Irrigation method (AWD IRRIGATION), with a proposed 40% water demand cutoff, replacing triple rice crops by fruit tree (TRC TO FTC) and replacing triple rice crops by Two rice crops in combining with AWD irrigation method (TRC TO TWC & AWD Irrigation).

The results showed that, for the TRC TO FTC, AWD IRRIGATION, and TRC TO TWC & AWD Irrigation methods, respectively, the impacted areas by the water stress from medium to critical levels are decreased to 11.2%, 4.6%, and 3.2% of the entire research area. In summary, it was determined that the TRC TO TWC & AWD Irrigation measure would be a suitable addition to the planned irrigation system to enhance the appropriate water management in the study region by 2030.

Considerably more work will need to be done to determine structural measures inside the freshwater area to reduce the remaining 3.2 % of areas still affected by the medium water stress to critical levels. Several interventions, such as pumping stations and dredging canals, could be feasible for conveying more water from the upper parts to the water stress-affected areas. Moreover, a limitation of this study is that the flood season was disregarded; several issues on pluvial flooding and river flooding are the main topics that must be solved in the water management sustainability views.

This study was also limited by the short-term annual flow used for quantifying the environmental flow using Tennant's method. Long-term annual flow data are generally required to apply hydrological methods in environmental flow calculation. Moreover, the uncertainty of the climate change scenarios was considered to cause the result uncertainties in the study.

CHAPTER 6. SUMMARY

A water accounting framework was applied to determine current and future water stress issues in order to improve the water management sustainability, particularly in the dry season in Ben Tre province. The study area, 14.611 ha (60% of Ben Tre province), has been faced with saline intrusions, causing severe agricultural damages and interrupting domestic water supply services; the authorities have planned to protect the study area from the salt intrusion by embankment routes and sluices by 2030, with targets for ensuring the water distributions in the climate change context.

Three primary water users were identified in the study: agriculture, household, and ecosystems. These users are implied by three pillars of sustainable development: economic development, social well-being, and environmental protection in the study area dominated by agricultural productions.

In general, the overall objective aimed to find suitable solutions to improve the appropriate water management in the study area under climate change and anthropogenic impacts in the year 2016 and year 2030. Three research questions were answered (i) Given the effects of climate change and anthropogenic influences, do the water resources that are currently accessible satisfy the needs of the population, agriculture, and environment? (ii) How adequately does the existing irrigation system solve issues in the water management of the study area? (iii) What are the proper measures for sustainable water management under the circumstances of anthropogenic pressures and climate change?

Fundamentally, the status and trends in water sources, water consumption, and accessibility were systematically studied in the pixel water concept with a spatial resolution of 1 hectare. A water balance calculation in a water accounting framework was spatially carried out to determine water stress indicator levels to assess the current and planned irrigation system's efficiency and select suitable measures in the study.

Water demand for agriculture was calculated using FAO methods from 2005 to 2020 and was projected using climate change scenario RCP4.5 in 2030. Domestic water need was quantified based on the population and water supply ratios per capita according to the building codes of Vietnam. Environmental flow requirements were determined by using Tennant's method, with a threshold of 10 % of annual renewable freshwater resources, which was calculated by using MIKE11 simulations. The total renewable freshwater sources were implied as usable water by separating water flow simulated by the MIKE11 model, utilizing the saline threshold of 2 g/l to distinguish between usable (< 2 g/l) and unusable irrigation water exceeding 2 g/l, introduced by FAO. As a result, the water stress per pixel was calculated as the proportion of the total freshwater withdrawn (agriculture and household users) to the total renewable freshwater resources after considering the environmental requirements.

Water stress was classified into five groups, including No stress (0-25%), Low (25-50%), Medium (50-75%), High (75-100%), and Critical (>100%). Accordingly, values below 25% can always be deemed safe (no stress); however, levels above 25% should be considered potentially and increasingly hazardous and should be qualified and reduced.

To answer the first two research questions, two scenarios were formulated the Year 2016 for the baseline and the Year 2030 for future context. The efficiency of the existing irrigation was assessed according to the water stress mapping and saline intrusion mapping by simulating the scenario Year

2016. Similarly, the planned irrigation system by 2030 was evaluated using the water stress indexes under climate change scenario RCP4.5 2030. In addition, the Mann-Kendall Test and Sen's slope and visual analytics approaches were carried out to determine the historical trends in the climate and hydrological parameters in the period from 2005 and 2020.

For the last research question, as the irrigation system by 2030 was not adequate in water management, three soft measures were recommended, focusing on water consumption reduction in agriculture, including the application of the Alternate Wetting and Drying Irrigation method (AWD IRRIGATION), with a proposed 40% water demand cutoff, replacing triple rice crops by fruit tree (TRC TO FTC) and replacing triple rice crops by Two rice crops in combining with AWD irrigation method (TRC TO TWC & AWD Irrigation). These measures were added to the planned irrigation system in 2030 and simulated under climate change scenario RCP 4.5. The water stress mappings of the simulations were made, comparing reductions in areas and crop areas by the water stress-affected to select the suitable measure among the three proposed measures.

The study objectives were achieved, resulting in several findings:

- i. In the research region, there were rising trends in the climatic (e.g., temperature, wind speed, evaporation) and hydrological parameters (e.g., water level, saline concentrations) between 2005 and 2020. If this trend continues, the average water demand for agriculture would rise by 3% by 2030. The saline isoline intruded deeper inland and for a longer period of time into the mainstream even while the upstream flow to Ben Tre province was growing.
- ii. The abundant amounts of surface water resources flowing into the study area, about 25,5 km³ and 23,3 km³ are more significant than the total water demand of 5.215 km³ and 5.234 km³ in the dry season in the scenarios of the year 2016 and the year 2030, respectively. Yet, the water resources are unevenly distributed temporal and spatially in the study area. Especially the saline water intrusion significantly causes severe water stress in the study area.
- iii. 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.
- iv. Therefore, three proposed measures were incorporated into the planned irrigation system, focusing on water-saving and water demand reduction in the study area. The results revealed that regions affected by the water stress from medium to critical level are reduced to 11.2 %, 4.6%, and 3.2 % of the total study area in TRC TO FTC, AWD IRRIGATION, and TRC TO TWC & AWD Irrigation measures, respectively.

In short, the TRC TO TWC & AWD Irrigation measure was found to be a suitable measure added to the planned irrigation system to improve the appropriate water management in the study area by 2030.

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APPENDIX

APPENDIX OF TABLES

Table 17. Summary of monthly discharge at My Thuan station from 2005 to 2020

Month	Q [m ³ /s]	SD [m ³ /s]	Volume [km ³]
Jan	3523.0	1199.3	9.44
Feb	2179.4	846.7	5.27
Mar	1782.6	613.1	4.77
Apr	1835.7	616.4	4.76
May	2593.1	688.2	6.95
Jun	4241.3	1560.5	10.99
Jul	7259.4	2112.6	19.44
Aug	11613.0	2777.1	31.10
Sep	13406.5	2682.5	34.75
Oct	13265.5	2471.5	35.53
Nov	9761.5	2589.6	25.30
Dec	5998.4	1771.0	16.07
Annual	6455.0		17.0

Table 18. Averaged agricultural water demand in different sectors in period 2005-2020 (Unit: 10⁶ m³)

Month	Freshwater aqua	Fruit tree	Triple rice crop	Two rice crop	Sum
Jan	0.00	98.89	32.95	3.37	135.21
Feb	0.00	113.77	39.08	16.40	169.24
Mar	0.00	125.89	41.80	27.00	194.69
Apr	25.24	110.19	11.22	18.13	164.79
May	1.04	49.61	19.38	5.23	75.26
Jun	0.50	26.95	15.86	7.91	51.22
Jul	0.62	27.57	10.93	13.32	52.43
Aug	0.68	31.84	2.96	8.84	44.32
Sep	0.30	15.50	8.32	1.51	25.64
Oct	0.41	19.99	11.94	7.37	39.72
Nov	1.69	62.55	20.81	21.96	107.01
Dec	0.00	79.78	14.42	24.19	118.39
Dry season	26.3	578.1	158.9	94.3	857.6
Year	30.49	762.54	229.66	155.23	1177.92

Table 19. Agricultural water demand in different sectors in Year 2030 (Unit:10⁶ m³)

Month	Freshwater aqual.	Fruit tree	Triple rice crop	Two rice crop	Sum
cc	0.0	100.4	33.1	3.4	136.9
Feb	0.0	115.4	39.5	16.6	171.5
Mar	0.0	127.8	42.3	27.4	197.5
Apr	25.3	112.2	11.3	18.4	167.2
May	1.1	51.7	19.8	5.4	78.1
Jun	0.5	28.5	16.5	8.2	53.7
Jul	0.7	29.0	11.3	13.9	54.8
Aug	0.7	33.6	3.0	9.2	46.5
Sep	0.3	16.4	8.6	1.6	26.9
Oct	0.4	21.3	12.5	7.7	41.9
Nov	1.7	63.8	21.1	22.3	109.0
Dec	0.0	81.4	14.5	24.5	120.4
Dry season	26.4	588.8	160.5	95.8	871.5
Year	30.8	781.4	233.6	158.6	1204.4

Table 20. Crop areas affected by the water stress in scenarios (Unit: ha)

Crop type	Scenarios	No Stress	Low	Medium	High	Critical
Triple Rice Crop (TRC)	YEAR 2016	1685	1085	764	438	15425
Two Rice Crop (TWC)	YEAR 2016	162	314	547	427	13612
Fruit Tree (FTC)	YEAR 2016	35458	11522	7848	4782	28664
Aquaculture (AQL)	YEAR 2016	63	26	33	2524	
Triple Rice Crop (TRC)	YEAR 2030	8525	1484	5291	2712	1385
Two Rice Crop (TWC)	YEAR 2030	9845	2066	2062	697	392
Fruit Tree (FTC)	YEAR 2030	83143	2615	1337	615	564
AQL	YEAR 2030	2159	532	214	42	51
Triple Rice Crop (TRC)	AWD IRRIGATION	9218	7331	2121	433	294
Two Rice Crop (TWC)	AWD IRRIGATION	11070	3137	624	138	93
Fruit Tree (FTC)	AWD IRRIGATION	83398	2745	1208	470	453
Aquaculture (AQL)	AWD IRRIGATION	2173	626	125	24	50
Two Rice Crop (TWC)	TRC TO FTC	9845	2067	2061	697	392
Fruit Tree (FTC)	TRC TO FTC	91786	4335	6995	2678	1877
Aquaculture (AQL)	TRC TO FTC	2159	540	207	41	51
Two Rice Crop (TWC)	TRC TO TWC & AWD IRRIGATION	22821	9672	1379	285	302
Fruit Tree (FTC)	TRC TO TWC & AWD IRRIGATION	83572	2758	1080	424	440
Aquaculture (AQL)	TRC TO TWC & AWD IRRIGATION	2203	605	116	27	47

Table 21. List of sluice gates in Ben Tre Province

Sluice Name	Width [m]	Sill level [m]	Number of Gates	Main tasks	Status
Binh Thanh	3.4	-1.7	1	SC+IR+ DR	Existing
Dinh Dien	3.4	-1.7	1	IR+ DR	Existing
Xeo Da	1.7	-1.7	1	SC+ IR+ DR	Existing
Ba Co	3	-1	1	SC+ IR+ DR	Existing
Tieu 2B	3.4	-1.7	1	SC+IR+ DR	Existing
An Binh Tay	4.5	-1.5	1	SC+ IR+ DR	Existing
Nha Tho	3.4	-1.7	1	SC+ IR+ DR	Existing
Vam Don	7.5	-3	2	SC+ IR+ DR	Existing
An Hoa	2.8	-1.4	1	SC+ IR+ DR	Existing
Binh Bat	6	-2	1	SC+ IR+ DR	Existing
Lang Sen	6	-2	1	SC+ IR+ DR	Existing
10 Cua	10	-3.5	1	SC+ IR+ DR	Existing
Ao Vuong	8	-2	1	SC+ IR+ DR	Existing
Cau Tau	6	-2	1	SC+ IR+ DR	Existing
Giong Trom	7.5	-2	1	SC+ IR+ DR	Existing
Phong Nam	2	-1	1	SC+IR+ DR	Existing
2 Cua	9	-4.5	1	SC+ IR+ DR	Existing
Rach No	4	-2	1	SC+ IR+ DR	Existing
Vam Ho	10	-4.5	1	SC+ IR+ DR	Existing
Cay Da	10	-3.5	1	SC+IR+ DR	Existing
Tong Can	5	-1	1	SC+ IR+ DR	Existing
Binh Thuan	1.4	-1.4	1	IR+ DR	Existing
Cau Vi	6	-2	1	SC+ IR+ DR	Existing
Xeo Vuon	2	-2	1	SC+ IR+ DR	Existing

Sluice Name	Width [m]	Sill level [m]	Number of Gates	Main tasks	Status
Chau Phu	4	-2	1	SC+IR+ DR	Existing
Giong Quy	6	-2	1	SC+ IR+ DR	Existing
Nam Da	3	-1.5	1	SC+ IR+ DR	Existing
Thuong Binh	4	-2	1	SC+ IR+ DR	Existing
Ba Hao	4	-2	1	SC+ IR+ DR	Existing
Cai Luc	5	-2	1	SC+ IR+ DR	Existing
Hoi Dong Tinh	5	-2	1	SC+ IR+ DR	Existing
Ban Quy	4	-2	1	SC+ IR+ DR	Existing
Rach Dieu	4	-2	1	SC+ IR+ DR	Existing
Tan Binh	1.4	-1.4	1	SC+ IR+ DR	Existing
Qua Lo k20	2	-1.7	1	SC+ IR+ DR	Existing
Co Rang	3	-2	1	SC+ IR+ DR	Existing
Giao Hoa	1.7	-1.7	1	SC+ IR+ DR	Existing
Ong Ho	5	-2.5	1	SC+ IR+ DR	Existing
Ca Cai	5	-2	1	SC+ IR+ DR	Existing
Ca Rang Sau	7.5	-2	1	SC+ IR+ DR	Existing
Tan Huong	7.5	-3	1	SC+ IR+ DR	Existing
Cai Muong	5	-3	1	SC+ IR+ DR	Existing
Rach La	3	-2	1	SC+ IR+ DR	Existing
Cai Bong	7.5	-2	1	SC+ IR+ DR	Existing
Cai Mit	5	-2	1	SC+ IR+ DR	Existing
Cha La	2	-1	1	SC+ IR+ DR	Existing
Muong Dao	7.5	-2.5	1	SC+ IR+ DR	Existing
Qua Lo Giong Truong	2	-2.5	1	IR+ DR	Existing
Son Doc	7.5	-3.5	2	SC+ IR+ DR	Existing

Sluice Name	Width [m]	Sill level [m]	Number of Gates	Main tasks	Status
Xeo Sau	5	-2	1	SC+ IR+ DR	Existing
Ba Lai	10	-4	8	SC+ IR+ DR	Existing
Ong Bo	4	-2	1	SC+ IR+ DR	Existing
Cai Ban	6	-2	1	SC+ IR+ DR	Existing
Ben Giong Nho	5	-3.5	1	SC+ IR+ DR	Existing
Ong Chau	5	-1.5	1	SC+ IR+ DR	Existing
Rach Cua	1.5	-1.5	1	IR+ DR	Existing
Rach Gia	2	-2	1	SC+ IR+ DR	Existing
Rach Muoi	10	-2	1	SC+ IR+ DR	Existing
Rach Rao	1.5	-1.5	1	IR+ DR	Existing
Rach Trai	5	-2	1	SC+ IR+ DR	Existing
Xeo La	1.5	-1.5	1	SC+ IR+ DR	Existing
Cong Vam Nuoc Trong	30	-6	3	SC+DR+IR	Planned
Cong Vam Thom	35	-5.5	2	SC+IR+DR	Planned
Cong Ben Tre	35	-5.5	2	SC+DR	Planned
Cong An Hoa	30	-6	4	SC+DR	Planned
Cong Thu Cuu	30	-5	3	SC+DR+IR	Planned
Cong Cai Quao	30	-5	3	SC+DR+IR	Planned
Cong Tan Phu*	20	-4	1	SC+DR	Planned
Cong Ben Ro	20	-4	1	SC+DR	Planned
Cai Ngang	2	-2	1	SC+ IR+ DR	Existing
TT. Giong TRom	3	-1.4	1	SC+IR+ DR	Existing

* Coupled with a pumping station of 20 m³/s; SC: Salt Control; IR: Irrigation; DR: Drainage

APPENDIX OF FIGURES

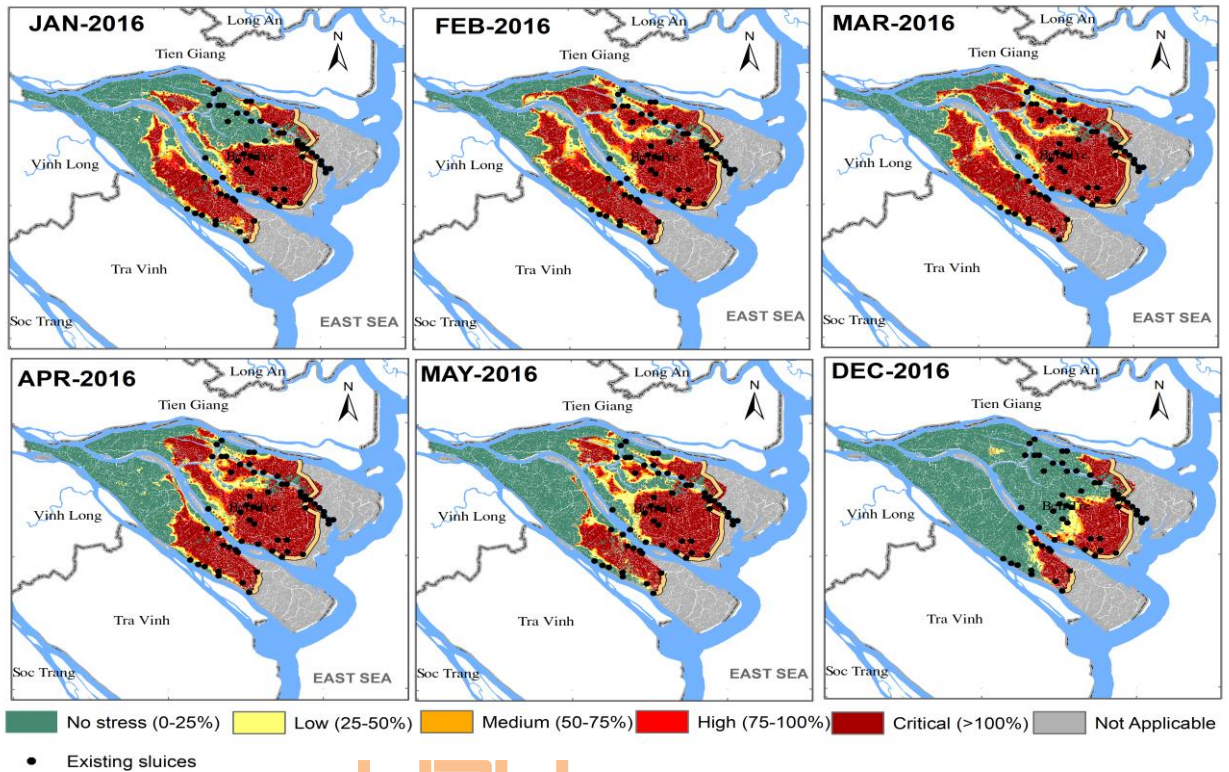


Fig.26. Water stress indicators in the dry season in scenario Y2016

Vietnamese-German University

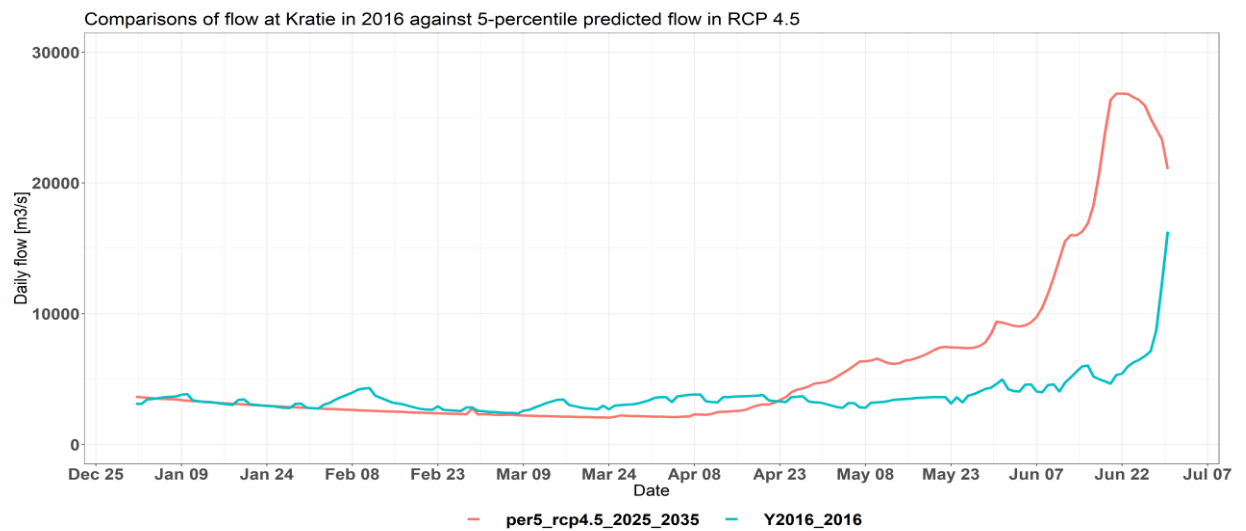


Fig.27. Upstream boundary flow at Kratie station in 2016 and RCP4.5 2030 using a percentile 95% of the projected flow from 2025-2035.

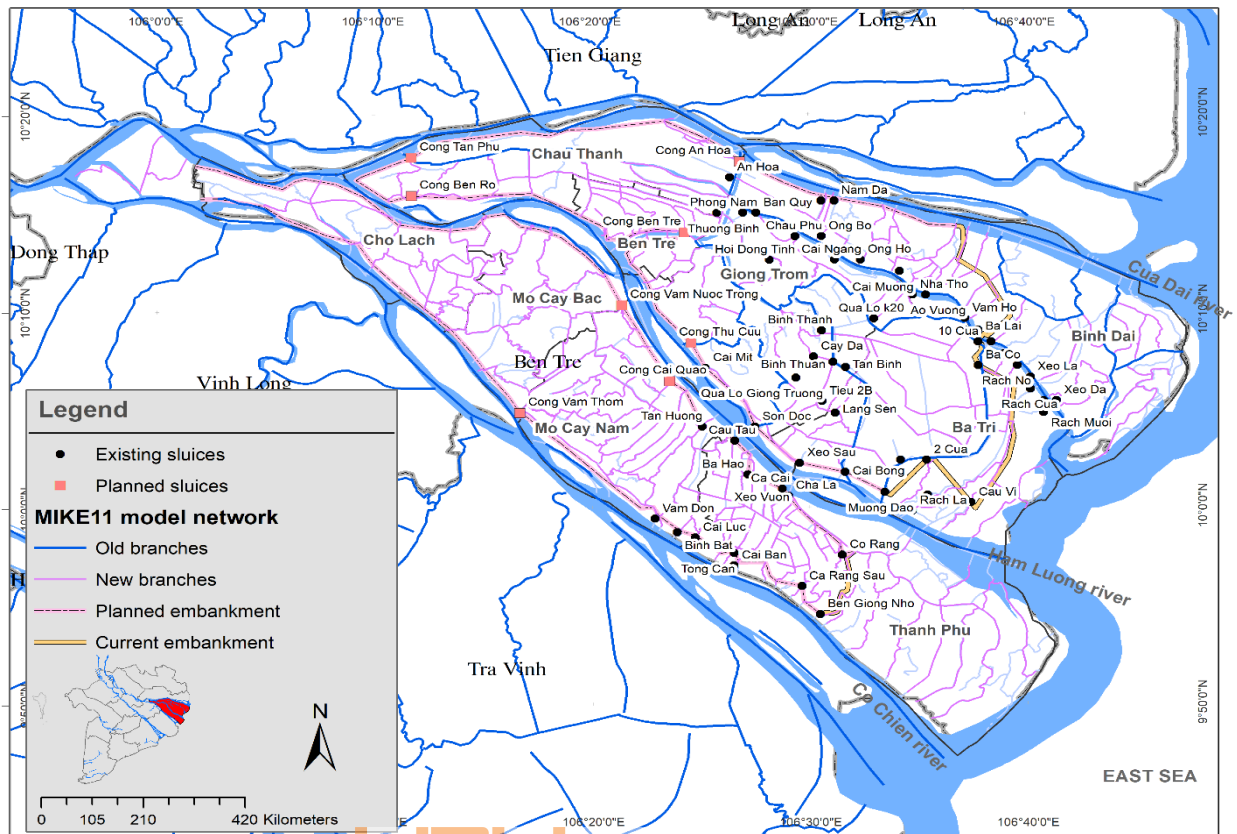


Fig.28. MIKE11 model network in Ben Tre Province. It indicates existing branches (blue lines) and added new branches (pink lines) in the model domain in Ben Tre Province.

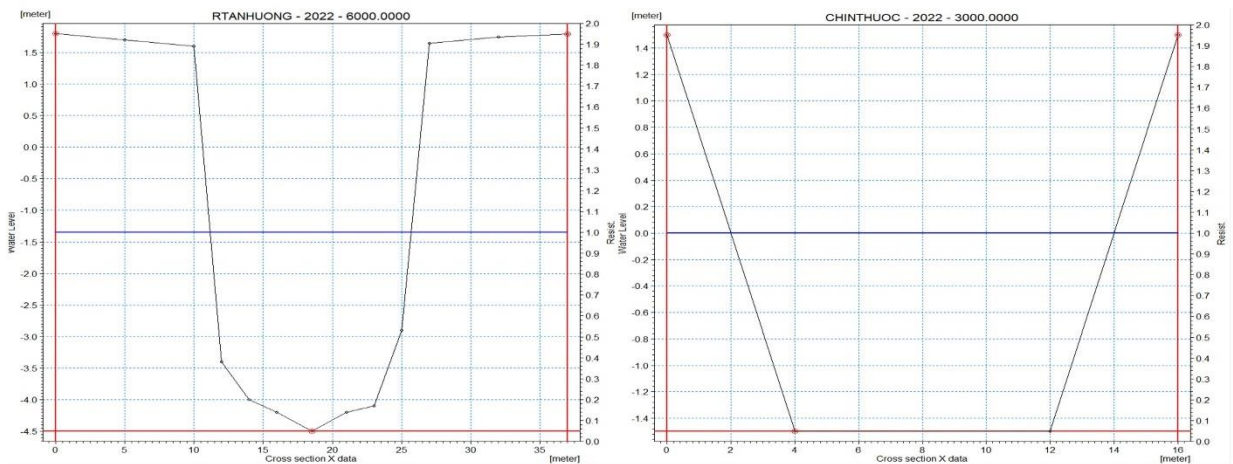


Fig.29. Typical cross-sections of measured data (left-side) and assumed data (right-side) in the MIKE11 model

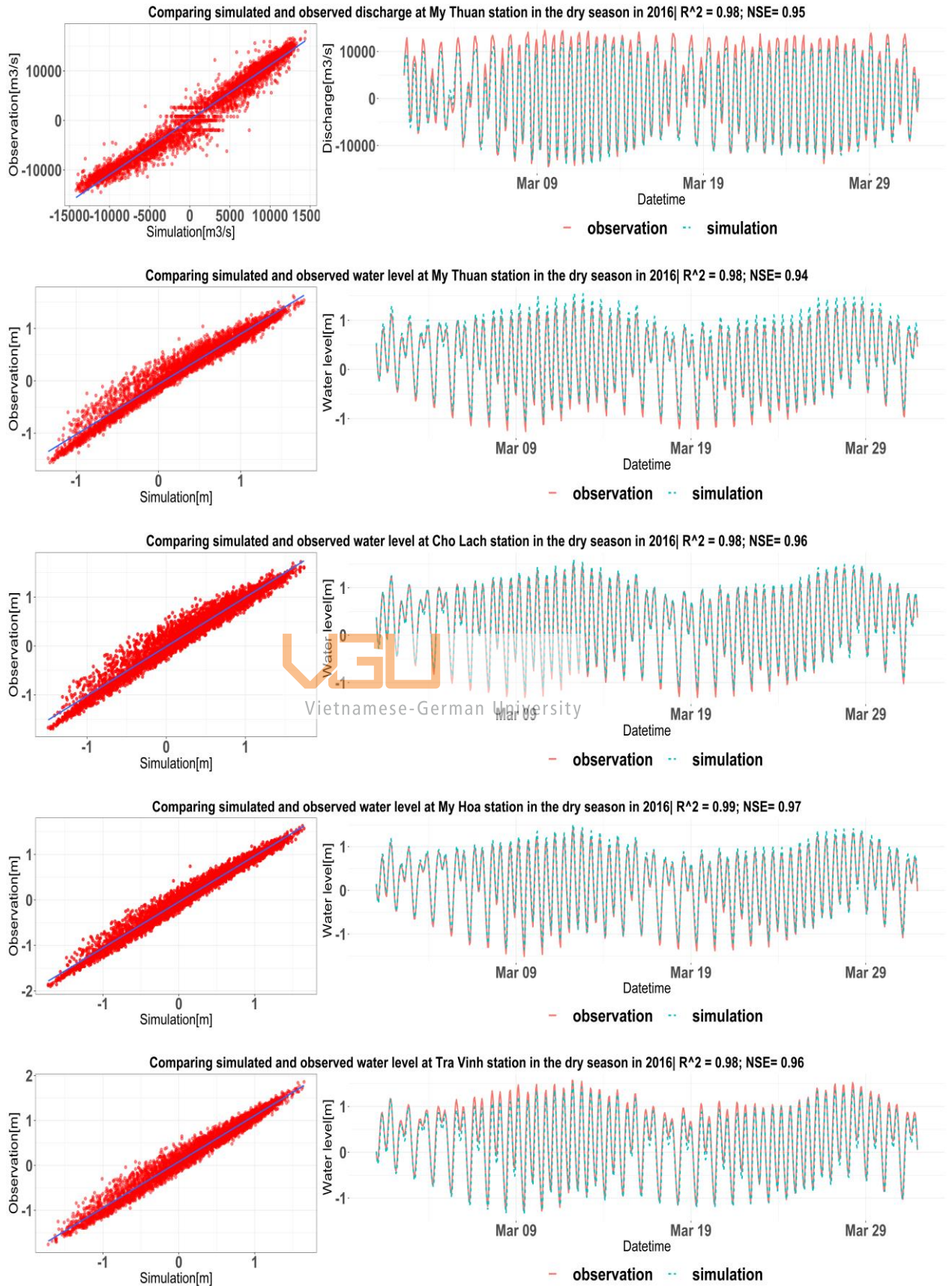


Fig.30. Comparisons of simulated data against measured data at several stations in the validated simulation

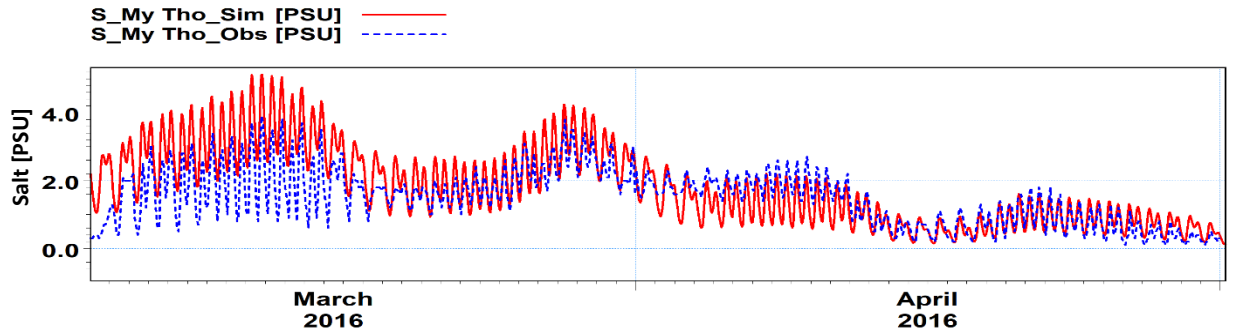


Fig.31. Comparison simulated saline concentration against observed saline concentration at My Tho station in the dry season 2016

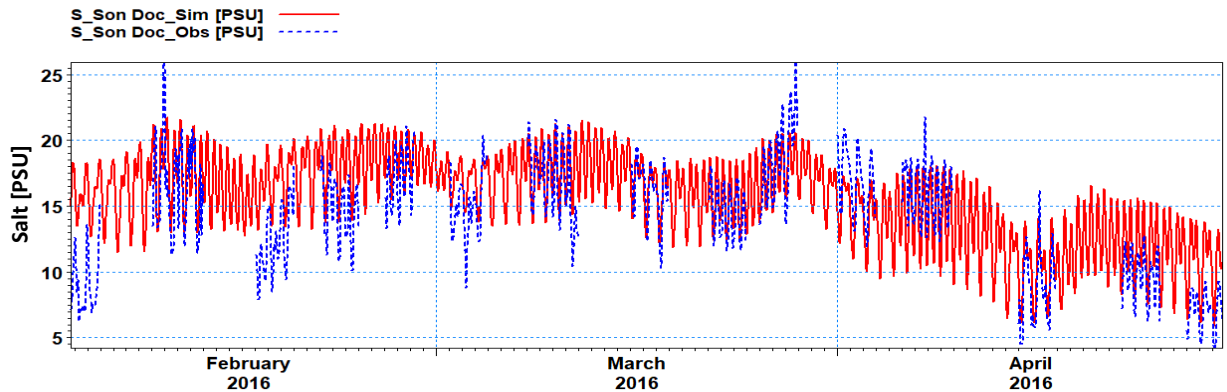


Fig.32. Comparison simulated saline concentration against observed saline concentration at Son Doc station in the dry season 2016

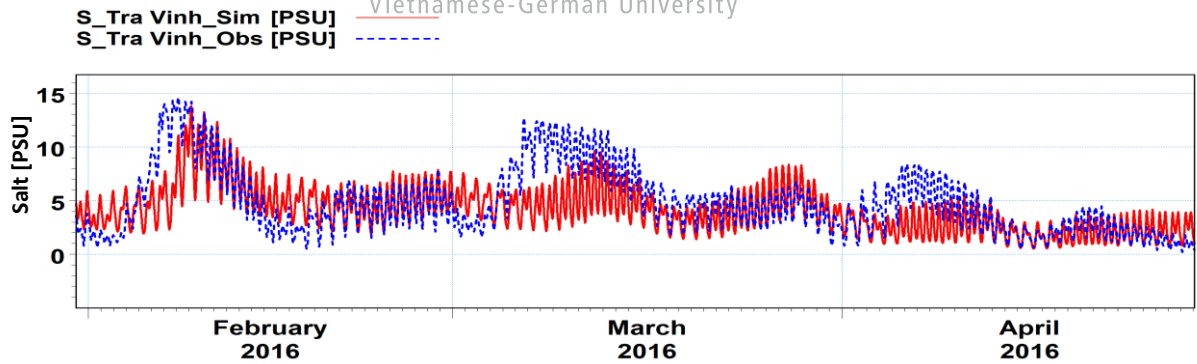
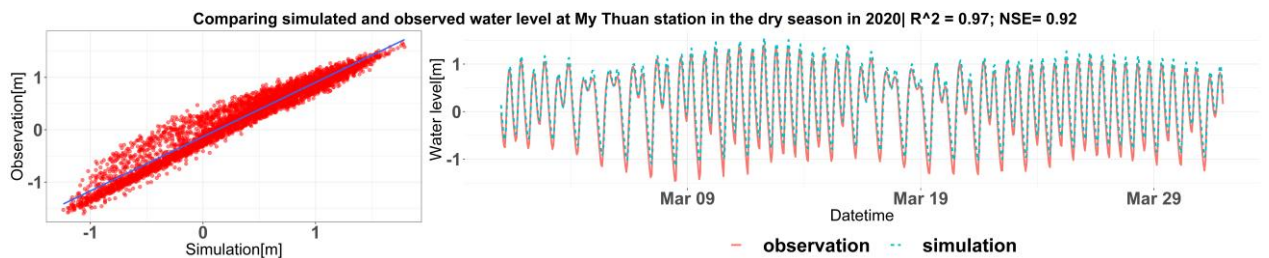


Fig.33. Comparison simulated saline concentration against observed saline concentration at Tra Vinh station in the dry season 2016



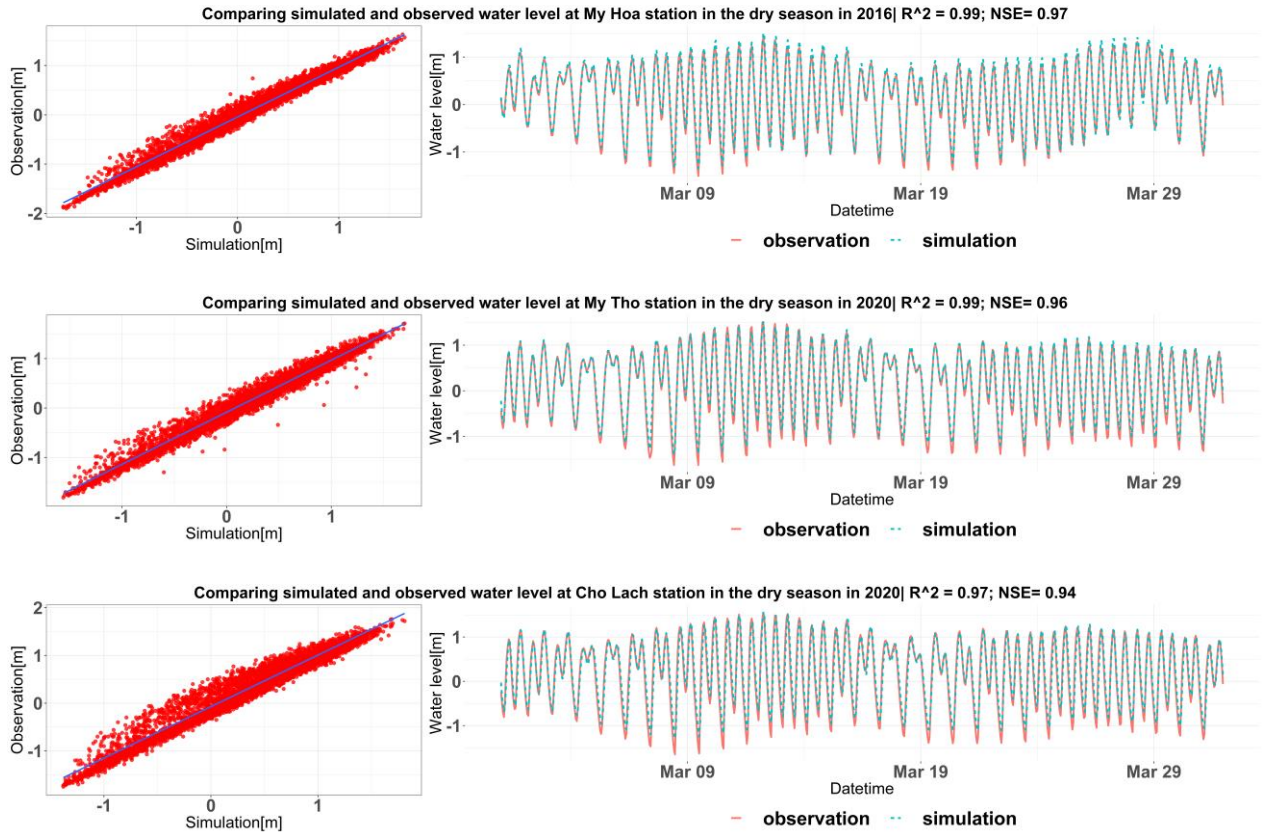


Fig.34. Comparisons of simulated data against measured data at several stations in the validated simulation

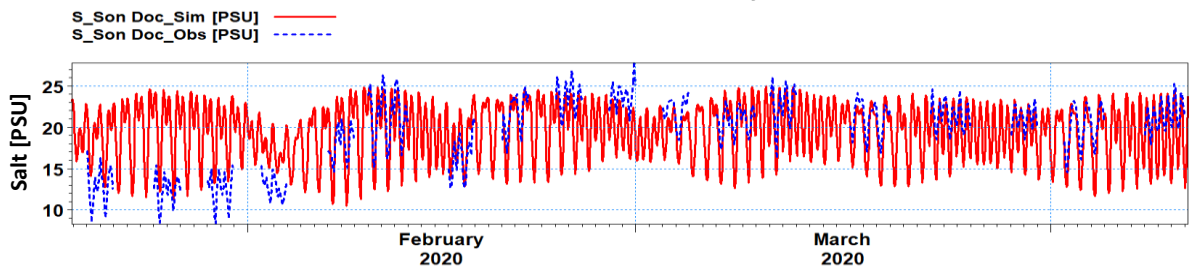


Fig.35. Comparison of simulated saline concentration against observed saline concentration at Son Doc station in the dry season 2020

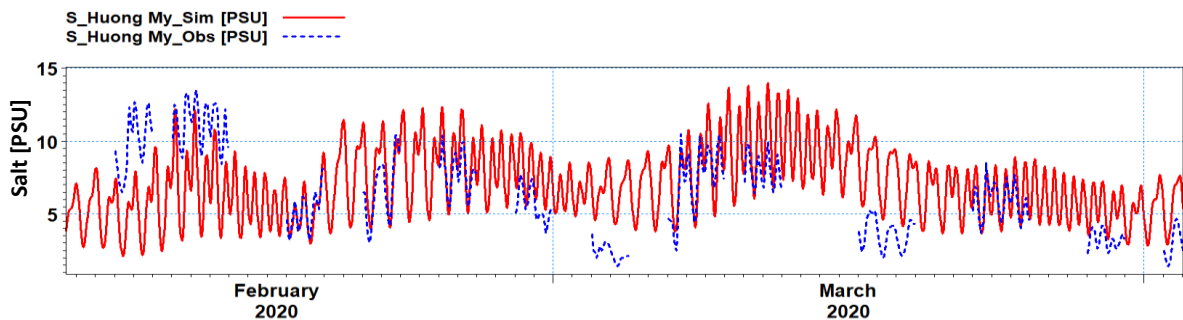


Fig.36. Comparison of simulated saline concentration against observed saline concentration at Huong My station in the dry season 2020

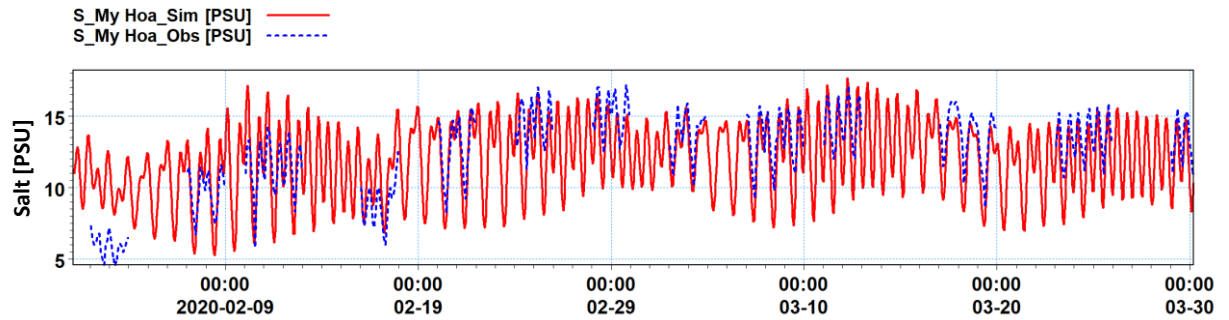


Fig.37. Comparison of simulated saline concentration against observed saline concentration at My Hoa station in the dry season 2020

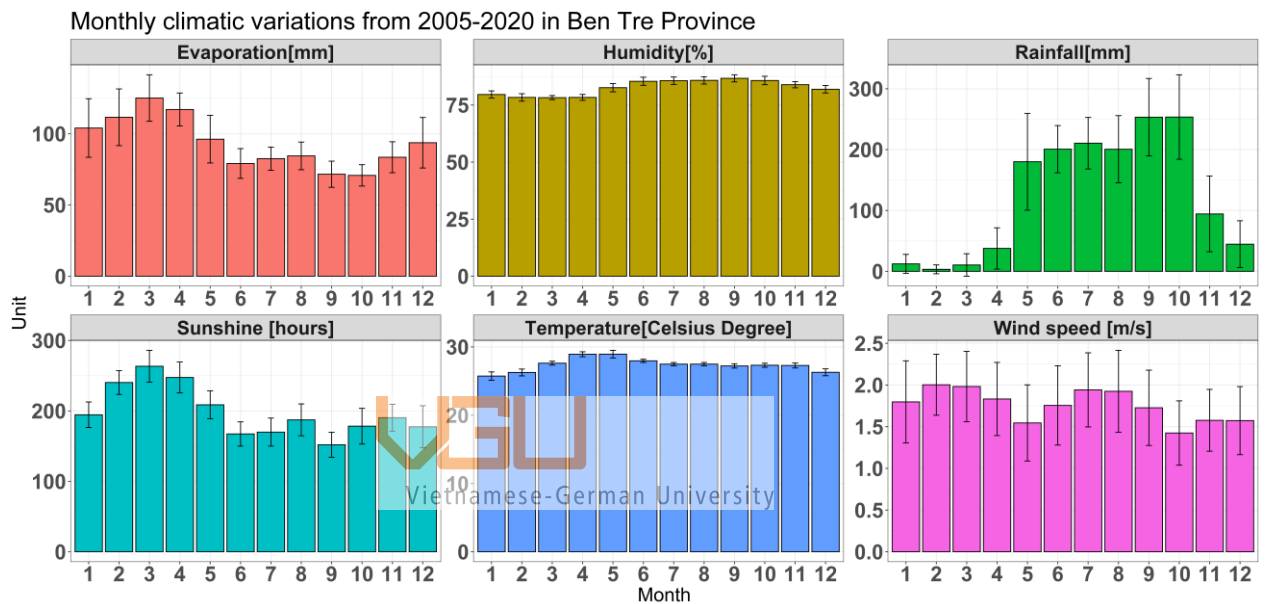


Fig.38. Variations of monthly climatic patterns in Ben Tre Province from 2005-2020



Fig.39. (a) Farmers prepared the water for the dry season (JICA, 2016); (b) Water storage for the orchard using plastic bags in Cho Lach district, Ben Tre province (VDMA, 2020).