Impacts and adaptive measures for groundwater use in the Mekong Delta.
Case study: Tra Vinh Province

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ผลกระทบและมาตรการปรับตัวต่อการใช้น้ำบาดาลในพื้นที่สันดอนแม่น้ำโขง กรณีตัวอย่าง -จังหวัดทราวินห์ ประเทศเวียตนาม-

นายตวน พรามแวน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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ตวน พรามแวน : ผลกระทบและมาตราการปรับตัวต่อการใช้น้ำบาดาลในพื้นที่สันดอนแม่น้ำโขง กรณีตัวอย่าง -จังหวัดทราวินห์ ประเทศเวียตนาม-. (Impacts and adaptive measures for groundwater use in the Mekong Delta. Case study: Tra Vinh Province) อ.ที่ปรึกษาหลัก : สุจริต คูณธนกุลวงศ์

เนื่องจากการเติบโตอย่างรวดเร็วของประชากรและการพัฒนาเศรษฐกิจในพื้นที่ลุ่มแม่น้ำโขงของเวียตนาม ทำให้ทรัพยากรน้ำผิวดินไม่สามารถตอบสนองต่อความต้องการได้พอ น้ำบาดาลจึงถูกใช้มากเกินความสามารถของแอ่งน้ำบาดาล ส่งผลให้ระดับน้ำบาดาลลดลง และเกิดการรุกล้ำของน้ำเค็ม ซึ่งเป็นปัญหาหลักซึ่งส่งผลต่อการจัดหาน้ำกินน้ำใช้ การเกษตรและการใช้ชีวิตในพื้นที่ลุ่มนี้ โดยเฉพาะในพื้นที่ติดทะเล จึงจำเป็นต้องมีภาพรวมของการใช้น้ำบาดาลเพื่อแก้ผลกระทบจากปัญหาดังกล่าว

จังหวัดทราวินห์เป็นจังหวัดติดทะเลในพื้นที่ลุ่มแม่น้ำโขง และมีการพึ่งพาน้ำบาดาลที่เพิ่มขึ้นจากพื้นที่ด้านเหนือจากด้านใต้ ซึ่งสอดคล้องกับปริมาณน้ำจืดในแม่น้ำสายหลักในช่วงฤดูแล้ง ในช่วงฤดูแล้งปี 2018 ประมาณการว่ามีการใช้น้ำบาดาล 346,279 ลบมต่อวันจากการสำรวจภาคสนาม โดยกว่า 52% เป็นการใช้เพื่อเกษตรกรรม เทคนิคเซนเซอร์จับอุณหภูมิผิวดินถูกน้ำมาใช้ในการประมาณการกระจายการใช้น้ำบาดาลในจังหวัดทราวินห์และพิสูจน์ว่าสามารถแสดงผลได้ดีเพื่อใช้ในการปรับปรุงการจัดการน้ำบาดาล ระบบน้ำบาดาลในพื้นที่ศึกษาได้พัฒนาจากระยะเริ่มใช้ พัฒนาสู่ระยะพัฒนา และกลายเป็นช่วงของการใช้มากเกิน จนทำให้สถานะน้ำบาดาลในปัจจุบันไม่มีความยั่งยืน เนื่องจากการใช้น้ำบาดาลที่เพิ่มขึ้นในช่วง 25 ปีที่ผ่านมา แนวคิดการกำหนดอัตราการใช้น้ำบาดาลที่ยั่งยืนทั้งในเชิงปริมาณและคุณภาพในระยะยาวได้ถูกนำเสนอและพิสูจน์ว่าเป็นประโยชน์จากการหาจุดสมดุลน้ำและการควบคุมการเคลื่อนตัวของน้ำเค็ม ผลการศึกษาพบว่า จะต้องลดอัตราการใช้น้ำบาดาลในจังหวัดทราวินห์ลง 49 % จากปี 2018 เพื่อให้เกิดความยั่งยืนของการใช้น้ำบาดาลในพื้นที่

ในการดำเนินการปรับตัวเพื่อการใช้น้ำบาดาลที่ยั่งยืน การกำหนดแผนการใช้ที่ดินใหม่ตามแผนที่ลุ่มแม่น้ำโขงเป็นมาตรการที่เหมาะสมที่จะลดความต้องการใช้น้ำบาดาลในจังหวัดทราวินห์ได้ แบบจำลองการปรับพฤติกรรมบนพื้นฐานทฤษฎีของฟอคได้รับการพัฒนาขึ้นเพื่อเข้าใจพฤติกรรมของเกษตรกรในการปรับเปลี่ยนกิจกรรมทางเกษตรในการรับมือกับการเปลี่ยนแปลงภูมิอากาศ แบบจำลองดังกล่าวช่วยนำสู่ข้อเสนอแนะเพิ่มเติมที่ชัดเจนในการนำแผนที่ลุ่มแม่น้ำโขงมาดำเนินการให้สำเร็จดีขึ้น โดยเพิ่มมาตราการจูงใจและทรัพยากรที่เหมาะสมให้กับแต่ละกลุ่มเกษตรกรและแต่ละพื้นที่

สาขาวิชา วิศวกรรมแหล่งน้ำ ลายมือชื่อนิสิต ....
ปีการศึกษา 2562 ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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KEYWORD: groundwater/ sustainable yield/ behavior analysis/ Tra Vinh Province/ Vietnam

Tuan Pham Van : Impacts and adaptive measures for groundwater use in the Mekong Delta. Case study: Tra Vinh Province. Advisor: Assoc. Prof. SUCHARIT KOONTANAKULVONG, D.Eng.

Because of the rapid growth of population and fast economic development in the Vietnamese Mekong Delta (VMD), the surface water resources are unable to meet these demands and groundwater is also over-abstracted. Groundwater depletion and saline water intrusion become the main problems that threaten drinking water supplies, farming systems, and livelihoods in the delta, especially coastal areas. It is necessary to provide a fully comprehensive picture of groundwater use (GWU) and its impact issues

In Tra Vinh Province, a coastal province of VMD, dependency on GW increases from north to south which has a strong relation with availability of freshwater in major rivers during the dry season. In the dry season 2018, GWU was estimated to be 346,279 m^{3}day^{-}1 based on the field survey data; approximately 52 % of this use is for agricultural activities. Land surface temperature sensing technology is proved to be a good tool for interpolating distribution of GWU. In Tra Vinh Province for better GW management. The GW system in the study area has moved from a pristine system to a developed system then become a depleted system at present. Thus, the existing status of groundwater resources is unsustainable due to increasing of 25 years of GWU. The concept for sustainable yields in both quantity and quality, in the long run, has been introduced and proved to be beneficial by determining equilibrium state and controlling saline GW movement. The results of the sustainable models indicate that the current GWU (2018) needs to be reduced by 49 % to match with the sustainable yield of the aquifer system in Tra Vinh Province.

In order to propose adaptive measures for sustainable GWU, a new land use structure of the Mekong Delta Plan is considered as a suitable measure to reduce a high proportion of GW demand in Tra Vinh Province. Adaptive behavior models (ABM) are developed based on Fogg Theories to understand behavior of local farmers in term of changing agricultural activities to cope with the effect of climate change. ABM can help to clarify additional recommendations to enhance the successful implementation of the Mekong Delta Plan by adding more incentive and resources suited to each specific farmers and zones.

Field of Study:	Water Resources Engineering	Student's Signature ....
Academic Year:	2019	Advisor's Signature ....

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BAU	Business as usual
EC	Electrical conductivity
GW	Groundwater
GWD	Groundwater demand
GWL	Groundwater levels
GWU	Groundwater use
LST	Land surface temperature
MDP	Mekong Delta Plan
MSL	Mean seawater level
HH	Household
HCMC	Ho Chi Minh city
n_{1-3}	Miocene
n_{2-2}	Middle Pliocene
n_{2-1}	Lower Pliocene
qh	Holocene
qp_3	Upper Pleistocene
qp_{2-3}	Upper - Middle Pleistocene
qp_1	Lower Pleistocene
TDS	Total dissolved solids
VMD	Vietnamese Mekong Delta

Chapter 1 - INTRODUCTION

1.1 Background

Almost two thirds of the world's population live within 400 km of the ocean shoreline; just over half live within 200 km, an area only taking up 10% of the earth's surface (Adegoke et al. 2012). Most of these coastal regions rely on groundwater as their main source of fresh water for domestic, industrial and agricultural purposes (Comte et al. 2016). As the world's population continues to grow at an alarming rate, fresh water supplies are constantly being depleted, bringing with it issues such as saltwater intrusion and increasing the importance of groundwater monitoring, management, and conservation (Amore 2012, Swathy 2016).

In Vietnamese Mekong Delta (VMD), the achievement of a sustainable balance between water demand and water supply is a major challenge for management of water resources due to the general trend of increase in water demand from population, agriculture and limited renewable freshwater resources. Because of the rapidly increasing population and very fast economic development in the VMD, the surface water resources are unable to meet these demands, groundwater was over-abstracted (Ha et al. 2015). Resulting groundwater depletion and saline water intrusion are the main problems that threaten drinking water supplies, farming systems, and livelihoods in the delta (Vuong 2013).

In some regions of the Mekong Delta, the ongoing exploitation has reached the capacity limits of the aquifers, challenging scientists and decision makers in order to satisfy the increasing water demand in the VMD (Wagner et al. 2012). New groundwater exploration studies are often hindered by the complexity of the subsurface structure and the hydrogeological system of the VMD, which still needs further investigations (Wagner et al. 2012). Thus, in order to exploit, use and manage the groundwater resource in coastal areas sustainably, further investigation on water resources in large scale of VMD is needed and integrated water resources management practices should be considered (An et al. 2014). Further investigation should be conducted following the tidal regime and seasons in order to: (i) examine interaction of groundwater between shallow aquifer and deep aquifer as well as these aquifers with surface water;

(ii) assess the effects of pumping activities on groundwater flow system; (iii) identify impacts of climate change and sea level rise on groundwater source in coastal aquifers (An et al. 2014).

Currently, in the Mekong Delta, the concept of sustainable GW resources utilization is taken into consideration particularly in the urban area and the coastal area (DONRE, 2012). Therefore, the decision-makers there have to be provided with adequate information on what is happening in the area's GW in order to formulate sustainable water resources development strategies. GW models play an important role in development and management of GW resources, and in prediction of effects of management measures such as assessment tools for evaluating recharge, discharge and aquifer storage processes, and for quantifying sustainable yield (Zhou et al. 2011). Several studies have been carried out on the impacts of the climate scenarios, groundwater pumping scenarios in the MDV. These results showed that groundwater pumping presented a more significant influence on the groundwater system than climate variability. However, there is no estimation of groundwater demand in the future by different climate change and socio-economic development. Previous studies defined groundwater demand amount in future same as current or increase by several ratios. Structural and non-structural measures have not been analyzed to reduce pressures on groundwater resources and meet sustainable yield of aquifers yet.

The UN-Water (2009) demonstrated that climate change is going to have a direct impact on the hydrologic cycle and, through it, water availability for different purposes. Climate change adaptation has become more important in terms of any development discussion (Keskinen et al. 2010, Tennberg 2012). Adaptive measures consider not only optimum adaptation strategies for projected change in drought, flood, and implications for water security within an integrated catchment framework but also the impact on long-term groundwater quantity and quality (Parry et al. 2007). In the coastal areas as VMD, where increasing urban and rural water demand has already exceeded sustainable levels of water supply, tiger planning and regulation are very necessary to remain sustainable (Parry et al. 2007). However, ongoing and proposed adaptation strategies are likely to buy some time and face many challenges due to uncertainties in future climate projections and inform adaptation decisions and poor response of local people to government guidelines and (Collins et al. 2013, Evers et al. 2018). In order to encourage local people to follow regional adaptive strategies, a better understanding of behavior factors needs to be carried out due to various decision making of adaptation.

For preparing the information mentioned above, it is necessary to carry out the field survey to investigate groundwater use distribution/pattern and how groundwater issues impact on socio-economic development for the Mekong Delta, especially in coastal areas. Furthermore, by using groundwater modelling approaches, this study was conducted to assess the sustainable yield of aquifers in a coastal province based on the proposed sustainable concept and criteria. By applying scenarios of climate and socio-economic development, projection of groundwater demand and the varying gaps of GW supply to meet sustainable yields in near future should be quantified and evaluated. Based on the results of models and evaluations, additional recommendations are proposed to improve adaptive proposals of the government to cope with sustainable GW development in the coastal Vietnamese Mekong Delta.

1.2 Objectives of the study

The main objective of this study is to propose adaptive measures to cope with sustainable groundwater yields of the aquifer system under climate change and socioeconomic development scenarios.

The specified objectives are to:

1) To explore the role of groundwater use and impact of GWU in Tra Vinh Province area.
2) To assess sustainable yields of the aquifer system and estimate groundwater demand by different scenarios of climate change and socioeconomic development in Tra Vinh Province area.
3) To propose adaptive measures to cope with sustainable yields of the aquifer system in Tra Vinh Province area.

1.3 Approach of the study

In order to achieve the objectives stated in section 1.2, the study approach is shown in Figure 1.1. The survey, satellite image and groundwater model data were collectively used to develop the best possible estimation of groundwater use distribution and pattern. The surveys were carried out during 19 to 29 March 2018 to set the baseline of GWU distribution, i.e., each distribution is extrapolated by land surface temperature (LST) from satellite images and the groundwater flow model was used to correct and verify distribution/pattern of GWU by space and time. Upon getting the best possible spatial distribution of GWU, the simulation of groundwater was developed to assess impact of long-term GWU. For assessing sustainable yields of the aquifer system, concept and criteria of sustainable yield are proposed for the study area with the concern of reducing impacts on both groundwater quantity and quality. The groundwater models developed for the study area were used to estimate the sustainable yield based on proposed criteria of sustainable yields. In term of proposing adaptive measures for groundwater use, Fogg Behavior Model (FBM) was applied to analyze human behavior from field survey data which derived various decision factors of new cropping and land use change to cope with the impacts of climate variabilities.

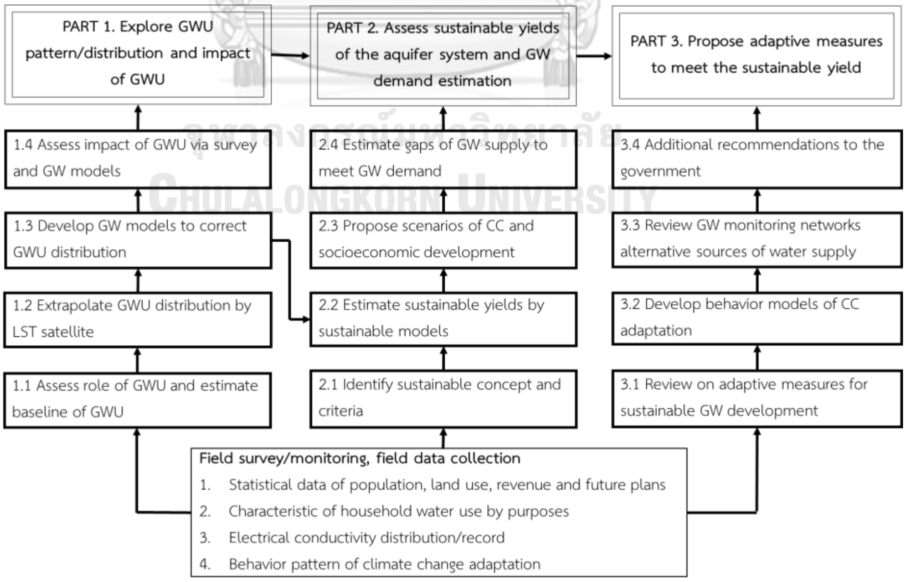


Figure 1.1 - Study approach

1.4 Scopes of the study

1.4.1 Scope of work

The research scope includes research background, fieldwork, models and analyzes. The research process, described in-depth below, established a groundwater dataset within the Tra Vinh Province, Vietnamese Mekong Delta (VMD) for the study.

Field surveys

In order to ensure sufficient coverage of local communities with groundwater consumption, groundwater use impact and behavioral factors in climate change adaptation, three different districts were selected for the socio-economic survey, and thus for the test run as well. In each district, the population was classified into strata of lower income group, middle-income group and higher income group by each commune due to the strong dependence of water use on the type and size of the residential property (Mullaney 2004). Three communes, represented three income group of each district, were selected for conducting the survey. In the study area, totoal number of househould are 288,666 households in 2018 (TVSO 2018). Based on the guideline of sample size calculation (Israel 1992), a deterministic sample size of 150 households was chosen for each zone (all together 419 samples: error 5 % with confidence level at 95 %), consisting of small to high groundwater users in the study area. The stratified random sampling model divides the ensemble into a couple of layers (or zones), and the sampling was conducted independently in each layer. When the statistical property within a layer shows similarity, and the variance within the layer is small and the variance between layers is large, the stratified random sampling could greatly improve the sampling efficiency (Deng et al. 2011).

Estimation of GWU distribution/pattern and assessment of GWU impact

In term of GWU distribution, the survey and analysis focused on domestic and agricultural uses including irrigation and aquaculture. Industrial use was not involved in the estimation of this study due to the existing available information of industrial wells under license. Moreover, groundwater is mainly exploited for household and agricultural activities of the Vietnamese Mekong Delta in general and the study area (Tra Vinh Province) in particular (Sanh 2010). GWU distribution was estimated by using the statistical data (population and land use) and extrapolated to non-data-areas by applying Land Surface Temperature (LST) from Satellite Images. In addition, groundwater modelling system (GMS) software was applied to simulate flow of GW to correct the distribution/pattern of GWU for both space and time based on the calibrated groundwater levels (GWLs).

The numerical model was developed to check the impact of long-term groundwater use on aquifers. The three-dimensional groundwater flow model MODFLOW-2000 and three-dimensional solute transport model (MT3DMS) were used for predicting groundwater flow and salinity transport from January 1994 to December 2018. The impact of over-exploitation includes storage depletion and salinity movement in the duration of 1994 and 2018. Land subsidence is not considered in this study due to unavailable of observed data in the study area even though with the strong correlation of GWL drawdown and land subsidence in the VMD (Minderhoud et al. 2017). GWU issues were identified through the survey to confirm the simulation of GW models.

Estimation of sustainable yield and groundwater demand

The concept of sustainable yield focused on reducing the impacts of over-exploitation including storage depletion and salinity movement in the duration of 2018 till 2030. When the aquifer system is simulated to meet the equilibrium state, GW drawdown will reduce to approximately zero (Elango 2005, Abdalla 2009). So, it can significantly reduce the rate of land subsidence in the study area. Two criteria corresponding with these impacts are applied for the groundwater sustainable model in order to estimate the sustainable yield of the aquifer system. The first criterion is to lead the aquifer system meet a new equilibrium state and the second one is to control salinity movement until 2030.

In order to estimate groundwater demand in the future, firstly total water demand in dry season is estimated by using information about population growth and land-use change of two socioeconomic scenarios. In addition, three scenarios of climate change are applied to estimate the duration without fresh surface water in the study area. Water demand is separated two groups including the ones uses only surface water and the others depend on both surface water and groundwater. Proportion of GW demand is estimated based on the dependence on GW varies different purposes among three zones and availability of fresh surface water during dry seasons. Lastly, groundwater demand estimation is compared with the sustainable yield to determine the gaps of groundwater supply by different scenarios of socio-economic development and climate change.

Proposal of adaptive measures for GWU

In order to recommend adaptive measures for GWU to meet sustainable yield in the future, measures are separated and reviewed by three aspects including demand side, supply side and management side. In the supply side, a review of water supply plans both in regional and local scale is carried out to assess the reducing proportion of GWU in the future by using alternative sources of water supply in the future. In term of management side~~s~~, a review of monitoring network design for both GWLs and salinity movement is conducted as an adaptive measure to improve the management of sustainable yields. The main point of this part is to analyze the impacts from land use plan in the Mekong Delta Master and Provincial Plans as an adaptive measure to meet the sustainable development of water resources in general and sustainable yield of the aquifer system in particularly. In term of implementing the master plan in the study area, behavior factors in climate change adaptation are surveyed and developed behavior models for specified areas based on Fogg Theories. These models provide more knowledge on behavior side to let the stakeholder know how to stimulate local people to follow the change in the master plans of the region and local.

1.4.2 Study area

The study area is Tra Vinh Province, which locates in the southeastern part of the Mekong Delta in Vietnam and lies between the coordinates of 9°31’38.2” to 10°04’45.1”N latitude and 105°56’57.1” to 106°35’1.7”E longitude. The region is situated southwest of Ho Chi Minh City and lies on the coastal plain of the Mekong Delta. The socioeconomic survey was conducted in the northern, middle and coastal zone by three representative districts such as Cang Long, Tra Cu and Duyen Hai district, respectively (Figure 1.2). Groundwater models simulated the whole area of the study area (2,341 km^2) and 13 layers including 7 aquifers and 6 aquitards.

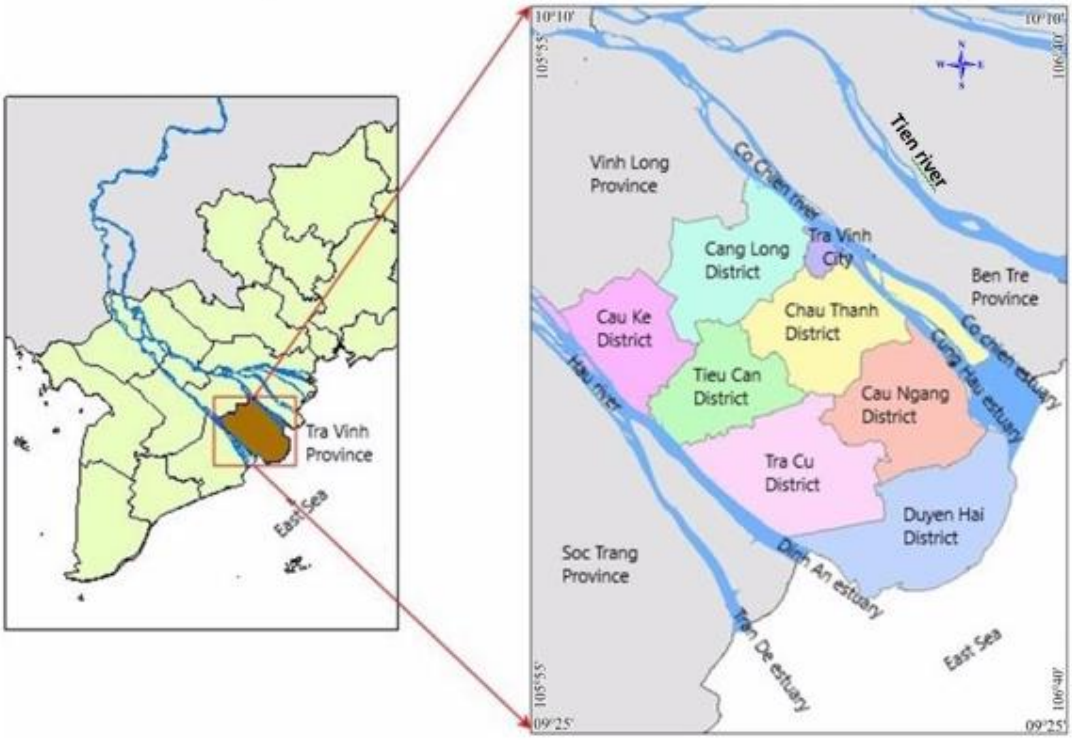


Figure 1.2 - Geographical location of Tra Vinh Province in VMD (Tran 2020)

1.4.3 Data used in the study

The data collection is summarized as Table 1.1. The collected data are mainly from the Division for Water Resources Planning and Investigation for the South of Vietnam (DWRPIS), and fieldwork of SALINPROVE project collection.

Table 1.1 - Summary of data collection for the study

Data name	Types	Quantity	Period of data	Sources
1.Hydrogeology data				DWRPIS & DONRE
1.1. Borehole strata	vertical section	72	2003-2016	
1.2. Geophysical	map (distribution , cross-section)	10	2003-2016	
1.3. Observed GWL	station	17	1994-2018	
1.4. GW abstraction	report	3	2013 & 2018	

Table 1.1 - Summary of data collection for the study (to be continued)

Data name	Types	Quantity	Period of data	Sources
2. Hydrology data				
2.1. River water levels	station	5	1994-2018	SIWRR
2.2. River cross-sections	map (distribution, cross-section)	134	1994 -2018	
2.3. In flow	station	3	1994 -2018	
2.4. Meteorology	station	6	1994 -2018	SRHMC
3. Socio-economic				
3.1. Statistical year	book	2	2007 -2018	DOS
3.2. Land use planning	book, map	7	2010, 2020, 2030	DONRE
4. Climate data				
4.1. Rainfall, temperature	3	2	1980 - 2018	SRHMC
4.2. Inflow	report	2	1994 - 2018	SIWRR
5. Field data				
5.1. EC measurement	dataset	746	2017	SALINPROVE project
5.2. Salinity observation	station	5	6/2017- 12/2018	SALINPROVE project

where:

DWRPIS = Division for Water Resources Planning and Investigation of the South of VN

SIWRR = Southern Institute of Water Resources Research

SRHMC = Southern Regional Hydrometeorology Center

DONRE = Department of Resources and Environmental (Tra Vinh Province)

DOS = Department of statistics (Tra Vinh Province)

SALINPROVE project = Mitigating groundwater SALINity impacts for imPROVEd water security in coastal areas under socio-economic and climate change

1.5 Significance and limitations of the study

1.5.1 Significance of the study

This study highlighted the significance of research with the following points:

1) The study is the first trial to collectively use field survey data to estimate the GWU distribution and correct/confirm the distribution/pattern with the technology of satellite images and groundwater model and the distribution/pattern derived will be used as an important basis for groundwater management study in the area.
2) The study is the first trial to estimate sustainable yield under the sustainable concept via newly developed GW models to simulate the complex hydrogeological setup of the study area and the sustainable yield derived will be used for sustainable groundwater management control in the study area.
3) The study is the first trial to propose additional adaptive measures for GWU with consideration of behavior analysis from the field survey data.

1.5.2 Limitations of the study

In this dissertation, there were the following limitations:

1) The sample size was relatively enough for 90 % significant - 419 interviewed respondents for regional planning. However more samples should be conducted to enhance the accuracy of the results for further local planning and implementation.
2) The groundwater model did not consider aquifer parts distributed on the sea due to lack of borehole data. If the aquifer boundary can expand wider towards the sea, the boundary condition of saline transportation model will reduce uncertainty.
3) Number of salinity monitoring stations is as available and duration of salinity monitoring is only two years, longer monitored data will enhance the estimation of sustainable yield.

1.6 Structure of the dissertation

The rest of the thesis is organized as follows.

Chapter 1 provides the study background, objectives, the approach and crops, the significances and limitations of the study and the structure of the dissertation.

Chapter 2 reviews development of GWU in the Vietnamese Mekong Delta (VMD), sustainable yield development and its application in the VMD, GW demand in the VMD, factors that affect farmer’s climate change adaptation and application of Fogg Behavior Theories on different sectors. The discussion highlight gaps of previous research in GWU distribution/pattern, application of sustainable concept in VMD and applications of Fogg Behavior Model (FBM) on groundwater resources field.

Chapter 3 describes the characteristic of study area such as the boundary and location, topography and climate, hydrology, groundwater development and management and general information of socio-economic. The descriptions of the study area highlight the current situation of water supply and use by two main sources including GW and surface water.

Chapter 4 describes the data used in the subsequent study, measurement of main variables, and detailed methods to operationalize research approach in order to fulfill study objectives. GW models and Fogg Behavior Model are the major data analysis techniques used. Satellite Images is used as a support tool for GWU distribution interpolation.

Chapter 5, 6 and 7 present analyzed results and findings corresponding with three studies objectives. Chapter 5 shows the results of GWU distribution/pattern and impact of GWU via field survey data analysis and groundwater model development. Chapter 6 presents the estimated results of sustainable yield by developing sustainable models based on concept and criteria of sustainability. Projected results of groundwater demand under various scenarios of socio-economic development and climate change is also presented in this chapter. Chapter 7 discusses the reviews of adaptive measures from government proposal and other literatures. Development of adaptive behavior models and design of groundwater monitoring network is presented in this chapter. Chapter 8 provides the overall discussions, conclusions and recommendations of the study.

Chapter 2 - LITERATURE REVIEWS

Groundwater (GW) is an important research topic, especially in the context of extreme water shortage for both domestic and agricultural purposes in the Vietnamese Mekong Delta (VMD). Several studies have examined impact of GW extraction in specific areas or scenarios. However, most studies have paid little effort to survey and estimate groundwater use (GWU). This section reviews gaps of previous studies in groundwater use estimation and application in the VMD. The importance of sustainable yield studies and application of sustainable yield concepts over the world and in the VMD were reviewed carefully to select the concept and tool to assess sustainable yield in the study area. Besides, a review of climate change impact on GW was provided to help clarifying which factors are the main drivers of change in aquifer components. Lastly, a majority of review studies have investigated behavior factors in climate change adaptation and applications of Fogg Behavior Model (FBM).

2.1 Groundwater use in VMD

2.1.1 Groundwater consumption and management

Groundwater consumption

The Vietnamese Mekong Delta (VMD) is located in southwestern Vietnam, one of the areas in the world that is most vulnerable to the impacts of climate change (DONREs, 2012). Due to many activities to cope with climate change in upstream and increasing of water demand for drinking and agriculture in the coastal area, GW has been playing an important role in local water supply, particularly in the areas of low rainfall and low lying coastal alluvial plains (Nam 2017). Since the 1960s, GW exploitation in the VMD to meet domestic, agricultural and industrial needs has dramatically increased (Danh 2008, Wagner et al. 2012). Dug wells and tube-wells are most popular in exploiting GW for household demand in the VMD, while big wells were constructed for industrial areas or water supply stations as part of the Rural Clean Water Supply Program (LittleJohn 2011).

About 4.5 million people depend upon GW for drinking (Ghassemi et al. 2000). In the largest city in the delta, there was 24 per cent of the population of Can Tho city, exploited GW for domestic purpose as drinking, cooking, bathing or gardening (IUCN

2010). Especially in rural or coastal areas where is difficult to access fresh surface water due to increasing salinity concentration in the dry season, this proportion also becomes much higher (Danh 2008, Eastham et al. 2008, Van et al. 2019). In VMD, it is estimated that as a million GW wells, distributed from shallow to deep aquifers at the depth of 10 to 300 m (MONRE 2011). The GW extraction increased significantly from around 1,2 mil.m^3/d in 2007 (DWRPIS 2009) and just over 2 mil.m^3/d in 2015 (Minderhoud et al. 2017) (Figure 2.1).

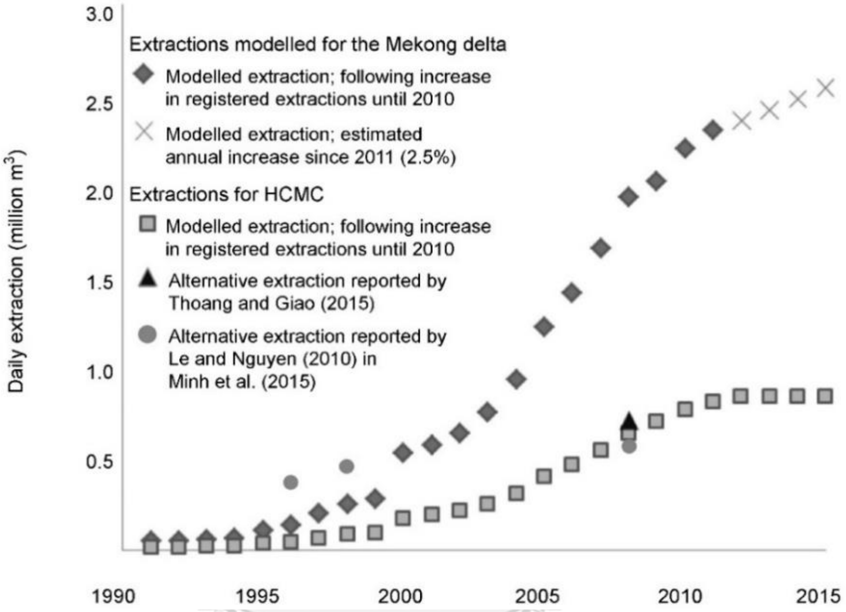


Figure 2.1 - Annual GW abstraction in the VMD and HCMC province (Minderhoud et al. 2017)

Summary of studies on GWU in Mekong Delta presents an increase trend of GW consumption since 2000s until now, however there were only few surveys which conducted the estimation of number and pumping rate of GW wells (Danh 2008, Vuong 2013). Other studies usually applied statistics of previous studies and used the linear interpolation to estimate GWU for their own studies (Minderhoud et al. 2017, Nam 2017, Hai 2018).

Groundwater use management

Since 2015, water resource planning in Viet Nam has been focused more on GW resources, but still relatively minor actions have been adopted to promote sustainable GW development. In Vietnam, large-scale GW wells of supply units and industrial zones need the license for construction and operation based on the 1999 Law on Water

Resources. However, local authorities usually meet many difficulties in implement these regulations due to low capacity and consistency (Danh 2008, IUCN 2010). According to the latest statistic from Vuong (2013),the VMD has around 553,135 GW wells in which only 932 wells were licensed for exploitation with capacity higher than 200 m^3/day which mainly used for drinking or industrial supply (IUCN 2010). The main proportion is small capacity wells own by local residents without any license. Although regulations on GW management have been promulgated, strategies of GW development still has to face many barriers due to gaps in assessment of potential or sustainable GW exploitation (Boehmer 2000). This resource seems to be effectively invisible and consequently ignored by policymakers (IUCN 2010).

GW abstraction is the main input of any GW simulation, however information about distribution and pattern of GWU show a big gap at the VMD. Most of previous studies input GW wells to models by average distribution so the model results could not present GWL distribution or salinity distribution with a high accuracy. Thus, it can give more understandings on household GWU by different purposes and its distribution. Filling the gaps of understanding of GWU pattern and distribution will help stakeholder and water managers to carry out the better simulation and assessment of GW. In order to meet sustainable GW development, role and impact of the GWU on the aquifer system throughout Mekong Delta need to be understood clearer, especially in coastal areas where the water supply has been facing more challenges.

2.1.2 Impact of groundwater exploitation over the world and in the VMD

Currently, many coastal areas in the world have been under intense pressure of over GW pumping and saline water intrusion (Polemio et al. 2019). Over GW exploitation is the main season which causes depletion of GW storage. The negative effects of the depletion may include exhausting GW wells or lake, declination of water quality; land subsidence, cost of exploitation (Leake 1997). The strong reliance on GW to meet the local demand near the coast has resulted in a significant GW depletion, altering in reversing the gradient of GW flow in coastal led to saline GW intrusion from sea (Yakirevich et al. 1998), and conflicts over the use, protection and development of the GW resources (Karim et al.). The pressure on water supplies and precious ecosystems in coastal areas is very high and will only be seen to increase in the future (Post 2005).

GW depletion has been a major concern in aquifer systems in many countries over the world (Famiglietti 2014). In several areas of China, over-exploitation or reduction of GW recharge or combination caused GW depletion in since the 2000s (Changming et al. 2001, Feitelson 2005, Zhou et al. 2013). In China, the rate of GW exploitation has experienced a dramatic rise from 57 km^3/year to 111 km^3/year in the period between the 1970s and 2000s (Zaisheng et al. 2006). After the 2000s, the average depleted rate is estimated by about 24 km^3/year in Central Valley of California (Konikow 2015). Long-term GW extraction also causes storage depletion in many developing countries. GW levels declined in a range of 45 to 50 m in Bangkok and 12m to 30m in Ho Chi Minh city, respectively after around 25 years of GW extraction (Ha et al. 2015, Minderhoud et al. 2017, Lee et al. 2018).

Monitoring data and simulation of the aquifer system of the delta for more than 30 years shows declination in both GW quantity and quality by numerical models as IMOD, VISUAL MODFLOW and GMS software due to increasing GW exploitation (DWRPIS 2009, IUCN 2010, Minderhoud et al. 2017, Van Pham et al. 2019). GW flow models in the period of 2000 and 2010 showed that GW resources in VMD were under depletion. The impacts of GW abstraction on the aquifer system were significant through the decreases of GWL with average 1.75 m for the main exploited aquifer (qp_{2-3}) and the decreases of the accumulative changes of storage with average 73.29 mil.m^3 per year for the whole VMD (Vuong 2013). In VMD, GW presents a heterogeneous in fresh-saline distribution by depth because of sea-level regression and transgression phases since million years ago (Van Pham et al. 2019). The salinity of GW extraction frequently increases due to GW storage depletion by overexploitation in the Mekong Delta (IUCN 2010). In the period of 2006 and 2010, the subsidence rate was estimated about 1.6 cm per year using InSAR data (Erban et al. 2014). Recently, Minderhoud et al. (2017) demonstrated that GW pumping caused the subsidence of the VMD on average by about 18 cm by last 25 years, with some areas subsiding by over 30 cm based couple packages of IMOD model. By land subsidence modeling suing IMOD software for Soc Trang Province, in the serious scenario of combining increasing pumping and low recharge condition, model simulation predicted that significant land subsidence be at 71.4 cm in 2035.

In summary, most of studies in the VMD applied numerical model to assess impact of GW extraction on the aquifer system. Reviews showed three main impacts including storage depletion, declination of GWLs, salinity movement and land subsidence. While GW flow models were always simulated with improvement of land recharge (Vuong 2013, Long et al. 2017), river conductance (Boehmer 2000, Van et al. 2018), hydraulic conductivity distribution (Van Pham et al. 2019) and GW transportation model lacked development of input parameters such as advective and dispersion coefficients. These coefficient values was referred from books or other areas without any calibration (Vuong 2013, Van Pham et al. 2019).

2.2 Sustainable groundwater development in the VMD

2.2.1 Impact of climate change on groundwater development

In term of climate change impact studies, there are fewer studies in GW due to the better visibility and accessibility of surface water (Silva 2018). In comparison with surface water, GW shows a more complicated relationship with climate variability (IPCC 2007). In the VMD, there are some studies in climate change impact on GW system. The results concluded that climate change is a major factor effecting on GW resource in the VMD. The hydrological models and GW models have determined the negative and positive impacts of three climate change scenarios including five GCMs under RCP scenarios to GW resources in VMD. In the late 21st century, average wet season recharge is estimated to remain unchanged at 28% as in base year (2010) (Shrestha et al. 2016). However, average dry season recharge is projected to reduce by 2 mm and 4 mm under RCP4.5 and RCP8.5 scenarios, respectively. By RCP4.5 and RCP8.5 scenarios, GW storage will go through a moderate rise to 120 and 160 mil.m^3 at the end of the century, respectively (Shrestha et al. 2016). In period of 2050 and 2100, the rate of decrease in GWLs is projected as 10 cm to 50 cm per year and saline GW areas of all aquifer are expected to increase by the end, except for Holocene aquifer (qh) (Vuong 2013). In addition, GW exploitation is demonstrated to be more influence on the GW system in comparison with the impact of climate change in some areas of VMD (Hai 2018).

2.2.2 Sustainable yield estimation of the aquifer system

The term sustainability has been in recession for a long history with development of sustainable yield concept depending on the types of aquifer yield (Maimone 2004). Since the 1980s, the sustainable concept was well known and was also applied for the management of GW resources development (Zhou 2009). Before there was the concept of sustainable yield, safe yield was widely applied by constraints of GW quality, supply, economic and law/regulations (Todd et al. 1980). While the sustainable yield is estimated by a certain amount of GW extraction for a long duration without impact on environment and socio-economic (Lin et al. 2019). For instance, e sustainable yield can be understood as "the allowable net draft at steady state for a selected equilibrium head" (Mink 1980) or GW system must reach equilibrium state (Sophocleous 2000, Bredehoeft 2002). In coastal aquifers, GW extraction can lessen GW flow toward the coastal line and cause salinization in areas of fresh GW (Roumasset et al. 2010). A capture of natural discharge can also define sustainable yield (Bredehoeft 1997, Bredehoeft 2004). he capture can be understood by deriving a proportion of GW storage but actually from surface water (i.e., river, reservoir and canals) (Sophocleous 1997).

In the VMD, there is no reliable understanding of the potential of GW because of limitation in GW technical assessment (Boehmer 2000, IUCN 2010). In VMD, sustainable yield was usually estimated based on a specified drawdown (Vuong 2013, Tran et al. 2019) or as a proportion of GW recharge, the proportion changing with different hydrogeologic conditions (Dong 2017) without the concern of impact of GW extraction. There is no research on sustainable yield of aquifers among VMD, applied the concept of sustainable yield to reducing impact of GW exploitation.

In summary, sustainable yield of the aquifer system in the study area needs to be estimated in order to maintain GW supply for essential demands and reduce impact of over-groundwater exploitation including both quantity and quality. Based on literature reviews, climate change does not present a high directly impact on change of GW situation in the near future, so the estimation of sustainable yield study is not necessary to involve climate change effect in the study area.

2.3. Groundwater demand estimation in the VMD

In the VMD, the most common sources of water for irrigation include rivers, canals and ponds (IUCN 2010). During dry season, climate change and upstream activities have been causing negative issues in the VMD including drought and saltwater intrusion (Nam 2017). In 2016, these issues also caused extremely water shortage in many coastal areas of the VMD. The GW extraction for domestic and irrigation are reported to be rapidly increasing since the 2000s in Viet Nam, especially in some urban and coastal areas of the VMD (Eastham et al. 2008, Nam 2017). In coastal province of VMD, the preference of the households for the different water supply sources was ranked as follows 39-60%, 7.8-39%, 1.9-6.4% and 2.1% for exploiting GW by tube-wells, using tap water network, harvesting rainwater and storing river/canal water, respectively (Chi et al. 2018). Can Tho city, a center socio-economic of the VMD, present a high dependence on GW supply for domestic activities, accounting for 52.4% total domestic water demand (Danh et al. 2015). These proportion can be applied to estimate GW demand for domestic use in the future based on scenarios of population growth (Tran et al. 2019). However, there is still a significant percentage of GW which use for agricultural activities such as irrigation and aquaculture. In most studies of GW prediction, the estimation of GW demand in the future is usually an assumption of business as usual (Vuong 2013, Shrestha et al. 2016, Bui et al. 2017) or increase or reduce specific percentages from the baseline. In general, GW demand studies in VMD focused mainly on impact of change in population and land use and paid little attention to climate change effect. A full estimation of GW demand under by scenarios of socioeconomic and climate change need to be carried out to understand impact range of these scenarios on GW demand in the future.

2.4 Behavior change in climate change adaptation

2.4.1 Concept of climate change adaptation

In term of climate change adaptation in VMD, Dang et al. (2012) summarized various adaptive measures such as shifting planting dates, adjusting planting techniques, switching and diversifying crops and varieties, shifting water inlets, expanding area under irrigation, soil conservation, crop rotation, changing crop management practices, diversifying income sources, and buying crop insurance from previous studies. Much literatures have emphasized the influence of the socioeconomic characteristics in determining farmers' decision to choose climate change adaptation strategies (Hassan et al. 2008, Bryan et al. 2009, Marie et al. 2020). However, previous studies have given less effort to understand psychological factors in terms of climate change adaptation (Grothmann et al. 2005), and these factors were short of integrating with socio-economic factors to understand more about the decision making of farmers in that process (Dang et al. 2012).

The VMD is considered as one of the most vulnerable areas by effects of climate change and extreme events over the world (Chinvanno 2011). In addition, heterogeneity in the implementation of adaptation strategies of climate change has reduced the efficiency of adaptive measures, especially crop and variety changing. Recognizing that there were uncertainty and heterogeneity in farmer decision-making to cope with climate change impact (Dessai et al. 2007), a better understanding of behavioral process of farmers in climate change adaptation will play a significant role in influencing policymakers (Dang 2014, Arunrat et al. 2017).

2.4.2 Behavior factors of climate change adaptation in the VMD

In the MDV, behavior factors were potential constraints to change of the farming systems or expansion of aquaculture: know-how of farmer, water, capital, labor and land size, market price/demand (Bosma et al. 2004, Bosma et al. 2005, Phong et al. 2007). Farmers and agricultural officers showed a different awareness of barriers to climate change adaptation (Le Dang et al. 2014). From the perception of farmers, the main barriers included land ownership, non-acclimatize, access to new agricultural technologies, market demand, habit, or maladaptation. While, agriculture officers believed that issues of demographics, supported capita, land extension, working experience in agricultural activities, and access climate variability information played an important role in barriers of farmer perception about climate change adaptation (Le Dang et al. 2014). These different points between farmers and officers can explain the unsuccessful adaptive strategies in VMD for many years. Base on reviews of empirical researches relevant to factors affecting varies decision of farmers in term of climate change adaptation, these factors were defined by five categories including demography and socio-economic conditions, existing resources, features of society and culture, human perception and psychology (Dang 2014).

Much literatures discussed the importance of socio-economic factors and physical resources in understanding farmers' climate change adaptive behavior. Most of them used a fuzzy mass of psychological theories that is not easy to present an organized and specific view. However, there is little research effort that went into combing motivation and ability factors which are important parts to understand human decision-making process to do adaptive measures under climate change in VMD.

2.4.3 Fogg Theory and its application

Fogg Behavior Model (FBM) is a new psychological model which is widely applied in concept persuasive technology (Fogg 2009b). Three factors of FBM consist of motivation, ability, and triggers to be able to adjust behavior. Since 2007, the earliest practical models were developed based on FBM to focus on designing new technologies to optimize motivation and productive uses (Fogg 2002, Fogg 2009a, Fogg 2009b). The models show the relationship between motivation, ability, and trigger by a friendly description for users (Fogg 2009a). Technology design is the main field, the FBM and other development from it are widely applied (Saparova 2012, Guimaraes et al. 2018) and following by the public health field (Agha et al. 2019). For instance, an application of FBM is carried out to design the health care plan for the employee in the United States (Boerger et al. 2018). he results showed a significant difference in factors including gender, age, working environment, and financial incentive by different utilizers. Kemler et al. (2018) demonstrated that it is difficult to change the health-related behavior of winter athletes in the Netherlands and their behavior change in injury prevention was estimated efficiently at 10%. In brielf, FMB has been widely applied in business and public health field in term of persuasion. In term of different decision-making, FBM can explore strategies for designing for behavior change to make/change habits, and to support conscious actions.

Chapter 3 - STUDY AREA CONDITIONS

In water resources research, the study area is always defined firstly. Actually, the study area river basin or sub-basin, however in some cases, they follow government boundaries such as province/city limits. In this study, Tra Vinh is situated in the central east of Mekong River Delta Region, in Vietnam covering an area of a 2,512 km². The province is located between two rivers: the Tien river and Hau river, which flow towards the South China Sea. In order to have a macro picture, this chapter describes main hydrological factors such as topography, climate, hydrology, hydrogeology, groundwater supplies and general information of socio-economic of Tra Vinh Province also includes.

3.1 Topography

The province of Tra Vinh is located in the southeastern part of the Mekong Delta in Vietnam and lies between the coordinates of 9°31’38.2” to 10°04’45.1”N latitude and 105°56’57.1” to 106°35’1.7”E longitude (Figure 3.1). Its northern boundary is bordered by the Ben Tre Province, in the south the Soc Trang Province, in the west the Vinh Long Province, and in the east the East Sea. Note that an islet is located between the Tien and Hau Rivers. The total natural area of Tra Vinh Province is about 2,341.2 km^2, with nine subordinate administrative unit. The provincial coastline stretches up to 65 km extending from Duyen Hai district to Chau Thanh district (Mai et al. 2014). The coastal delta affected by the interference of sea and river features prominently in the provincial topography, forming sunken and flat areas alternated with arched sand ridges running in parallel with the coast, which become higher and larger towards the sea. The Tra Vinh Province is part of the lowland area in the Mekong Delta having an elevation range of +0.4 meters to +1 meters (occupying 66 % of the area of the province), is suitable for agriculture production linked to its irrigation and drainage by gravity. The sand dunes have an average height of +1.0 meter to +3.0 meters. The region can be easily distinguished by its big quantities of mounds and sand caves and a complex network of rivers and canals.

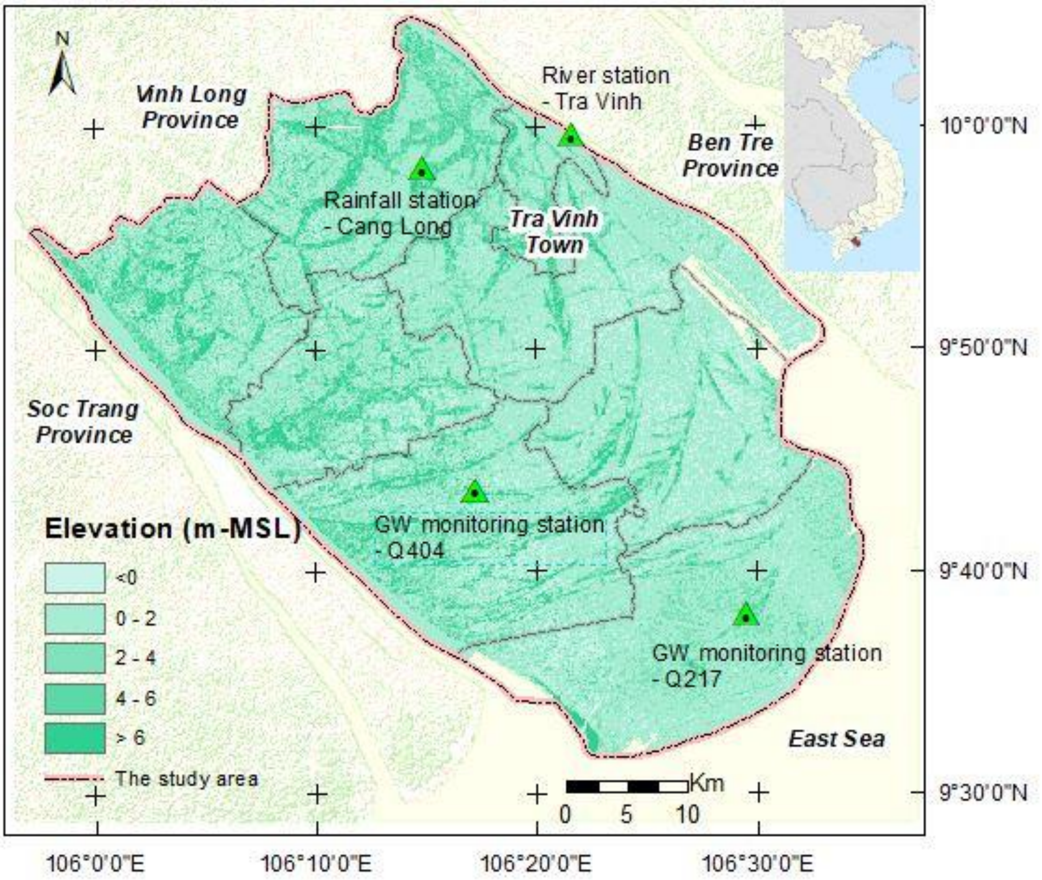


Figure 3.1 - Location and topography of Tra Vinh Province

3.2 Climate

Located in the Mekong River Delta, Tra Vinh province has typical characteristic of humid tropical climate which are highlighted by the uniformly high temperature, plenty of sunlight, and abundant rainfall. The average temperature is about 26.6°C in, ranging from 18.5°C to 35°C. Maximum temperature commonly occurs in April and May, while the minimum temperature takes place in December and January. The province receives an average sunshine hour of 7.7 per day (Mai et al. 2014) which is a great advantage for growing crops. Tra Vinh climate is with two distinct seasons which are dry and rainy season. The rainy season lasts from May to November and dry season stretches from December to April next year. The data recorded at Cang Long weather station (Figure 3.1) shows the variation of rainfall to a significant degree. Average rainfall in rainy season is 1617 mm whereas there is only 198 mm averagely in the dry season (Figure 3.2).

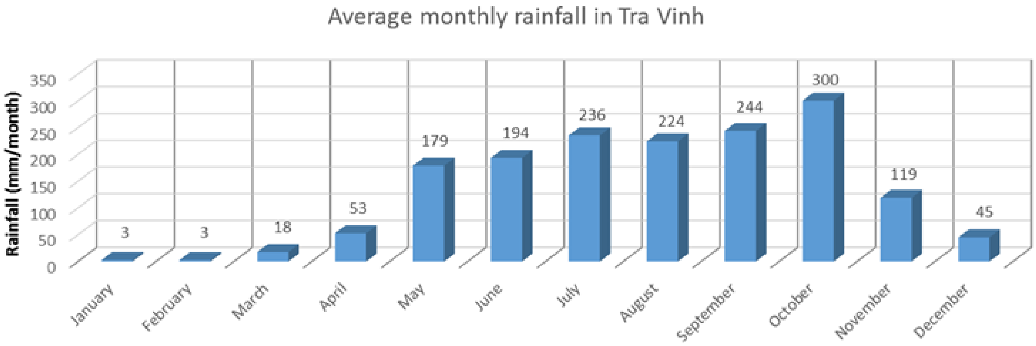


Figure 3.2 - Average monthly rainfall in Cang Long station from 1987 to 2016 (Silva 2018)

The Mekong Delta has the total evapotranspiration 809 mm to 841 mm per month (Bui et al. 2017), Tra Vinh province alone has the rate of evapotranspiration up to 130-150mm per month. In a spatial scale, high evaporation rates occur in the sand ridges in the south and the region near the coastline. When evapotranspiration is higher than rainfall, salt tends to rise as a result of the capillary actions and concentrated in the surface layer (Mai et al. 2014).

3.3 Hydrology

In Vietnam, the Mekong Delta river system consists of two major distributaries - the Tien and Hau rivers - and the man-made canal network (IUCN 2010). At Tan Chau station, the discharge occupies 84% of total VMD freshwater flows through the Tien River, and another 16% is observed at Chau Doc station on Hau River (Eslami et al. 2019). The maximum wet season discharge and minimum dry season discharge at Tan Chau station are 60,000 m^3/and 2,000 m^3/s, respectively (Anh et al. 2018). The fundamental characteristic of the hydrologic regime in VMD is very complex and involves the tropical monsoon climate.

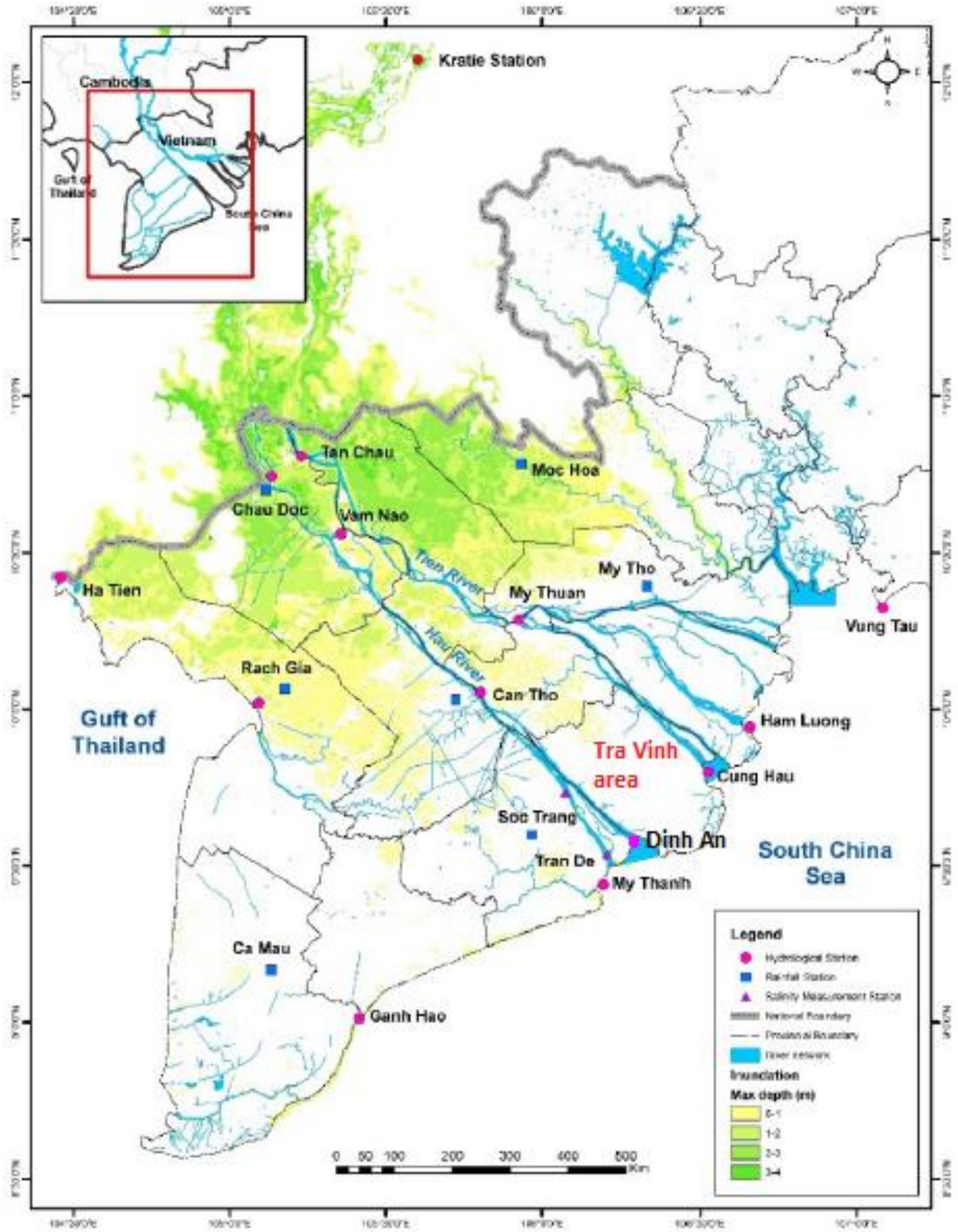


Figure 3.3 - River/canal distribution and observed stations in the VMD (Anh et al. 2018)

Tra Vinh Province locates at the river mouths of the VMD between two large rivers, Tien and Hau Rivers, is influenced by the hydrographic processes of the East Sea and flow from up-stream of VMD (Ta 2018, Dang et al. 2019). In Tra Vinh Province, boundaries of fresh/saline water fluctuate by seasonal and strongly depend on interaction mechanism of upstream flow and saltwater intrusion from the sea. (Nguyen et al. 2008, Dang et al. 2019, Eslami et al. 2019). At Tra Vinh station (Figure 3.4), freshwater is available during the wet season and begins to disappear from late January or February to early wet season (late May to early June). In the period from 1993 to 2017, the longest durations with saline water at Tra Vinh station were in 2005 and 2016, accounting for 100 days and 94 days, respectively (Dang et al. 2019). Depended on upstream flows, the freshwater boundary in the estuaries changed by each month and year (Dang et al. 2019). In February of 2005, the fresh/saline water boundary moved into inland over 25 km from the coastal line (Figure 3.4). In Tra Vinh Province, understanding of changing in fresh/saline water boundaries and duration without freshwater is very important to identify alternative sources for freshwater supply in dry season (Dang et al. 2019).

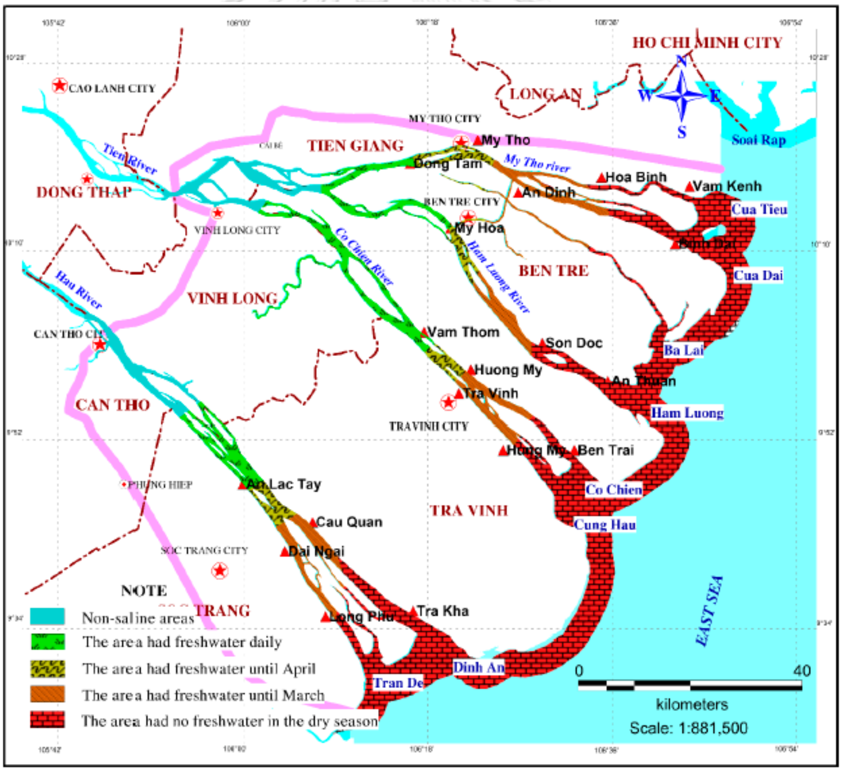


Figure 3.4 - Freshwater zones in the dry season (January to May), 2005 (Dang et al. 2019)

3.4 Groundwater development and management

3.4.1 Geology and hydrogeology

Stratigraphy of VMD ranges in different tectonic phases from Precambrian to Holocene age, corresponding to formations of intrusive, extrusive rocks and sedimentary (Anderson 1976). These rocks consist of granite, gneiss, quartzite, and crystalline types of rocks. The basement of stratigraphy is defined by intrusive and extrusive rock, while cover layers consist of eight sedimentary formations and are distributed by time from middle-upper Miocene (N12-3) to Holocene (Q23) formations (Vuong 2013, Silva 2018). Each formation is divided by two parts: composition of low permeability silt, clay, or silty clay in the upper part (aquitard); and higher permeable and includes of fine to coarse sand in the underlying part (aquifer) (Vuong 2013, Van Pham et al. 2019). Two hydrogeological cross-sections (Figure 3.5, Figure 3.6 and Figure 3.7) provide a whole view about spatial distribution and connections of eight sedimentary formations in the VMD (Vuong 2013).

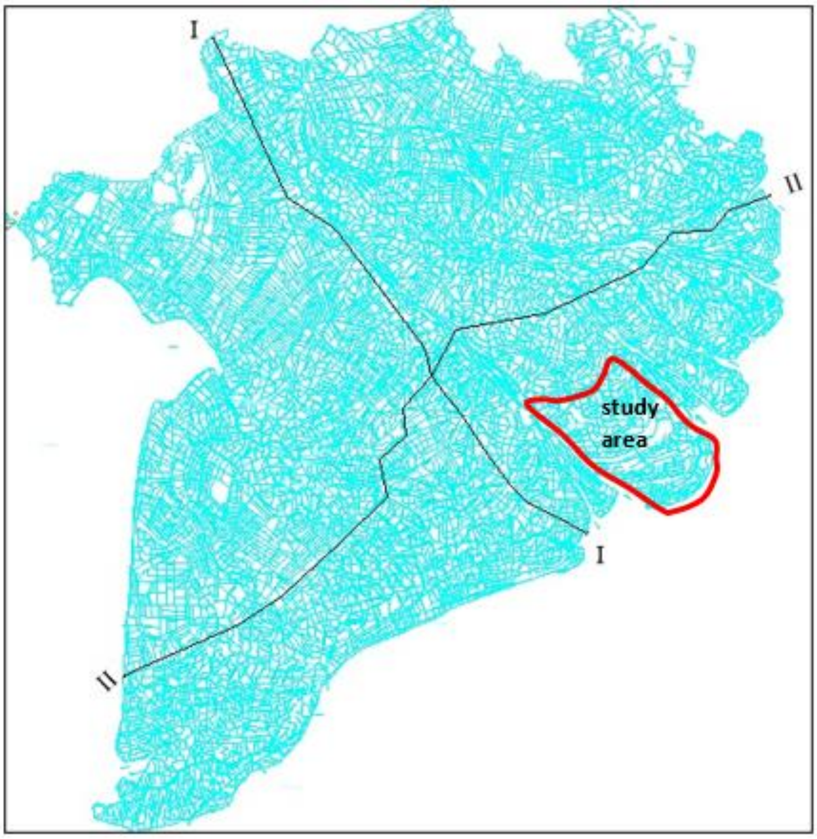


Figure 3.5 - Layout of cross-sections (Vuong 2013)

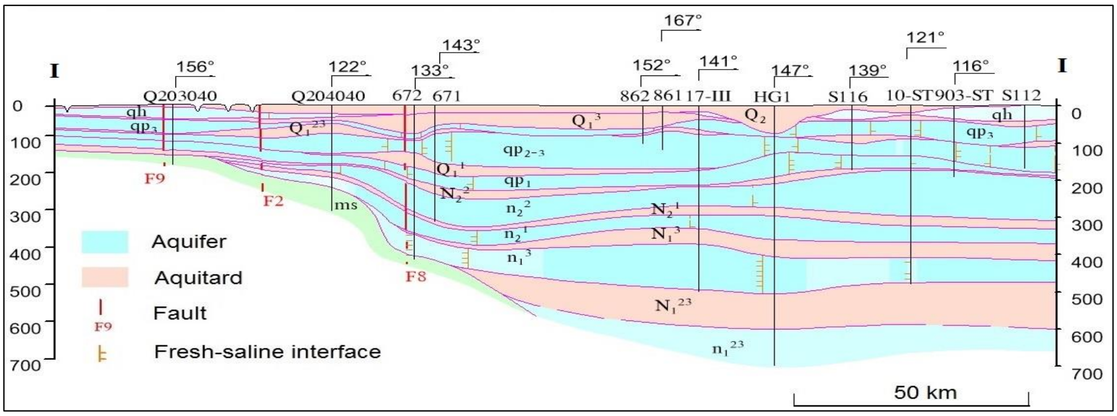


Figure 3.6 - Hydrogeological cross-section (I-I) (Vuong 2013)

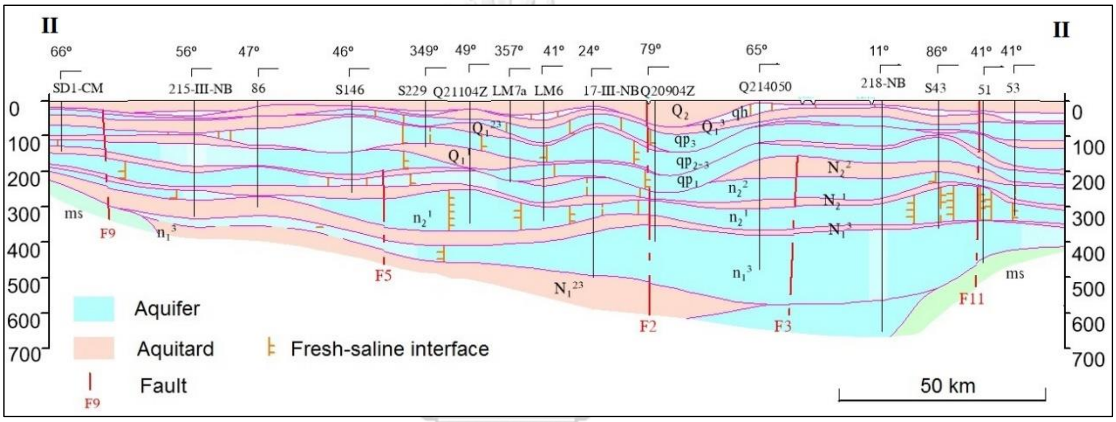


Figure 3.7 - Hydrogeological cross-section (II-II) (Vuong 2013)

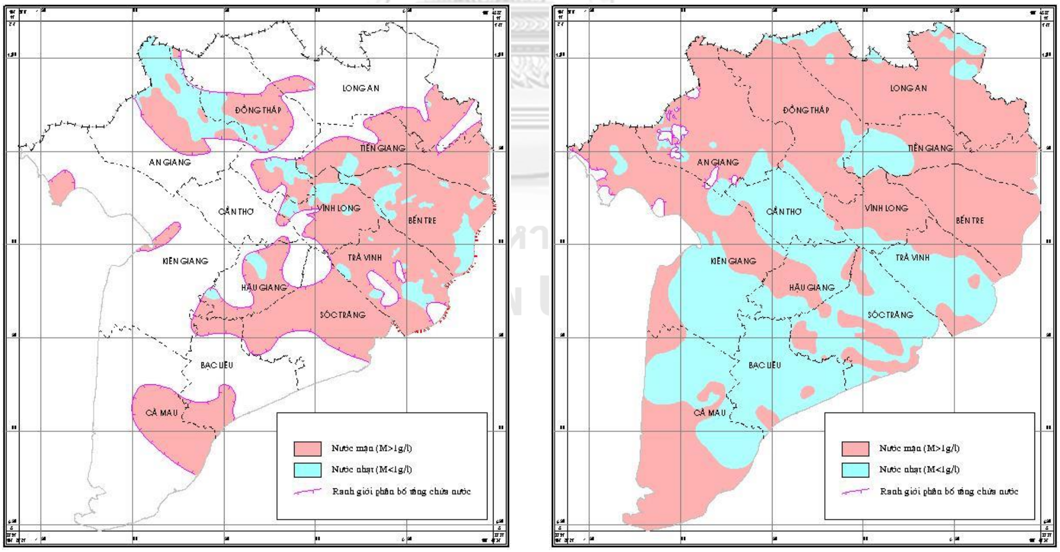
Eight hydrogeological aquifers broadly distributed in Tra Vinh Province include three types of confined, unconfined, and semi-confined aquifers (Deltares 2011). The eight aquifers, from ground surface to deeper, are Holocene, Upper Pleistocene, Upper-middle Pleistocene, Lower Pleistocene, Middle Pliocene, Lower Pliocene, Upper Miocene and Upper-Middle Miocene. Only one shallowest aquifer is defined as an unconfined aquifer, consists mainly of clay silt and sand with high organic matter due to interaction with surface water (Bui et al. 2017). Characteristic of lithology and aquifer/aquitard properties are presented in detail in Table 3.1.

Table 3.1 - Characteristic of lithology and aquifer/aquitard properties

Formation	Average thickness (m)	Average depth (m)	Lithology		Horizontal HC (m^3/s)	
			Upper part	Lower part	Upper part	Lower part
Holocene (qh)	15.5	16.9	peat or sandy clay with high organic matter.	consists of fine sand	4×10^{-7}	8×10^{-5}
Upper Pleistocene (qp_3)	29.1	47.9	low permeability, consist of silt to sandy clay.	high permeability, composition of fine to coarse sand	4×10^{-7}	6×10^{-3}
Upper-Middle Pleistocene (qp_{2-3})	41.5	86.8	low permeability, consist of silt to sandy clay.	high permeability, composition of fine to coarse sand	4×10^{-7}	2×10^{-3}
Lower Pleistocene (qp_1)	38.1	146.5	low permeability, consist of silt to sandy clay.	high permeability, composition of fine to coarse sand	8×10^{-8}	1×10^{-4}
Middle Pliocene	51.3	206.5	low permeability, consist of silt to sandy clay.	high permeability, composition of fine to coarse sand	9×10^{-8}	2×10^{-3}
(n_{2-2})	53.8	274.8	low permeability, consist of silt to sandy clay.	high permeability, composition of fine to coarse sand	3×10^{-8}	5×10^{-4}
Lower Pliocene	37	358	low permeability, consist of silt and weathered silty clay	high permeability, composition of fine to coarse sand	1×10^{-8}	8×10^{-5}
Miocene	<400	-	limited information			

3.4.2 Distribution of fresh/saline groundwater

The VMD aquifers present a very heterogeneous distribution of fresh/saline groundwater and not clear following in-depth (Vuong 2013). The main reason is explained by regressive and transgressive sea-level ver the past few millennia (Van Pham et al. 2019). Neogene-Q formations were found offshore stratigraphy with thickness from 550 m to 650 m and mainly consist of sand, clay and interpose siltstone (Anderson 1976). The Upper Miocene level from 450 m to 820 m thick is composed of sand and clay interleaved. Closed to the present coastline, fresh GW was found at more than 150 to 450 m below ground surface level (Van Pham et al. 2019). However, the area with fresh groundwater occupies about 20 % to 30 % area of VMD, except only the shallowest aquifer with small distribution of freshwater around 2 % of the VMD area (Figure 3.8) (Vuong 2013). Good quality groundwater, with TDS in range of 200 to 1,000 mg/l, generally is found in the east and southeast portions of the study area. Most fresh groundwater infiltrated the subsurface during a period of low sea-level, at least more than 20 ka ago (Van Pham et al. 2019).



a) Shallowest aquifer (Holocene - qh)

b) Main exploited aquifer (Upper-Middle Pleistocene - qp_{2-3})

Figure 3.8 - Distribution area of saline and fresh groundwater in aquifers (Vuong 2013)

3.4.3 Current situation of groundwater supply

In Tra Vinh Province, GW is mainly abstracted for domestic activities including drinking, cooking, bathing, washing and gardening. Besides, some crops or farming ponds also use GW to ensure enough irrigation demand. Total GWU was estimated to be about 187,685 m^3/d in 2007 (Sanh 2010), accounting about 40% for domestic use. In the period of 2004 and 2008, GW abstraction increased almost two times due to a rapid growth in number of households using GW for domestic activities (Sanh 2010). The most recent report showed that 224,773 m^3/day was abstracted in whole province of which mainly was abstracted in qp_3 (20%) and qp_{2-3} aquifers (70%), a small amount was exploited in qh aquifer, qp_1 aquifer, and other aquifers (n_{2-2}, n_{2-1} and n_{1-3}) have not been yet exploited. Total number of abstraction wells is 88,927 wells, of which number of well with capacity ≥200 m^3/day is 114 wells (official wells*) and that of well with capacity <200m^3/day is 88,813 wells (non-official well**) (Vuong 2013) (Table 3.2). The Decree No.27/2014/TT-BTNMT dated 30/05/2014 of the Ministry of Natural Resources and Environment formed the basis for groundwater resources licensing within Vietnam territory. Besides, each province or region has proposed their own planning for GW exploitation, utilization and protection. However, Tra Vinh Province is one of locality that has not fully implemented the GW exploitation plan yet. Up to now, licensing of GW exploitation mainly depends on the decree or circular of Government and MONRE.

Table 3.2 - Statistics of abstracted wells in Tra Vinh Province in 2010

No.	Aquifer	Groundwater abstraction (m^3/day)		
		Official well	Non-official well	Total
1	Holocene (qh)	0	7,800	7,800
2	Upper Pleistocene (qp_3)	0	73,920	73,920
3	Middle Pleistocene (qp_{2-3})	42,000	119,000	161,000
4	Lower Pleistocene (qp_1)	3,200	0	3,200
Whole province		53,200	200,720	245,920

official well: big wells (>200 m^3/d) were licensed to exploit groundwater by DONRE

***non-official well: household wells (<200m^3/d) were not licensed to exploit groundwater (mainly made by local households)*

Because of the rapidly increasing population and very fast economic development in the VMD, the surface water resources are unable to meet these demands, groundwater was over-abstracted (Ha et al. 2015) in many areas of VMD including Tra Vinh Province. Resulting groundwater depletion and saline water intrusion are the main problems that threaten drinking water supplies, farming systems, and livelihoods in the delta especially in the coastal province as Tra Vinh (Vuong 2013). In the coastal zone (see location of Q217-station in Figure 3.1), observed groundwater levels show a significant declination by 40 cm/year and 60 cm/year from 2000 to 2018 in qp_{2-3} and n_{2-2} aquifer, respectively. Only the shallowest aquifer (qh) presents a stable fluctuation of GWLs in the period of 2000 and 2018 (Figure 3.9). Besides, the rapid decrease of GWLs also caused the land subsidence in some locations of Tra Vinh Province, with mean subsidence rate about 20 cm due to the impact of 25 years of GW abstraction (Minderhoud et al. 2017).

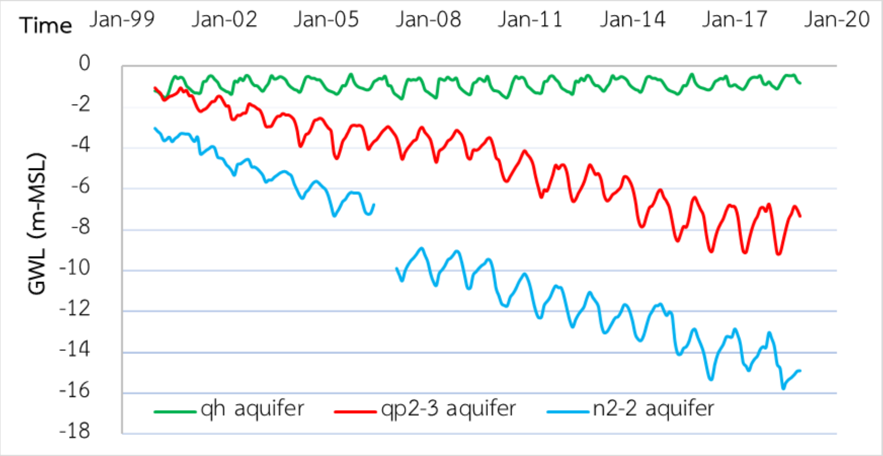


Figure 3.9 - Time series of GWLs at Q217 station

3.5 General socio-economic information

According to statistics in 2018 of Tra Vinh Province Statistical Office (TVSO 2018), population of the province is more than 1 million (8% of the VMD population) which distributes by 288,666 households, in which number of poor households account for 13.23% (Nguyen 2018). The population growth rate of the province was 0.18 %/year in the period of 2007 and 2018. Among provinces of VMD, Tra Vinh has the largest number of Khmer people, occupying for more than 31% of the total province population. The province economy is 39% agriculture, 20% industry and 35% services. In 2018, the gross regional domestic product (GRDP) growth was estimated at 11.05%. The total social development investment capital reached over 22.8 trillion VND (981.5 million USD) and domestic revenue, 3.7 trillion VND (159.2 million USD). The ratio of poor households was reduced by 2.44%. Province's latest five-year development plan concentrates in strengthening maritime economics including high-tech aquaculture, forest-aquaculture, tourist and energy industries (PPC-TV 2015).

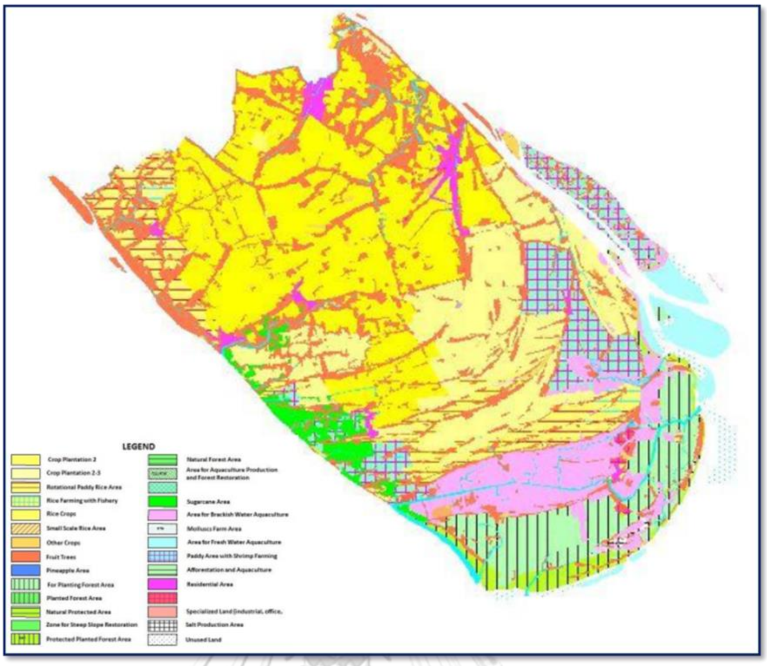


Figure 3.10 - The land use map of Tra Vinh Province (Silva 2018)

About 89% of Tra Vinh’s land, corresponding to around 184,024 ha, is mainly used for agriculture activities including paddy, annual crops, perennial crops, orchards, aquaculture, forest and salt cultivation. With conditions of soil and potential of water resources, a large part of the land has been used for growing food including paddy (33% of total land), aquaculture (33% of total land), annual and perennial crops (5% of total land) (Nguyen et al. 2020). Since the early 2000s, agricultural production land has decreased dramatically due to change paddy fields into shrimp farming and perennial crops in the middle and northern part of the study area. In the coastal part, aquaculture is the main economic activity due to the availability of saline water all year round. In Tra Vinh Province, the production forest area is about 4,300 ha, accounting for 65% of the total area of forest. See more detail of land use distribution in Figure 3.10.

Chapter 4 - RESEARCH METHODOLOGIES

This chapter shows methodologies to operationalize the conceptual theories, in order to fulfil the objectives of the study. It explains specific methods/theories and the application of these methods/theories to carry out the expected results. The study investigated GWU issues and propose adaptive measures to meet sustainable yield of the coastal aquifer system of VMD as in the flowchart of research methodologies shown in Figure 4.1. This research can be divided into the 3 main parts, i.e., (i) to estimate groundwater use distribution/pattern including assessment of the current impact of GWU, (ii) estimations of sustainable yields of the aquifer system and groundwater demand under various scenarios of climate change and socio-economic development, and (iii) to recommend additional guidelines via behavior analysis and estimation of reduced gaps in GW supply to cope with sustainable yields of the aquifer system.

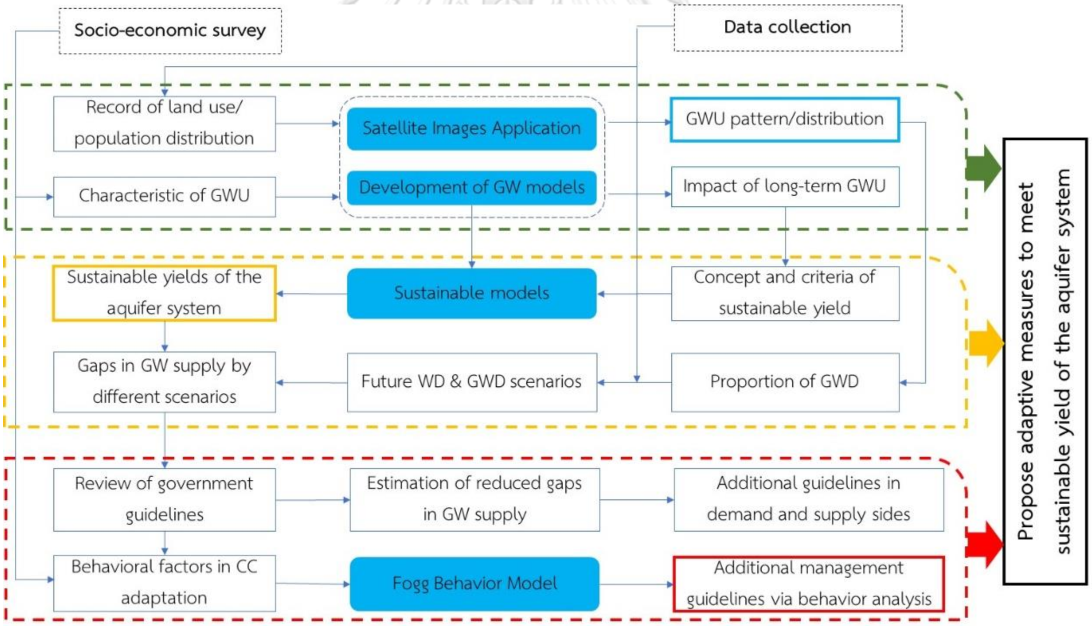


Figure 4.1 - Flow chart of research methodology

4.1 Socioeconomic survey

Survey methods are applied to provide a more detailed picture of groundwater use and its issues. Based on different fresh/saline distribution of both groundwater and surface water, consumption and issues of groundwater show distinguishing features. For surface water in the study area, characteristic of saline intrusion present in three difference zone including zone which freshwater is at all seasons, freshwater depends on seasons (it can be moderate or hard to improve) and saline water is at all seasons. (Scarrott 2009) (see more detailed in APPENDIX 2). Besides, Kriging Interpolation (Surfer 11) is applied to simulate distribution of salinity groundwater based on total dissolved solids (TDS) levels by using an electrical conductivity (EC) dataset with 746 measurement points of three shallowest aquifers in Tra Vinh area from the EC campaign of SALINFROVE project (APPENDIX 1). The salinity map presents the North-South gradient of salinity concentration for the three aquifers. By combining the characteristic of saline intrusion in surface water and distribution of saline groundwater, three-zone of the study area are identified including coastal zone (Duyen Hai district), northern zone (Cang Long district and Tra Vinh town), middle zone (Tra Cu, Cau Ke, Chau Thanh, Tieu Can and Cau Ngang).

In each zone, 140-150 questionnaires are prepared with the distribution of questionnaires based on the guideline of sample size calculation (Israel 1992). A high-income commune, a moderate-income commune and a low-income commune in each zone are selected to conduct the survey by a classification of GDP per capita of communes. Random sampling is used to pick up the respondent of every village at selected communes. With high homogeneous in saline/fresh distribution of water resources, and consideration of different levels of respondent poverty, analysis of surveyed data of three communes can ensure sufficient coverage of local communities in behavior of groundwater use and be used for represent the whole corresponding zone.

The other objective of the survey is to collect information about behavioral factors in term of implementing various adaptive measures of individual households to cope with effect of climate change. The other objective of the survey is to collect information about behavioral factors in term of implementing various adaptive measures to cope with climate change impact. The sample size with 150 questionnaires per zone, occupies less than 1% of total household in each zone. According to number of household in the study area (over 250,000 households), the sample size is considered to be good enough for drawing conclusions about all of households in each zone in regional scale due to high variety in behavioral factors of each adaptive measures as well as impact of external factors on the human psyche. However, with a zonal classification based on the potential of water resources and income level, the representative samples can present differences in behavioral factors among three proposed zones.

A drafted questionnaire of the socio-economic survey was pretested with the participation of local residences, local officers and stakeholders at three zones to check and add information relevant to behavior of groundwater use at three different zones. Based on the feedbacks of the test-run, the survey questionnaire was modified and improved to plan for carrying out the socio-economic survey and data processing. Then, the socio-economic survey was conducted by the survey team of SALINPROVE project from 19 March 2018 to 29 March 2020 with a collection of 419 survey questionnaires for all three zones (Figure 4.2).

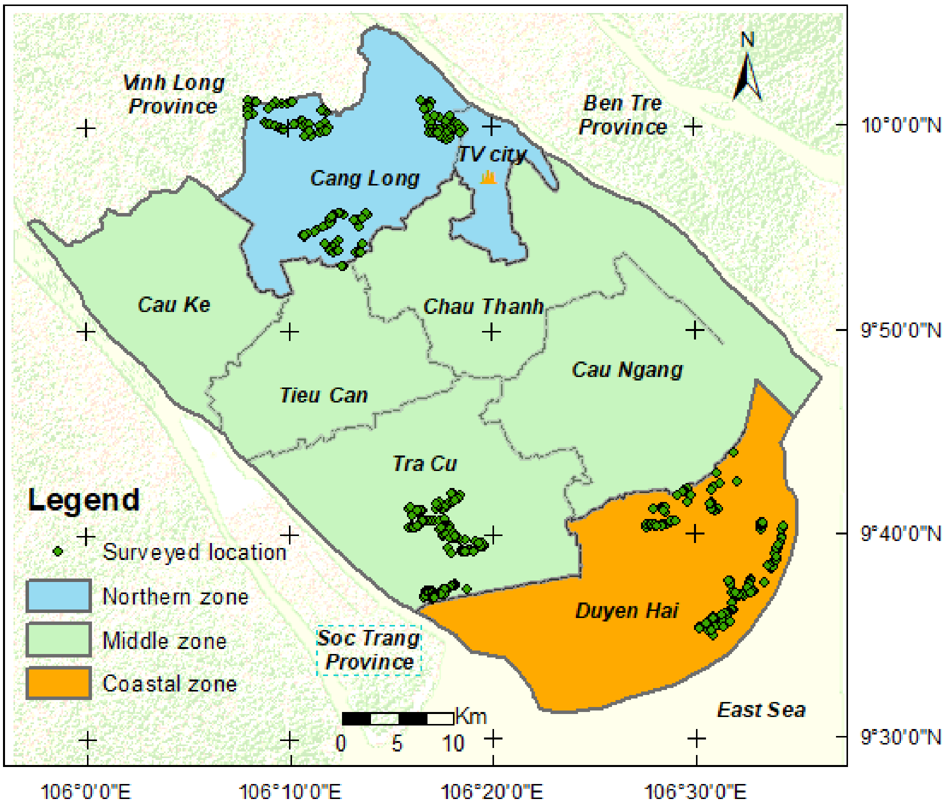


Figure 4.2 - Distribution of survey questionnaires in three zones

4.2 Estimation of GWU distribution/pattern and assessment of GWU impact

4.2.1 Estimation of GWU distribution/pattern

a) GWU distribution estimation

SPSS tool and Excel are applied to analyze statistics of the survey data by zonal classification. Water supply for domestic use is separated by five methods including bottle, tap water, tube-wells, rain-harvesting, and pond/canal storage. Besides, GWU for agricultural use focuses on for irrigation and aquaculture. By assessing the dependence on GW in domestic and agricultural use, role of GW in three different zone is carried out to understand the importance of GW supply through three zones. Average GWU per household and percentage of HH using GW for domestic use of each zone are identified as the baseline based on the survey data to extrapolate total GWU for domestic use in corresponding zone. In addition, average GWU for 1 ha irrigation and aquaculture area of each zone are used to estimate total GWU for agricultural use of corresponding zone.

Percentage of the total surveyed household and mean of groundwater use (GWU) by each supply method is used as a baseline to calculate GWU of each district by using population and land use data in Tra Vinh Province.

Table 4.1 - Functions of GWU pattern estimation

GWU pattern	Descriptions	Function
Domestic use	Mean GWU by bottle	DB_j
	Mean GWU by tap water	DT_j
	Mean GWU by tube-wells	DW_j
	Average GWU per HH	$GWU_{Dj} = DM_j + DT_j + DW_j$
	Total GWU for domestic	$\Sigma GWU_{dj} = GWU_{dj} * PD_j$
Agricultural use	Mean GWU for aquaculture	GWU_{aj}
	Total GWU for aquaculture	$\Sigma GWU_{aj} = GWU_{aj} * A_{aj}$
	Mean GWU for irrigation	$GWU_{ij} = MA_i \times A_{aj}$
	Total GWU for aquaculture	$\Sigma GWU_{ij} = GWU_{ij} * A_{ij}$
	Total GWU for agriculture	$\Sigma GWU_{agj} = \Sigma GWU_{aj} + \Sigma GWU_{ij}$
GWU in dry season		$GWU_{dryj} = \Sigma GWU_{dj} + \Sigma GWU_{aj}$

Where: PD is percentage of household using GW for domestic use (%)

A_a is area of fresh-brackish aquaculture (ha), A_i is area of irrigated area (ha)

j varies three zones (northern, middle and coastal zone)

b) Modification of GWU distribution by using distribution of land surface temperature (LST)

Based on literature reviews and survey, GW was mainly exploited via tubed wells which mainly distributed at in household land to supply water for domestic demand including gardening. Besides, a number of tube-wells are located at planting areas (annual crops, aquaculture) for more convenient in irrigation, especially in sand dunes which are suitable for annual crops as watermelon, onion, pepper during the dry season. In other words, GWU was distributed more in household land or sand dune area and less in the paddy field or other irrigation areas with high soil moisture. Therefore, the distribution of tube-wells or GWU cannot be on average by any zone. In order to modify the distribution of GWU in each zone, land surface temperature (LST) distribution from Satellite Images is applied to represent the distribution of GWU due to separated distribution of household lands and sand dunes of LST values (Fisseha et al. 2011).

Landsat 8 OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) images are opened and provided Thermal Infrared (TIRS) bands (Band 10 and 11, 100 m spatial resolution resampled to 30 meters) that can be used for Land Surface Temperature (LST) estimation with good spatial resolution. The Landsat 8 LST is computed by fusing images of MODIS LST and Landsat 8 brightness temperature (Tb), provided by Hazaymeh et al. (2015). The information acquired from Landsat 8 Images is processed in Raster Calculator Tool of ARC-GIS software in order to calculate the LST. To achieve the LST distribution from Landsat 8 images, the process includes the major following steps as Figure 4.3.

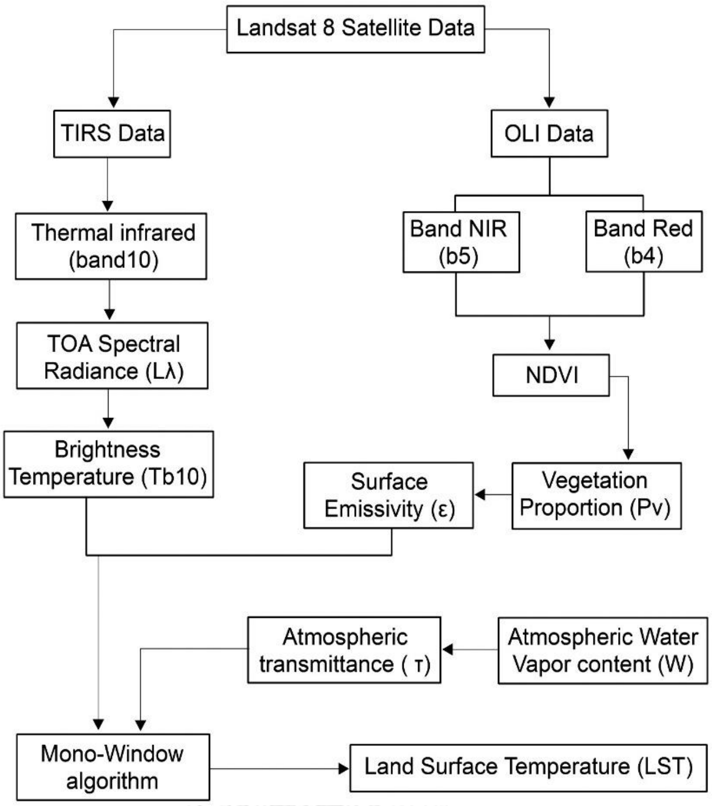


Figure 4.3 - The process of LST estimation from Landsat 8 image (Bendib et al. 2017)

Step 1: Top of Atmosphere (TOA) Radiance:

Using the radiance rescaling factor, Thermal Infra-Red Digital Numbers can be converted to TOA spectral radiance.

$$L\lambda = ML * Q_{cal} + AL$$

where:

$L\lambda$ is TOA spectral radiance (Watts/ (m^2 * sr * μm)

ML is radiance multiplicative Band (No.)

AL is radiance Add Band (No.)

Q_{cal} are Quantized and calibrated standard product pixel values (DN)

Step 2: Top of Atmosphere (TOA) Brightness Temperature:

Spectral radiance data are converted to top of atmosphere brightness temperature using the thermal constant values in Meta data file.

$BT = K_2 / \ln (K_1 / L\lambda + 1) - 272.15$

where:

BT = Top of atmosphere brightness temperature (°C)

$L\lambda$ = TOA spectral radiance (Watts/(m^2 * sr * μm))

K1 = K1 Constant Band (No.)

K2 = K2 Constant Band (No.)

Step 3: Normalized Differential Vegetation Index (NDVI):

The Normalized Differential Vegetation Index (NDVI) is a standardized vegetation index which is calculated using Near Infra-red (Band 5) and Red (Band 4) bands.

$$NDVI = (NIR - RED) / (NIR + RED)$$

where:

RED is DN values from the RED band

NIR is DN values from Near-Infrared band

Step 4: Land Surface Emissivity (LSE):

Land surface emissivity (LSE) is the average emissivity of an element of the surface of the Earth calculated from NDVI values.

$$PV = [(NDVI - NDVI_{min}) / (NDVI_{max} + NDVI_{min})]^2$$

where:

PV is proportion of vegetation

NDVI are DN values from NDVI Image

$NDVI_{min}$ is minimum DN values from NDVI Image

$NDVI_{max}$ is maximum DN values from NDVI Image

$E = 0.004 * PV + 0.986$

where:

E = Land Surface Emissivity

PV = Proportion of Vegetation

Step 5: Land Surface Temperature (LST):

The Land Surface Temperature (LST) is the radiative temperature which calculated using Top of atmosphere brightness temperature, wavelength of emitted radiance, Land Surface Emissivity.

$$LST = BT/(1 + W * (BT / 14380) * \ln(E)$$

where:

BT = Top of atmosphere brightness temperature (°C)

W = Wavelength of emitted radiance

E = Land Surface Emissivity

Estimation of GWU distribution

The total GWU in each zone (GWU_{dryj}) is estimated by the statistical data and baseline of GWU via the field survey mentioned in the previous section. The ratio between LST cell value and sum of all LST cell in each zone are applied to estimate GWU value by cell (GWU_S) from the total GWU (GWU_{dryj}) in corresponding zone.

$$GWU_s = GWU_{dryj} \times LST_c/Sum\ (LST_c)$$

where:

LST_c is temperature value of cell.

GWU_c is GWU value of each cell

j are zones (northern, middle and coastal zone)

On the other hand, the population and land use data at the commune level are used to estimate total GWU of 17 communes in Tra Cu District. This estimation is compared with the sum of GWU_s by distributed area of 17 corresponding communes to verify the application of LST Satellite images in this study.

c) Estimate average dry season GWU pattern by years

In order to estimate GWU pattern from 2007 to 2018, the linear correlation of the referred estimation of GWU for domestic in 2007 and that in 2018 are used to interpolate average dry season GWU for domestic of remaining years. In addition, GWU for agriculture is estimated based on availability of freshwater during dry season. For the remaining period from 1995 to 2007, a referred estimation of GWU in 1995, 2000 and 2007 are applied to estimate average dry season GWU for remaining years by using the linear interpolation.

d) Correction and verification of GWU pattern

A groundwater flow model (MODFLOW) is developed to verify the spatial distribution of GWU in March 2018 by steady calibration. On the other hand, the transient model is used to verify time series of average dry season GWU from 1995 to 2018 via calibration of groundwater levels (GWLs). The ratio of GWU between wet and dry seasons is also corrected in calibration process. The process of GW model development is presented in more details in the next section

4.2.2 Assessment of GWU impact

a) Development of GW models

In order to study the impact of long-term groundwater use on aquifers, the Groundwater Modeling System (GMS) is applied to simulate the three-dimensional GW flow by MODFLOW module and three-dimensional salinity GW transportation by MT3DMS module (Mass Transport Three-dimensional for Multi-Species). Simulated duration is from January 1994 to December 2018 and is divided by 300 time-steps (monthly). MODFLOW simulates the piezometric heads via fluxes from cell to cell flux during the flow computation, then it is subsequently used to be the flow field for simulating transport simulation in MT3DMS module.

In term of simulating GW flow and salinity transportation, two equations described advection, dispersion, source of fluid, sorption (Zheng et al. 2002, Zheng et al. 2012) as below:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+q_s=S_s\frac{\partial h}{\partial t}$$

$$\frac{\partial}{\partial xi}\left(D_{ij}\frac{\partial C}{\partial xj}\right)-\frac{\partial}{\partial xi}(v_iC)+\frac{q_s}{\theta}Cs-\lambda\left(C+\rho_b\theta\right)C=R\frac{\partial C}{\partial t}$$

where:

K_{xx}, K_{yy} and K_{zz} are the HC values along the x, y, and zcoordinate axes and may be function of space [L/T];

h is the piezometric head [L]; **t** is time [T]

q_s is the volumetric flux of GW sources/sinks per unit volume [1/T] with positive values indicating flow into the GW system

S_s is the specific storage of the porous material and may be function of space [1/L]

C is the dissolved concentration of species k, ML^{-3};

θ is the porosity of the aquifers, dimensionless;

T; i x is the distance along the respective Cartesian coordinate axis, L;

D_{ij} is the hydrodynamic dispersion coefficient tensor, L^2 T^{-1}; i v is the seepage or linear pore water velocity; LT^{-1};

q_s is the volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative), T^{-1};

C^k_s is the concentration of the source or sink flux for species k, ML^{-3};

$\sum R_n$ is the chemical reaction term, $ML^{-3}T^{-1}$.

For groundwater flow model

In order to simulate GW flow, to begin with, a conceptual model is defined to represent the modelled area including the model domain, boundary conditions and layer properties. The conceptual model for aquifers in the study area is developed base on available hydrogeological data. In the conceptual model, the data are assigned to the grid via a GIS tool. The first step of simulation is to create a suitable grid pattern based on the MODFLOW domain. Boundary conditions are identified by specified and general head boundary that represents the coastal line and the boundary on north, west and east of the model domain, respectively. The input parameters are initial GWLs, hydraulic conductivity, GW recharge, river water levels and conductance and GW pumping. The groundwater flow model is calibrated by hydraulic heads of 17 observation wells by considering the variations during the period of 1/1994 to 12/2008 and the period of 1/2009 and 12/2018 of observed GWLs data is used for the verification process.

For salinity transportation model

For stimulation of GW salinity transportation, total dissolved solids (TDS) is used as the simulated parameter. Three packages in MT3D module (advective package and dispersivity package and source/sink mixing package) and a variable-density flow package in SEWAT module were used with same time scale of the calibrated groundwater flow model. ICBUND value of the distribution area of the aquifers in the modeling area is assigned a value of 1 (the area with TDS content changes over time). Typically, calibrated parameters are used to define the longitudal dispersivity, and porosity in this study based on observation data of 5 monitoring wells along saline interface from July 2017 to December 2018.

b) Exploration of GWU impact on aquifers

Based on GWLs distribution, drawdown of GWLs can be carried out to understand impact of GWU in different areas. Distribution of depleted cones based on GWLs map also identifies the area which is prone areas of saline intrusion as well as land subsidence. Besides, an analysis of GW balance consist of GW budget, estimates the inflow components, outflow components and changes in storage of the aquifer system. A GW balance can be analyzed by spatial and temporal distribution or aggregation of parameters (Nam 2017). The impact on aquifers is assessed by comparing inflow and outflow rates. Outflow exceeding inflow can forewarn of falling GW levels, reduced rainfall recharge, or salinity movement as previously significant declination of GWLs. According the defination of conceptual mode, Based on the conceptual GW balance in the study, the equation of GW balance in this study is described as below:

$$(GWI + P + RR_i + DP) - (GWO + RR_o + Q) = \Delta GWS$$

where: GWI is the inflow of aquifers (lateral flow); LR is the recharge from precipitation; RR is the recharge from the rivers (river leakage); DP is the deep percolation from the upper layer; GWO is the outflow of aquifers (lateral flow); Q is the certain GW pumping (GW abstraction); ΔGWS is the change in groundwater storage.

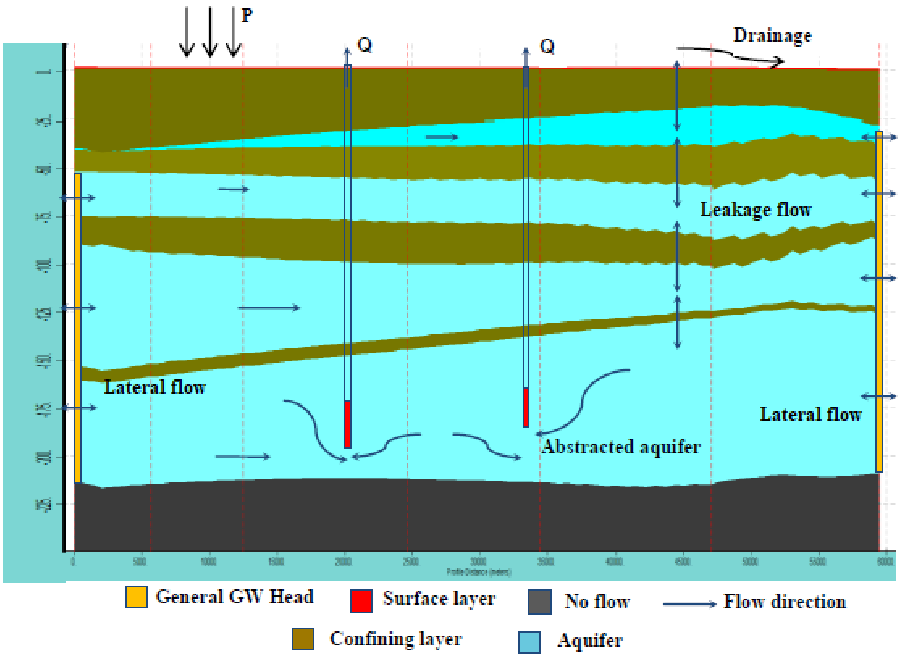


Figure 4.4 - Conceptual GW balance (Nam 2017)

By simulation of TDS transportation using MT3DMS, movement of fresh/saline interface (identified TDS contour) is identified in response to the salinity source. The areas having total dissolved solids (TDS) in GW greater than 1,000mg/l is considered to be the area having saline GW. Comparison of TDS contours at different time-steps can estimate the increasing area of saline GW and the average rate of increase. Furthermore, based on the survey data, distribution of GWU issues is used to verify impacts of long-term GWU and assessed by developed GW models.

4.3 Estimation of sustainable yields and GW demand

4.3.1 Estimation sustainable yields of the aquifer system.

Identification of sustainable concept and criteria

In order to consider the gaps of traditional safe yield concept in term of GW management, the sustainable yield is introduced as a newer and comprehensive concept. The sustainable yield concept can be dived three categories of constraint including environmental, economic and political constraint for a certain region. (Koch et al. 2012). On the other hand, the sustainable yield concept focuses more on GW pumping impacts on a GW system with the broader definition as “The amount of ground water that can be safely withdrawn from a groundwater basin annually, without producing an undesirable result” (Meyland 2011). Undesirable results are the consequence of GW pumping that consist of the GW storage depletion, the saline GW intrusion, the land subsidence, the exhaustion of streamflow, the contravention of current water rights and increase of pumping cost (Alley et al. 1999).

In this study, undesirable results of aquifer are identified by exploring impacts of long-term in the above section. The first sustainable criterion is proposed to enable the aquifer system to meet a new equilibrium state in time. By applying this criterion, the groundwater level will be stable and change in GW storage will reduce to approximately zero. The second sustainable criterion is proposed to control saline GW movement as present. The area of saline water is controlled to not extend more specified percentage in the near future.

Estimation of sustainable yields

Numerical models are known as a very useful tool to predict effects of GW pumping, so it is applied efficiently in sustainable yield estimation (Zhou 2009). Numerical models can carry out a certain sustainable yield based on different constraints or criteria of sustainability. (Kalf et al. 2005). Therefore, numerical models can be applied to determine response yields with various criteria of sustainable yield.

GW flow and salinity transportation in the previous section (same modules) is used to develop sustainable models. The simulation time of sustainable yield is extended more 12 years from January 2019 to December 2030 and is divided into 444 stress periods (monthly step). All parameters were kept unchanged as 2018 except only GW abstraction. In order to estimate sustainable yields by the sustainable model, GW abstraction is reduced by following steps as below:

- GW abstraction of all wells in three zones since 1/2020 from 5% to 50% (in 2018) until GWLs fluctuates stable (select points at depleted cone and center of each zones) and change in GW storage ~ 0. Total GW abstraction of the sustainable model at the new equilibrium state is considered as sustainable yield of aquifer based on the first sustainable criteria.
- After the aquifer system reach to a new equilibrium stat, GW abstraction of wells which locate in expanded areas of saline GW continue to be reduced more until area of saline GW of the main exploited aquifer ($qp_{2\text{-}3}$) in 2030 < or = 105 % of area of saline GW in the base year (2018). The existing GW abstraction in the sustainable model is consider as sustainable yield based on the second criteria.

The estimated sustainable yield is compared with the estimated GWU in 2018 to identify reduced proportion of GW abstraction in each zone to meet sustainable yield of the aquifer system by different criteria of sustainability.

4.3.2 Groundwater demand estimation

In VMD in general and Tra Vinh Province in special, as the alternative surface water supply resources are not satisfied with the water demands, the water demand mostly relies on the GW supply. The GW demand also depends on the availability of fresh surface water during dry season. In some dry years with very low rainfall, when the duration of available fresh surface water lasted less than 1 month during the dry season, farmers had to use more GW to satisfy domestic and some agricultural demands. In addition, the past water demand at Tra Vinh Province is estimated by using the data such as the records of population, water consumptions (domestic water supply, industry, agriculture, and aquaculture). The proportion of GWU per total demand is analyzed by the definition of the water year variations.

In order to understand the impact of climate change and socio-economic development on groundwater demand in this study, two scenarios of socio-economic development are selected to estimate future water demand by using data of population growth and land-use change. In addition, the proportion of GWD by total water demand in the future is estimated based on annual rainfall projection by two climate change scenarios and the estimated proportion in the past. GW demand by different scenarios is computed by the projected proportion of GW demand and total projected water demand. The difference between projected GW demand and sustainable yield of the aquifer system is considered as gaps of GW supply in future by different scenarios of climate change and socio-economic development.

4.4 Recommendations of adaptive measures for GWU

In order to propose adaptive measures to meet sustainable GW development, firstly, a review of government strategies for climate change adaptation in the Mekong Delta is conducted and classify adaptive measures in different sides including supply, demand and management side. The main task of this part is to develop behavior models for three zones of the study area by applying Fogg Behavior Model (FBM) in order to understand difference of behavior factor distribution in term of adaptive decision for climate change in the past. Lastly, additional guidelines are proposed to reduce gaps in GW supply by alternative supply plan or land use change. In addition, improvement of management side is also noted by review and suggestions of monitoring network design and focusing on incentive and additional factors to let more response from human side in term of implementing adaptive strategies.

Application of Fogg Behavior Model (FBM)

Fogg (2009a) proposed a behavior model that explains how behavior occurs and what contributes to it. In FBM, three factors are defined to understand a certain behavior can be performed or not. Three factors are presented at the same time by motivation, ability (simplicity), and triggers with subcomponents of each factor. (Figure 4.5). These elements must happen at the same time in order for behavior to result. The FBM is proved to be very useful in analysis of behavior change and design of persuasive technologies (Fogg 2009a, Fogg 2009b). The expected behavior can be defined by "motivation x ability x trigger" and if it doesn't occur, there is definitely lack at least one of those three components is missing. With a high enough motivation. When a good enough motivation can match with the ability to perform a behavior, it simply requires only a trigger to make the behavior happen. The activation threshold (Figure 4.5) separates triggers by two parts of triggers, the upper ones can lead behavior change and the lower ones show no behavior change. A trigger can be understood as a cue or call to action that makes someone done their certain behavior. For ability, it can be considered easier or simpler to cause a particular behavior. While motivation relates to attitude change to make a behavior happen.

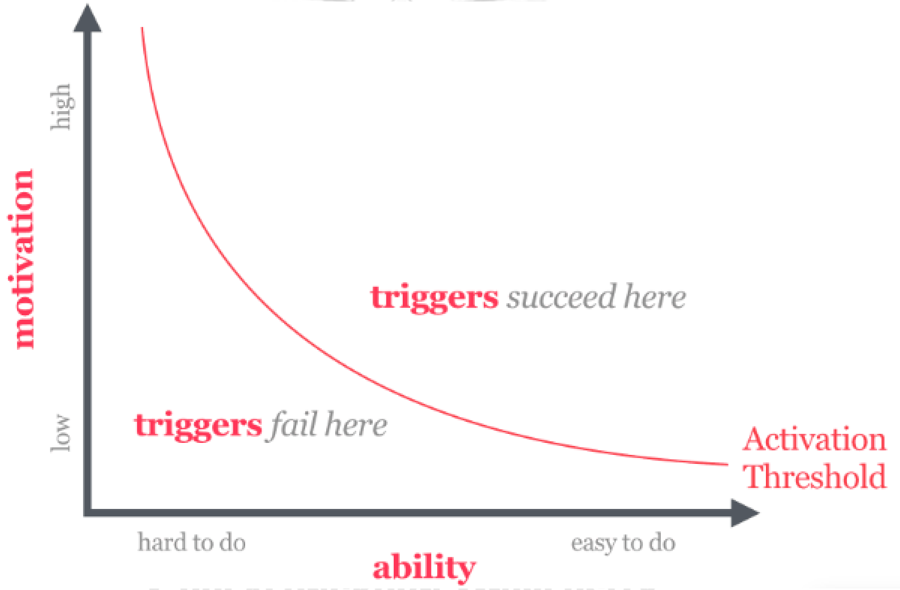


Figure 4.5 - Three factors of the Fogg Behavior Model (Fogg 2009a)

In the Vietnamese Mekong Delta, some studies have discussed cognitive and psychological factors in regard to adaptive behavior of farmers (Bosma et al. 2004, Bosma et al. 2005, Dang 2014, Le Dang et al. 2014). Farmers, who usually presented a high positive attitude in adaptive measures to cope with climate change impact, concerned about these impacts on their agricultural activities (Le Dang et al. 2014). In other words, concern about the climate change impact motivate farmer's decision in adaptive strategies. In addition, market price or demand always play a significant role in farmers' decision-making about adopting adaptive measures like expanding aquaculture and salt-tolerant crop (Bosma et al. 2004, Bosma et al. 2005, Phong et al.

2007). Farmer's assessment of market price or demand can motivate their decision to change or not change any agricultural activities in term of climate change adaptation. Access to the resources determined adaptive capacity at various scales (Wall et al. 2006). In other words, the main barrier to the adaptive decision makinng of farmers is access to resoures including extension, information, credit and water (Bryan et al. 2009). First factors which significantly affected to farmer's decision on climate change adaptation includes access to information about climate change and adaptive strategies. If farmers can easy access to this information, and they will feel more simplicity to follow the adaptive strategies. Besides, other factors are defined as access to resources including capital, irrigation, education, and health care (Dang et al. 2012, Le Dang et al. 2014). Generally, Generally, if farmers can access to more resources, they will have more simplicity or high ability to lead their decision-making in term of climate change adaptation.

In summary, factors influencing farmers’ adaptative decision can be separated by two groups following three main elements of Fogg Behavior Model (FBM), i.e., motivation, ability factors and trigger point for decision making. Motivation factors include concern about the effects of climate change (M1) and concern about market price/demand. While ability factors present various components of access to resources such as: easy access to information about climate change and adaptive measures (S1); access to technological knowledge (S2); easy access to irrigation (S3) and easy to access to capital/credit (S4). These factors were transferred to the questionnaire to interview how different among respondent lead to their own different decision in changing or non-changing agricultural activities (defined as a trigger point) to adapt to climate change impact. In term of analysis of survey data, percentages are used to estimate weight of each factor for each respondent. In order to develop adaptive behavior model (ABM), a fix weight is assigned for each answer in term of behavior factor survey. Total weight of motivation and ability factors were estimated by sum of all single factors by using coefficient represent the different percentages comparison in the same group. Two linear functions are proposed to estimate weight of motivation and ability factors as below:

Motivation weight: $\sum M = a_1M_1 + a_2M_2$

Ability weight: $\sum S = b_1S_1 + b_2S_2 + b_3S_3 + b_4S_4$

where:

M_1, M_2, S_1, S_2, S_3 & S_4 = 1 or 0 depends on answer of respondent is Yes or No, respectively for having these factors

a_1, a_2: motivation coefficient corresponding with proportion distribution of 2 motivation factors

b_1, b_2, b_3, b_4: ability coefficient corresponding with 4 ability factors

The adaptive behavior models present scattered plots of motivation and ability weight of all samples in each zone to understand different distribution of behavior factors with identified target and different stringers represented by trigger line (Figure 4.6).

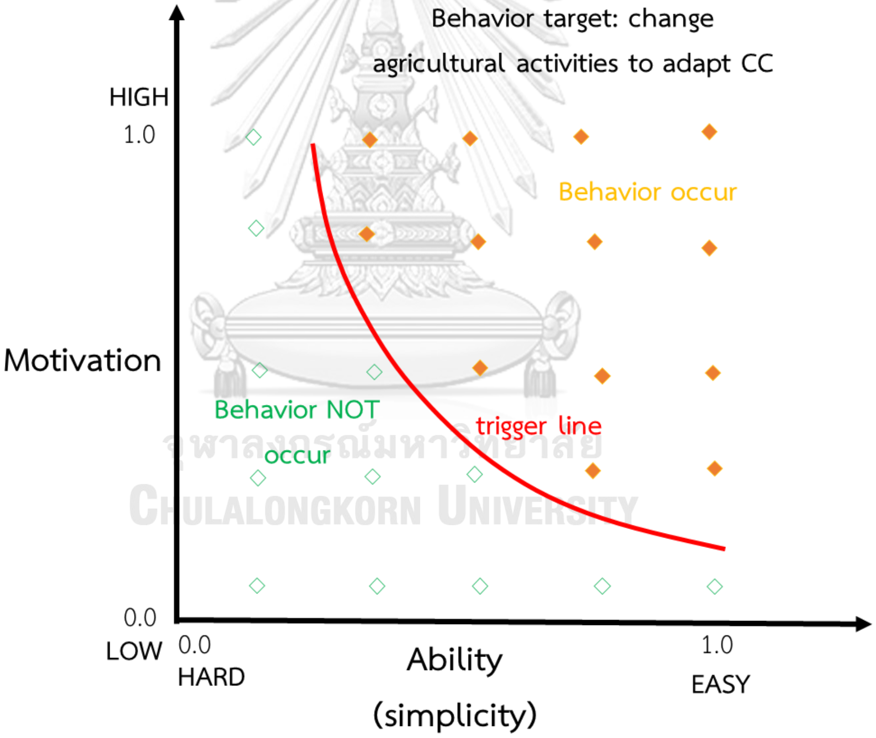


Figure 4.6 - Application of FBM in changing agriculture activities

Chapter 5 - ROLE OF GROUNDWATER USE AND ITS IMPACT

This chapter presents an estimation of spatial and temporal variability of groundwater use (GWU) data to the GW simulation and develop GW models to assess impact of GWU on the aquifer system. In section 5.1, the investigation data also analyzed to explain the role of GWU for different use purposes. Then, the GWU distribution and pattern are estimated by application of satellite image and groundwater modelling in section 5.2. Section 5.3 shows a detailed procedure of GW modelling consisting of input data, process of calibration and validation and result of errors. An assessment of the impact of GWU issues on local socioeconomic is presented in section 5.4.

5.1 Role of groundwater use

5.1.1 In domestic use

In Tra Vinh Province, water is supplied for domestic use via five supply methods including bottled water, tap water, rain harvest, tube-wells and pond water store. If bottled water, tap water and rainwater were targeted primarily for drinking, cooking and bathing, tube-wells went mainly to serve laundry and gardening demand. Generally, the preference of the households for the different water sources is ranked as follows: 61%, 58%, 53%, 45% and 2% for tube-wells, tap water, bottled water, rainwater harvesting and pond water store, respectively (Table 5.1). The results show that tube-wells is the most preferred water supply method in the middle and coastal zone due to available and low cost of groundwater pumping. the tap-water supply presents a higher quality due to standard of Vietnam QCVN 02: 2009/BYT which accounts for 56% and 45% of the total surveyed HH in the middle and coastal zone, respectively. In the northern zone, tap water is the main water supply method for household water demand which occupies 76% of the total surveyed HH in this zone and there is only 25 % of it exploited GW via tube-wells. For domestic activities, local people show a priority on groundwater instead of other sources such as surface water or rainwater. (Table 5.1). However, they still use other water sources like rainwater and river water for their daily activities although without high consumption. Rainwater harvesting is stored in the rainy season by tanks or jars and used mainly for drinking and cooking during the dry season. The rainwater harvesting shows the highest proportion in the northern zone, about 86% and the proportion decreases significantly to the south with only 16 % in the coastal zone (Table 5.1). There is only less than 2% in all three zones used surface water which is stored by small ponds or canals. In contrast with rainwater harvesting, the proportions of bottled water show an increasing trend from north to south of the study area. Bottled water is produced by small private companies which source water is taken through tap water or tube wells and mainly used for the drinking purpose.

Table 5.1 - Ratios of different water supply methods in Tra Vinh Province.

Zone	Number of surveyed HH	Ratios of water supply methods (%)				
		Bottled water	Tap water	Tube-wells	Rainwater harvesting	Pond water store
Northern zone	140	25%	76%	29%	84%	6%
Middle zone	139	53%	56%	67%	34%	1%
Coastal zone	140	80%	42%	86%	16%	0%
Total	419	53%	58%	61%	45%	2%

Most of surveyed HH usually uses a combination of different water supply methods to satisfy total domestic demand and suitably with specified purposes such as drinking, cooking, bathing or washing. Among five water supply methods, GW is available in tube-wells, bottled water and tap water. During the dry season, a number of HH in the study area uses water for domestic with only one source of water is from groundwater via tube-wells or tap water network which is transferred from big stations of GW exploitation. In addition, the bottled water is also produced from GW via tap water or tube-wells in that area. These households are considered as completely dependent on GW during the dry season. The highest percentage of surveyed households which completely depended on GW shows in the coastal zone, around 89 % and there were 12 and 66% in the northern and middle zone, respectively (Figure 5.1.). Other remaining households used groundwater in combining with other sources as rainwater or surface water. In other words, these households are partly dependent on GW in term of domestic use during the dry season. The result shows that the proportion of surveyed HH which is partly dependent on GW, were 22%, 34% and 11% in the northern, middle and coastal zone, respectively (Figure 5.1.). In the northern zone, there is 66% of total surveyed HH did not use any GW for their domestic demand due unavailability of GW in a part of this zone (Figure 5.1.). These households show a non-dependent on GW in the dry season like this is not found in the middle and coastal zone.

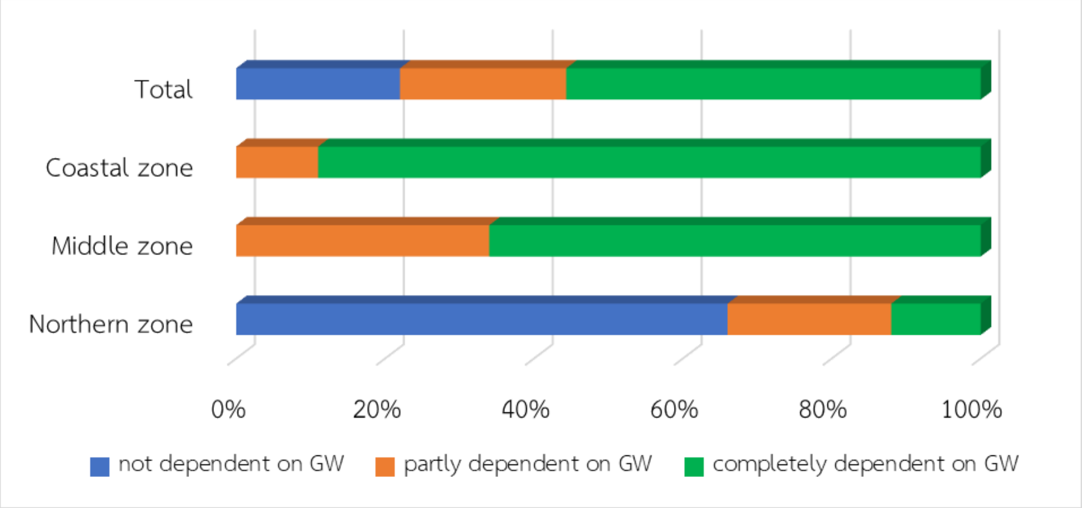


Figure 5.1 - Dependence of domestic use on GW in Tra Vinh Province

5.1.2 In agricultural use

Agriculture plays a significant role in developing the economy of the coastal area of VMD. Agricultural water use accounted for 86% of all water abstraction from the Mekong river (Smajgl et al. 2013). In Tra Vinh Province, irrigation water is mainly taken from surface water however this source can't maintain supply capacity due to availability of freshwater. In fact, river water sources always are plentiful even in the dry season. However, the mechanism of salinity water distribution in estuary areas is strongly dependent on discharge from upstream. In particular, salinity concentrations higher than 4 % (TDS ~ 4 g per liter) are deemed unsuitable for crops and aquaculture (Nguyen et al. 2014).

In the coastal zone of Tra Vinh Province, GW is considered as the main source for irrigation demand because fresh surface water is known to be not available throughout the dry season. In the dry season, planting paddy is usually alternative by other annual crops like watermelon, pepper, onion and peanut with higher value and less water requirement. In the dry season of 2018, area equipped for irrigation is currently about 282.5 ha of which 100% are equipped for irrigation with mean of irrigation consumption about 31.6 cubic meters per hectare day^{-1} (Table 5.2). In the northern zone, that has availability of fresh surface water, main crops are coconut, paddy and some orchards. Although GW is exploited a high proportion for domestic use, however, it occupied a very small proportion of irrigation demand. Conjunctive use clearly presents in the middle zone by access water for irrigation. At the start of the dry season (in January and February), freshwater is still available in main rivers and canal system, most farmers preferential use water from canals and ponds for crop irrigation. However mid and later in the dry season (March, April and May), the contribution of freshwater decrease dramatically. When the discharge at Tan Chau station is less than 2,000 m^3/s, there is no freshwater in this zone. This implies that most area of the middle part cannot access to freshwater since that time until the early rainy season (late May or June) or earlier in case of releasing more water from upstream dams. As a result, GW is exploited more to fill the shortage of crop irrigation. Food crops include paddy, maize still must be dependence on surface water due to high crop demand and large planting area. During the dry season of 2018, there is 32 % and 46 % of total surveyed HH used GW for irrigating orchards and annual crops, respectively (Table 5.2).

In Tra Vinh Province, there are two types of aquaculture including freshwater aquaculture and saline/brackish water. The area of saline/brackish aquaculture accounted 25,648 ha, approximately 83% of the total aquaculture area in 2015 (General statistical office, 2016), were located primarily in coastal districts. Freshwater aquaculture area occupies only 0.5 to 3.4%, mainly distributed in the northern zone where freshwater is more available. However, cultivation of shrimp in areas where the salinity concentration of water is low and changed over time tended to affect shrimp growth, causing diseases that resulted in low productivity. When enters peak time of the dry season, salinity concentration always increases rapidly due to the higher temperature and saltwater intrusion. In order to maintain salinity concentration in farming ponds, farmers usually exploit GW to mix with available water in ponds. In the dry season of 2018, GW exploitation for shrimp farming lasted continuously from 7 to 20 days for 13 % and 30 % of the middle and coastal zone, respectively (Table 5.2).

Table 5.2 - GWU proportion for agricultural use

Zone	Proportion of GWU for agricultural activities				
	Food crops	Perennial crops	Orchards	Annual crops	Aquaculture
Northern zone	non-use	non-use	7%	9%	n/a
Middle zone	non-use	non-use	32%	46%	13%
Coastal zone	non-use	non-use	87%	100%	30%

5.2 Estimation of GWU distribution/pattern

5.2.1 Baseline of GWU

For domestic use, consumption of GW of each surveyed HH is summarized from all water supply methods. On average, each household used approximately 1.3 m^3 of GW to satisfy its domestic demand. Mean of GWU varies from 0.95 $m^3 day^{-1}$ per HH to 1.35 $m^3 day^{-1}$ per HH and its trend increased from northern to coastal zone (Table 5.3). Besides, GW is also exploited for irrigation and aquaculture via tube-wells. GW irrigation mainly distributed on sand dune areas and supplied water for some annual crops including onion, watermelon, pepper and vegetables. On the other hand, an amount of GW is used for aquaculture with the main objective is to maintain salinity concentration of farming ponds due to saltwater intrusion and high temperature during the peak time of dry season. Mean of GWU for irrigation and aquaculture are estimated by 25.7 and 30.8 $m^3 day^{-1}$ per ha, respectively (Table 5.3).

Table 5.3 - Baseline of GWU by different purposes

Purpose\zone		Northern	Middle	Coastal	Total
Domestic ($m^3 d^{-1}$/HH)		0.95	1.26	1.35	1.2
Irrigation $m^3 d^{-1}$/ha	Onion	24.6	23.4	27.7	25.2
	Watermelon	n/a	39.2	38.7	39
	Pepper	n/a	13.1	14.4	13.8
	Vegetables	20.6	28.2	32.4	27.1
	Orchards	n/a	26.3	28.8	27.6
	Average	22.6	26	28.4	25.7
Aquaculture ($m^3 d^{-1}$/ha)		30.1	30.1	32.2	30.8

5.2.2 Estimation of GWU pattern

For domestic use

GWU for domestic use of each zone is estimated based on ratio of HH using GW and baseline of GWU for domestic. In 2018, Tra Vinh Province has about 77,079 households. In which, a high number of surveyed households uses GW as the main source for domestic use, it occupies 82% of total surveyed households in the coastal zone due to the saline surface water problem. In the northern zone, the ratio of HH using GW is lowest; around 26%. Distribution of household number in three zones is applied to estimate total GWU for domestic in corresponding zones. The result shows that total GWU for domestic of Tra Vinh Province is 167,676 m^3/d in which the proportion of the northern, middle and coastal part were 8%, 77% and 16 %, respectively. See more detail in Table 5.4.

Table 5.4 - GWU estimation for domestic

Zone	Ratio of HH using GW	Number of HH	Total domestic GWU (m^3d^{-1})	Percentage %
Northern zone	26%	53,238	13,150	8%
Middle zone	66%	154,391	128,392	77%
Coastal zone	82%	23,608	26,134	16%
Whole province	58%	77,079	167,676	100%

For agricultural use

Baseline of GWU for aquaculture in each zone is used to extrapolate to the whole zone based on statistical data of the brackish aquaculture. Brackish aquaculture mainly distributes in the coastal zone, about 1,273 ha and a part of middle and northern zone. In the coastal zone, the estimated GWU for aquaculture is 41,015 m^3/d during the dry season of 2018 (Table 5.5). GW provides 2,167 and 21,483 m^3/d for aquaculture use in the northern and middle zone, respectively (Table 5.5). According to statistical data of land use in 2018, area of some annual crops is used to estimate total GWU for irrigation by zone based on baseline of GWU from the surveyed results. The estimation shows a highest amount of GWU for irrigation in the middle zone due to largest distribution of sand dunes as well as main annual crops in the dry season, accounts for over 70%

of total GWU for irrigation of the study area. The estimated GWU for irrigation is 8,505 m^3/d and 23,699 m^3/d in the northern and coastal zone, respectively. The total GWU for agricultural activities is 178,603 m^3/d, presented a similar amount with total GWU for domestic during the dry season of 2018 (Table 5.5).

Table 5.5 - GWU estimation for agricultural activities

Zone	GWU for annual crops		GWU for aquaculture		Total agriculture GWU (m^{3}d^{-1})
	Area of annual crops (ha)	Irrigation GWU (m^{3}d^{-1})	Area of aquaculture* (ha)	Aquaculture GWU (m^{3}d^{-1})	
Northern zone	378	8,505	72	2,167	10,672
Middle zone	3,205	81,734	714	21,483	103,217
Coastal zone	837	23,699	1,273	41,015	64,714
Whole province	4,421	113,938	2,059	64,665	178,603

The estimated groundwater use of the study area is 346,279 m^3/d in dry season of 2018. In which, the coastal zone (Duyen Hai district) occupies 23 % of total GWU of the whole province although population and area of this zone are accounted for around 10% and 13% of the whole province, respectively. In northern zone, GW is mainly exploited to satisfy domestic demand with total GWU is around 23,832 m^3/d. In the middle zone, total GWU is 231,609 m^3/d in which proportion of GWU for domestic and agriculture use are 55% and 45%, respectively (Figure 5.2).

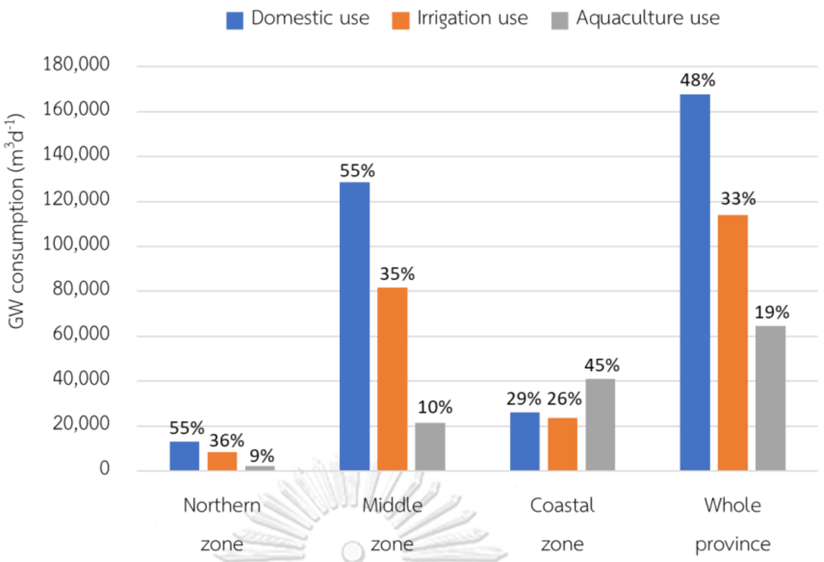


Figure 5.2 - The estimated GWU of Tra Vinh Province in the dry season 2018

5.2.3 Estimation of GWU distribution

Modification of GWU distribution by applying LST distribution

Land surface temperature (LST) from Landsat 8 Image (acquisition date 22 Feb 2018) is simulated by using ARCGIS 10.4. Figure shows the distribution of LST in Tra Cu district, high temperature area presented for households, roads and sand dunes distribution. The range of low LST is from 14 to 25 ^{o}C, represented for paddy fields, surface water areas which use less GW for irrigation. See details in Figure 5.3.

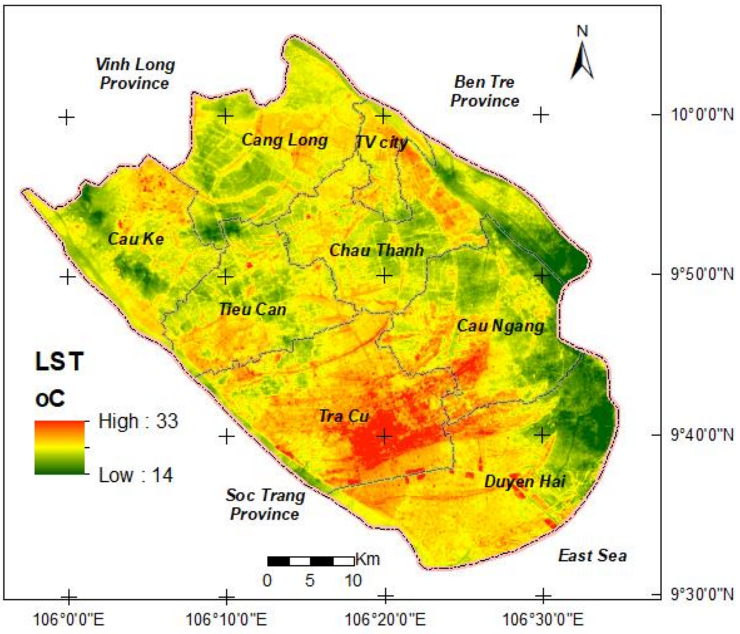


Figure 5.3 - LST distribution using Landsat 8 Image

Total GWU in each zone is redistributed in more detail by applying the distribution of LST. The result shows that the GWU per cell increased gradient from north to the south and is much higher in sand dunes and housing areas. The coastal area presents a much higher GWU compare with two remaining areas due to a high amount of GWU on a small area of this zone. See more details in Figure 5.4.

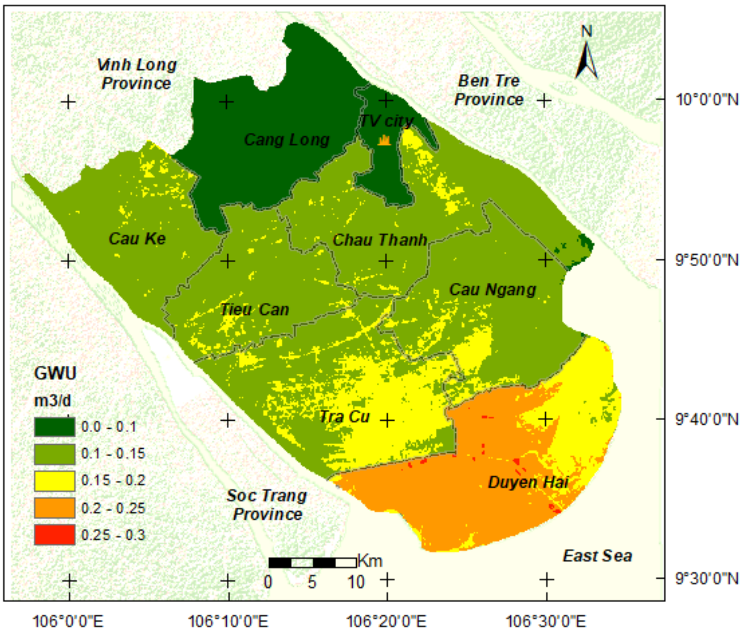


Figure 5.4 - GWU distribution of Tra Vinh Province during the dry season of 2018

On the other hand, GWU by commune is estimated by using baseline of GWU and data of land use and population at commune level of Tra Cu District (Figure 5.4) to verify the GWU distribution applying LST distribution (Figure 5.5). From the map of GWU distribution, sum of GWU by 17 communes is estimated by using zonal statistic tool of ARCGIS (Figure 5.5). The result shows a statistically significant positive correlation between these two estimations (adj-R^2 = 0.646) (Figure 5.6). Therefore, the distribution of LST can be used to interpolate GWU to areas which detailed information of housing or land use are not available.

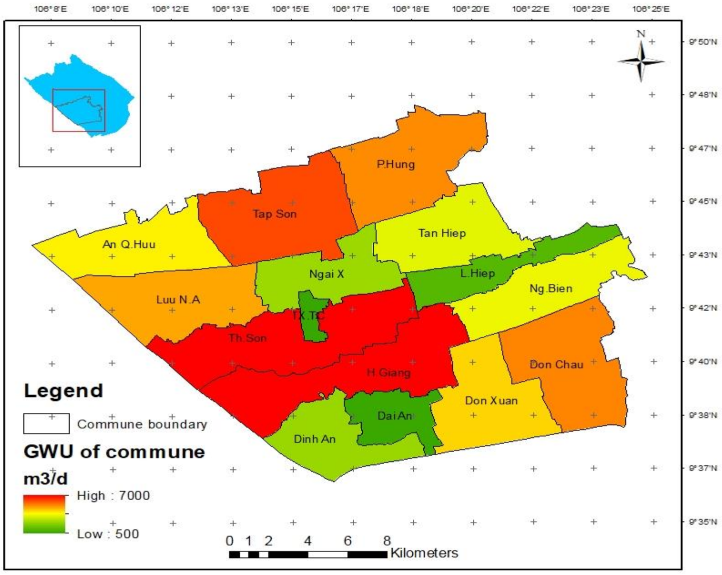


Figure 5.5 - GWU of 17 communes of Tra Cu district by applying LST distribution

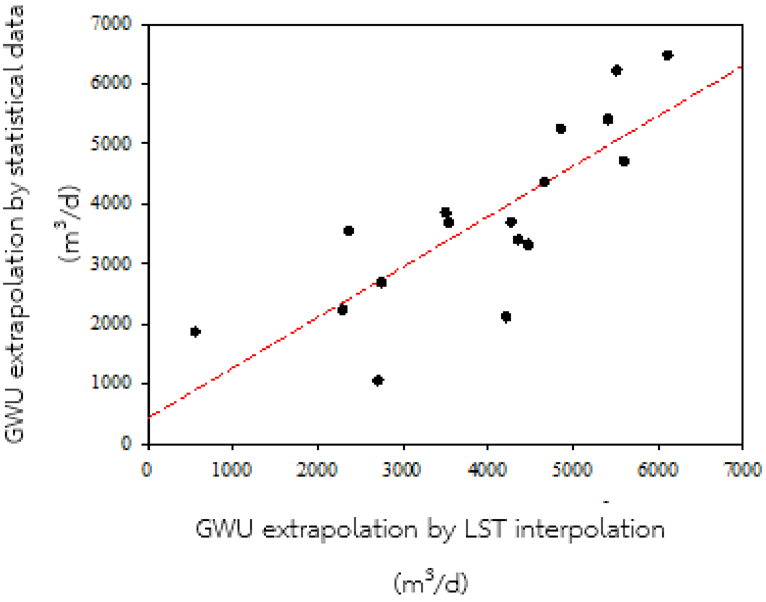


Figure 5.6 - Comparison of GWU by different method of estimation

Interpolation of GWU pattern distribution by year

For Tra Vinh Province, GW accounted for 187,000 m^3/d in dry season 2007, and this has increased by almost two times to 346,279 m^3/d in that of 2018. That explains the significant decrease of GWLs in main exploited aquifers (qp$_3$ and qp$_{2\text{-}3}$) after the 2000s (see more detail in section 3.4.3). GWU for domestic activities increases rapidly due to growth in the percentage of household using GW between 2007 and 2018, accounting 15% for the whole study area. In addition, the standard of drinking water supply also increased from 60 liters/day per capital to 85-100 liters/day per capital between 2007 and 2018, respectively. For agriculture activities, GWU shows a light increase, accounting only 25,000 m^3/d in this period. Statistical data of annual crops, agricultural between 2007 and 2018 also show a similarity in planting area of annual crops, orchards and aquaculture. So, agricultural water demand seems to not change much in this period. However, depending on the availability of fresh surface water during dry season, GW can be exploited with varies amount.

While agricultural use in the coastal zone is strongly dependent on GW by all demand of water, that of the northern zone is more dependent of surface water due to much better controlling of saline intrusion during the dry season in this zone. The middle zone is the most sensitive area with GWU for agriculture due to changes availability of freshwater by years. Figure 5.7 shows comparison of average dry season flow at Tan Chau (Figure 3.1) and seasonal difference of GWLs at the middle zone (observation well-Q404030 - Figure 3.1). Before 2006, GWLs showed a light fluctuation between wet and dry season (less than 10 cm per year) due to small GW pumping in this period. However, there is high varies of GWLs between wet and dry season in the period of 2007 and 2018. In some dry years (2013,2016), when average dry season is low, local people had to exploit more GW to satisfy their demand mainly via tube-wells due to high number of days without freshwater in these years, accounting 23 cm and 35 cm for 2013 and 2016 (Figure 5.7). However, the amount of GWU for agriculture seems to be lower in the wet year (2009, 2012) due to a shorter duration without fresh surface water. Therefore, GWU for agriculture in the middle zone is strongly dependent on up-stream flow or duration without freshwater in the study area.

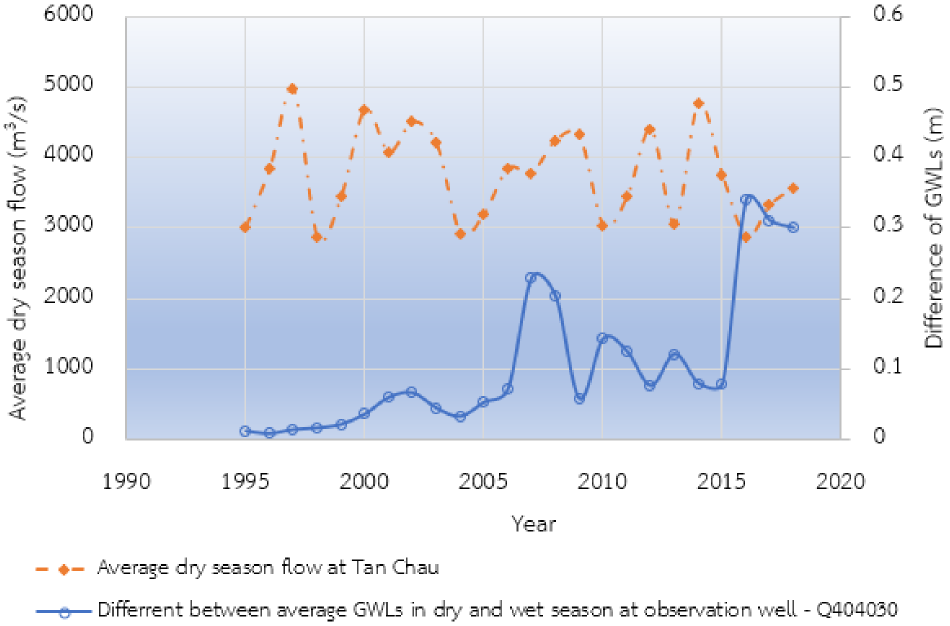


Figure 5.7 - Comparision between average dry season flow at Tan Chau and seasonal difference of GWLs at observation well (Q404030)

For the period from 2007 to 2018, GWU in dry season is estimated by linear interpretation between that of 2007 (Sanh, 2007) and 2018 (this study). In term of GWU for agriculture in dry season, the amount of GWU is adjusted based on average dry season flow in this period. For the period of 1995 and 2007, GWU of each year is estimated by using linear interpolation of GWU between GWU in three years including 2007, 1995 and 2000. GWU in dry season of 1995 and 2000 is estimated by percentage of total GWU of the VMD in the same year, accounting 20,000 m^3/d and 50,000 m^3/d in 1995 and 2000. Figure 5.8 presents the time series of average dry season GWU from 1994 to 2018. The corrected GWU shows a significant increasing since 2000s in the middle and coastal zone. In 2018, the estimated GWU is higher around 3 times than the one in 2005 for these two zones. There is a slowly growth of GWU in the northern zone due to availability of surface water and salinity distribution of GW. The total GWU is only 235,000 m^3/d in 2010, occupied only about 75% of current GWU in 2018. Average wet season GWU is estimated by 70% of average wet season for all three zones and the percentages is corrected by calibration of GWLs in the groundwater flow model.

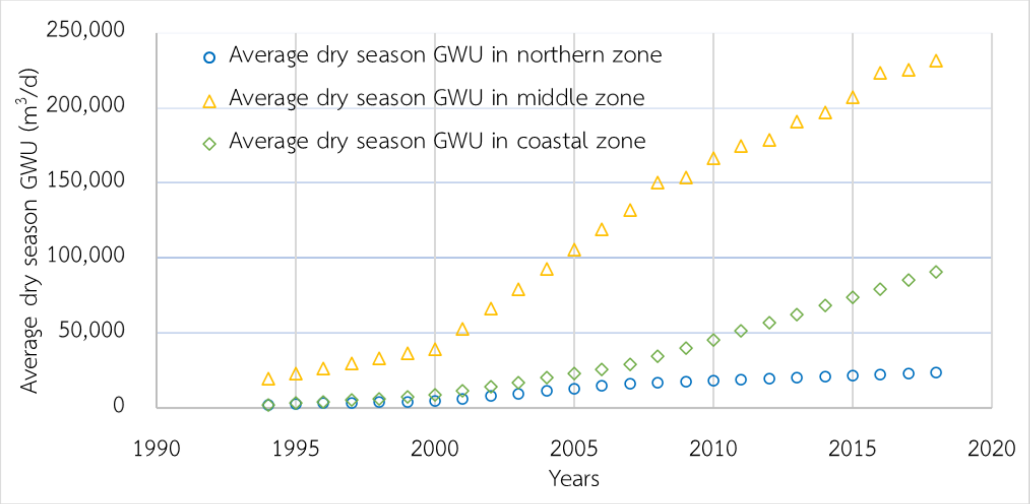


Figure 5.8 - Estimation of average GWU in dry season by years

5.2.4 Verification of GWU distribution by GW flow model

Verification of spatial and pattern distribution of GWU

In order to verify GWU estimation, GWU of each zone by time and space is inputted into pumping package of GW models (detailed description of model development in the next section). The most common way of inputting GW pumping is to convert total GWU of any specified area by a number of wells with same rate of pumping for each single image well. In this study, application of images wells with equal distribution in each zone and the GWU distribution by applying LST distribution are also used to compare accuracy of the estimated method based on calibration result of groundwater flow model. GWU in the wet season is surveyed in this study, so it is defined by 70% of GWU in the dry season for all three zones. During the model calibration, these percentages of three zones were corrected to improve simulated GWLs based on observation ones. The results show that GWU distribution by using LST distribution present a much better correlation between simulated and observed GWLs at the time-step of March 2018 of 13 observation wells (Figure 5.9).

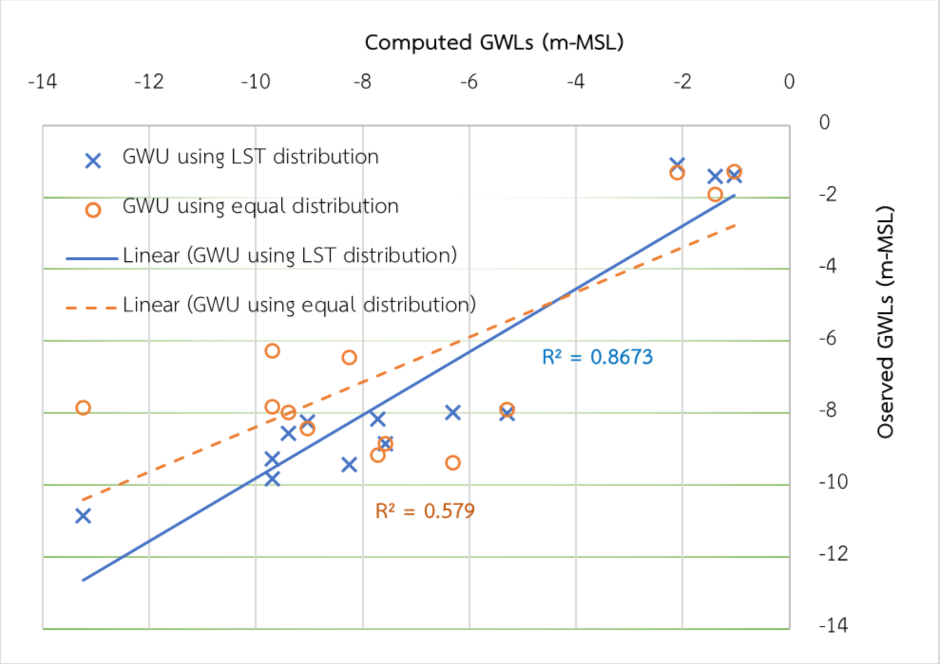


Figure 5.9 - Comparison of correlation regression of different GWU input by equal distribution and application of LST distribution

Correction/verification of long-term GWU pattern

The calibration process of GWLs is carried out using 13 time series of monthly GWLs from observation wells extending 15 years from 1995 to 2009. Calibrated results show a good match between observed and simulated GWLs, with high R^2 (see more details in section 5.3.2 and APPENDIX). Visual comparison in the observation wells also suggests that the GWU estimation is reasonably good. Ratio of average wet season GWU and average dry season GWU is corrected by 55%, 64% and 73% for the northern, middle and coastal zone, respectively.

5.3 Development of GW models

In this study, two models of GW include simulation of flow and salinity movement by MODFLOW and MT3DMS package in GMS software. In this study, the conceptual model is defined to simulate the whole area of Tra Vinh Province and 7 aquifers from Holocene (qh) to Miocene (n_{1-3}). The distribution of layers is simulated based on the hydrogeological formation. The bottom elevations of the 13 layers were interpolated from 56 boreholes in the model domain (DWRPIS 2009). By using Kriging method, the groundwater system in Tra Vinh Province modelling into 13 layers, representing 7 aquifers and 6 aquitards. Layers of 1, 3, 5, 7, 9, 11, and 13 represented for aquifers. Layers of 2, 4, 6, 8, 10, and 12 represented for aquitards. See layer simulation by 3D view and fence section in the Figure 5.10 below.

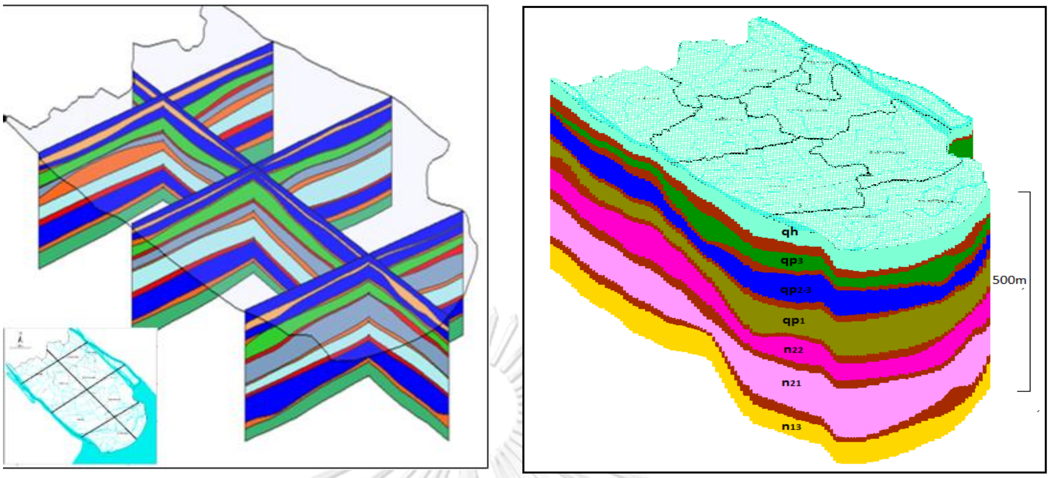


Figure 5.10 - Aquifer system and the fence section of the layers in the model

Domain and model grid

The domain area of the model is 2,341 km^2, covering the whole area of Tra Vinh Province. The model with the length of X axis is 75,000m, the length along the Y axis is 67,000m. The model domain is divided into 135 rows and 151 columns, with a total of 20,100 grid cells. The size of each grid is 500mx500m. Grid cells outside the model area assigned inactive.

5.3.1 Construction of groundwater flow model

Boundary conditions

Referring to the boundary conditions, river boundaries were assigned at the Hau and Tien River and their main branches. The depth of the riverbed ranges from 5 to 10 meters, cutting into the Holocene aquifer, were assigned to the first layer of the model (Figure 5.11). General head boundary is assigned at the distribution boundaries for the northwest of the model at layer 1 and the northeast, northwest, southwest of the model at the layer 2 to layer 13 using water level data of different nearby GW monitoring station and the regional model results (Vuong 2013). Specified head boundary is assigned for 65 km of the southeastern coastal line of the study area to all layers of model, the head values on these boundaries were taken as a time-dependent specified head boundary is provided using the seawater level observation (Figure 5.11).

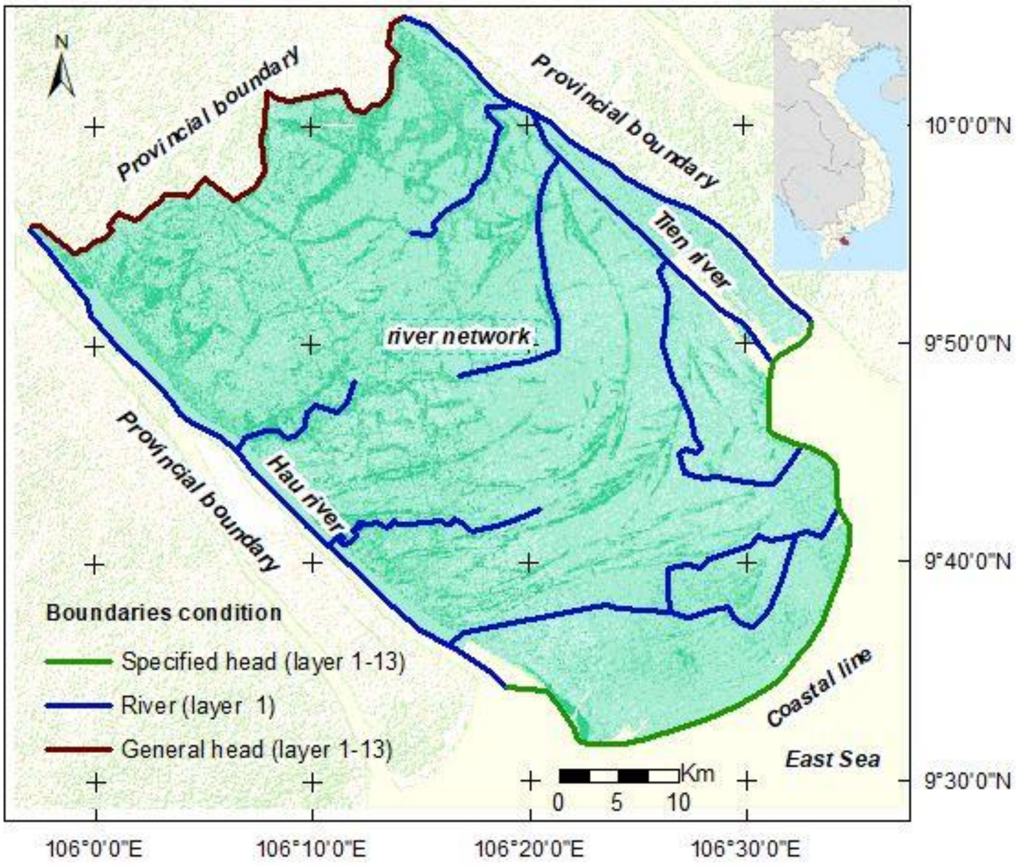


Figure 5.11 - Assign boundaries condition for the model

Hydraulic parameters

Aquifer properties are represented by hydraulic conductivity (HC) and storage coefficients. Hydraulic conductivity includes horizontal HC (K_h) and vertical HC (K_v). While storage coefficients consist of specific storage (S_s) and specific yield (S_y). These parameter values are assigned by different zones and aquifer. For aquifer layers the horizontal hydraulic conductivity range from 9.4 m/d to 33.8 m/d, while its values of storage coefficient range from 0.5×10^{-5} to 0.75×10^{-3} (Table 5.6).

Table 5.6 - Hydraulic parameters of the aquifers in the study area (DWRPIS 2009).

Aquifer	No. layer (number of polygons)	Average value of parameters for each aquifer			
		K_h (m/d)	K_v (m/d)	S_s	S_y
qh	1 (2)	10	1	0.00075	0.12
qp_3	3 (3)	25	2.5	0.00038	0.18
qp_{2-3}	5 (4)	18.6	1.9	0.00073	0.17
qp_1	7 (3)	25	2.5	0.00001	0.12
n_{2-2}	9 (3)	22	2.2	0.00032	0.18
n_{2-1}	11 (2)	33.8	3.4	0.00005	0.18
n_{1-3}	13 (2)	9.4	0.9	0.0001	0.18

Rainfall recharge

In the VMD, the main recharge of the shallow aquifer is from rainfall (Vuong 2013, Shrestha et al. 2016). In areas of sand dunes or high sand content, the rainfall recharge shows a high percentage of preparation, while the large apart of the topsoil shows a very low permeability in rice fields or other crops (Silva 2018). The previous study also developed a potential map of rainfall recharge based on the field/laboratory test and analysis of hydrogeological and land use data (Figure 5.12) in which the potential area of sand dunes is of high recharge rate and the area of clay and silt is of low recharge rate (Silva 2018). By using results of infiltration capacity test at the field and the groundwater fluctuation method (Sophocleous 1991, Crosbie et al. 2005), a one-dimensional recharge is calculated at four locations of the study area. The amount of recharge to the GW system of four points is interpolated to the whole study area by the potential map. In the study area, the annual rainfall recharge is estimated to be range from 8% to 12% of total annual precipitation.

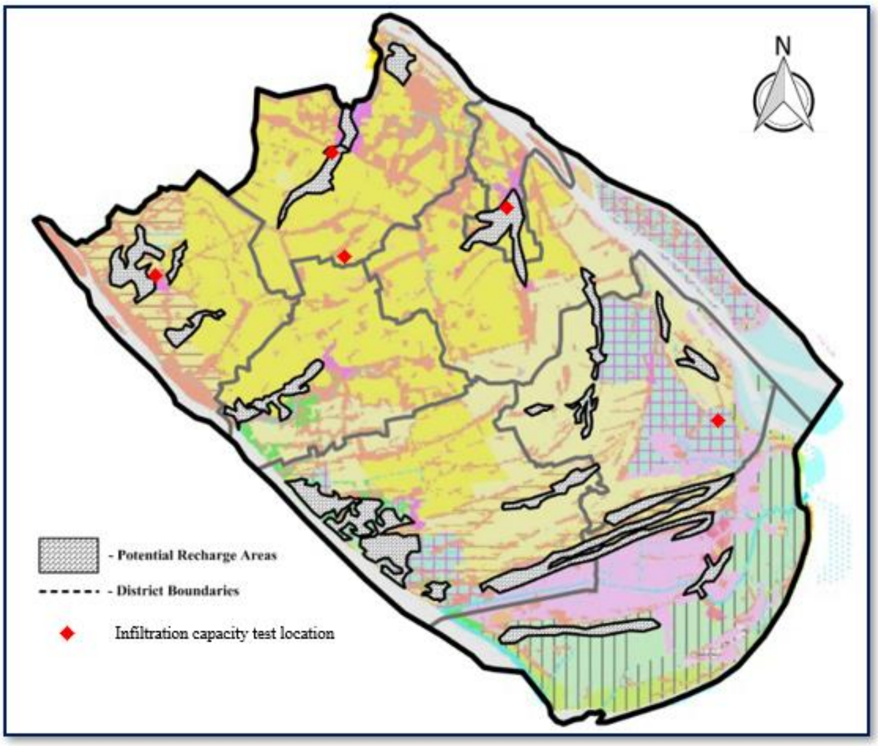


Figure 5.12 - Potential recharge zones in the province of Tra Vinh (Silva 2018)

River water levels and conductance coefficient

In the VMD, the interconnection between surface water and groundwater is described as being insignificant due to the thickness of the top clay layer (30 to 50m). The limited river conductance from the previous model (Boehmer et al. 2000) is estimated based on the interpolated function of interaction parameter (Van et al. 2018). River conductance of each main river/canal section is inputted into the river leakage of the shallowest aquifer (qh). Water levels at limited river stations are linearly interpolated to other nodes of rivers and canals.

Observation wells

In the study area, time series of monitoring GWLs has lasted from late 1992 to present. The number of GW monitoring wells are 3, 1, 2, 0, 3, 3, and 1 for aquifer qh, qp_3, qp_{2-3}, qp_1, n_2^2, n_2^1 and n_1^3, respectively. The initial GWLs are assigned by the average monitoring GWLs and linear interpolation in January 1994 at 13 observation wells (Figure 5.1) in the National Monitoring Network (DWRPIS 2019). The monthly GWL of 13 monitoring wells (Figure 5.13) are inputted directly into the model. The time series is 25 years from 1/1994 to 12/2018.

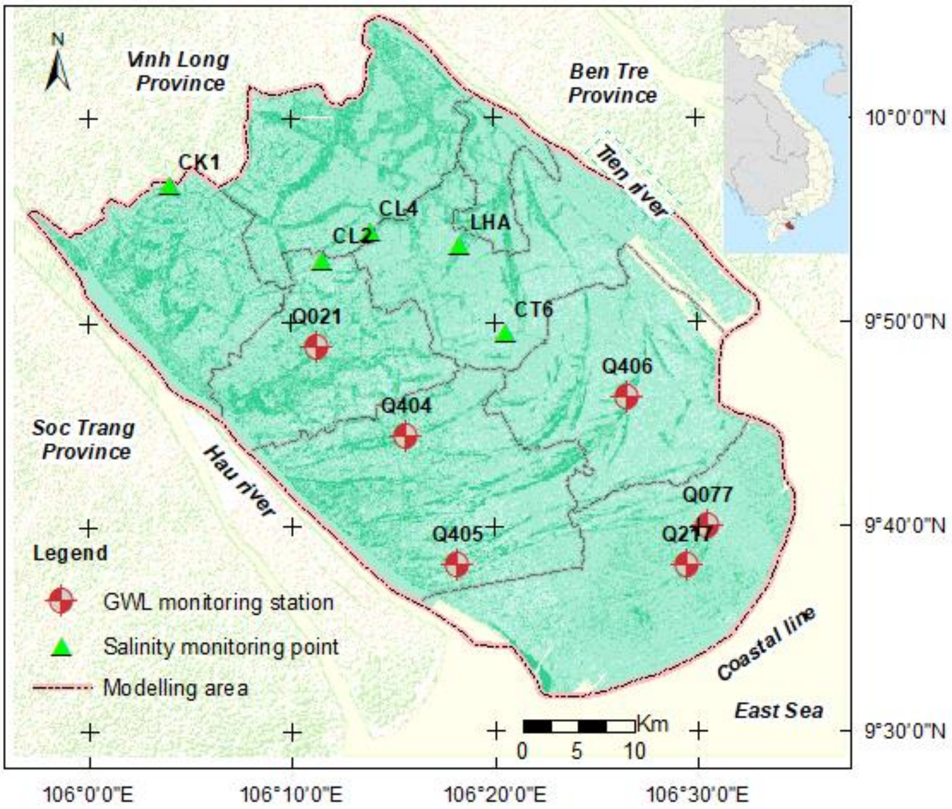


Figure 5.13 - Distribution of GWL monitoring wells in Tra Vinh Province

5.3.2 Saline GW transportation model

For simulation of saline GW transportation, total dissolved solids (TDS) is used as the simulated parameter. Three packages in MT3D module (advection package, dispersion package and source/sink mixing package) and a variable-density flow package in SEWAT module are used. ICBUND value of the distribution area of the aquifers in the modeling area is assigned a value of 1 (the area with TDS content changes over time). ICBUND of the narrow band distributes along 65 km of coastline is assigned a value of -1 (area with constant TDS content). The initial TDS content of the fresh and saline GW area are assigned a value of 500 mg/l and 5,000 mg/l, respectively. Initial TDS content of the narrow band distributed along 65 km of coastline is assigned a of 35,000 mg/l for the shallowest aquifer (qh). The minimum fluid density is assigned a value of 1,000 mg/m^3 and the maximum fluid density is assigned a value of 1,025 mg/m^3. Density/concentration slope is assigned a value of 0.7143. Ratio of horizontal transverse dispersity to longitudinal dispersity (TRPT) is assigned a value of 0.1 and ratio of vertical transverse dispersity to longitudinal dispersity is assigned a value of 0.01. The molecular diffusion coefficient (D_m) is assumed to be 86.4×10^{-4} m^2/d (Van Pham et al. 2019). The longitudinal dispersion coefficient is assigned a value of 50 for all aquifers and the effective porosity is assigned by 0.25 (Van Pham et al. 2019), representing aquifer and aquitard layers. Coefficient of longitudinal dispersion and effective porosity is adjusted by calibration process at 5 observed points of salinity concentration along the fresh/saline interface of the Upper-Middle Pleistocene aquifer (qp_{2-3}) aquifer (Figure 5.13).

5.3.2 Calibration results

For GW flow model

Timer series of GWL at 13 monitoring wells are compared with simulated GWL during the calibration process (Figure 5.13). In this process, hydraulic parameters are adjusted to lead fluctuation of simulated GWLs close with monitoring one based on trial and error method. The error performance of the model includes Root Mean Square Error (RMSE) and the coefficient of determination (R^2). Figure shows RMSE and R2 value of 13 monitoring in calibration and validation period. In the calibration period, RMSE values show a reasonable simulation, range from 0.47 m to 0.98 m. This range of the validation period is 0.53 m to 1.02 m. In addition, visual comparison of monitoring wells in the shallowest aquifer (qh) and the main abstracted aquifer (qp_{2-3}) also suggests that the model is reasonably good (Figure 5.14). See more detail of calibration results in APPENDIX 4.

Table 5.7 - RMSE and R^2 value during calibration and validation (unit: m-MSL)

Aquifer	Wells	Calibration		Validation	
		RMSE (m-MSL)	R^2	RMSE (m-MSL)	R^2
qh	Q217020	0.55	0.75	0.53	0.71
	Q07701A	0.47	0.78	0.51	0.68
qp_3	Q4042020	0.67	0.85	0.63	0.81
qp_{2-3}	Q40403T	0.47	0.89	0.53	0.84
	Q217020	0.68	0.79	0.81	0.75

Table 5.7 - RMSE and R^2 value during calibration and validation (unit: m-MSL) (to be continued)

Aquifer	Wells	Calibration		Validation	
		RMSE (m-MSL)	R^2	RMSE (m-MSL)	R^2
n_{2-2}	Q217030	0.86	0.71	0.92	0.65
	Q40403Z	0.75	0.68	0.82	0.59
	Q406040	0.98	0.64	1.02	0.57
n_{2-1}	Q217040	0.88	0.61	-	-
	Q40404T	0.74	0.63	-	-
	Q40505M1	1.12	0.58	-	-
n_{1-3}	Q021050	1.23	0.55	-	-

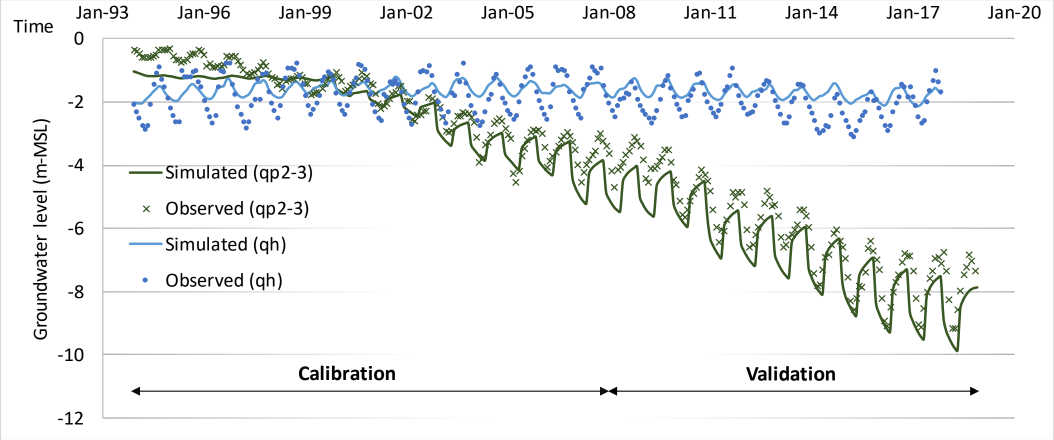


Figure 5.14 - Comparison of simulated and observed GWLs in calibrated and validated periods

For TDS transportation model

In similarity with GW flow model, the trial and error method is applied to calibrate this model based on 2 years data of TDS observation at 5 points of the qp2-3 aquifer (Figure 5.19). During the calibration process, longitudinal dispersion and effective porosity are adjusted to obtain reasonable agreement between computed TDS and monitoring ones. The calibrated model presents an average RMSE of 37.5 mg/l and the trend that the computed TDSs lightly higher and less fluctuate than the monitoring one is described (Table 5.8). This model uses seasonal GW pumping sot it maybe effect to results of computation. In general, the computed results with of the 5 monitoring wells presents the high value of R^2 except only in the observation of CT6 (Figure 5.15). In general, observed TDS increased lighltly from 939 mg/l to 1,000 mg/l. However, there is a big difference of TDS in dry and wet season, accounting 130 mg/l. It can be explained by errors during sampling collection or low protection of well.

Table 5.8 - Errors estimation of TDS calibration

Observe wells	ME (mg/l)	RMSE (mg/l)	R^2
LHA	7.6	30.6	0.859
CL2	-23.9	27.9	0.551
CL4	31.7	33.2	0.890
CT6	-0.2	53.6	0.338
Ck1	17.6	42.2	0.748
Average	6.56	37.5	0.657

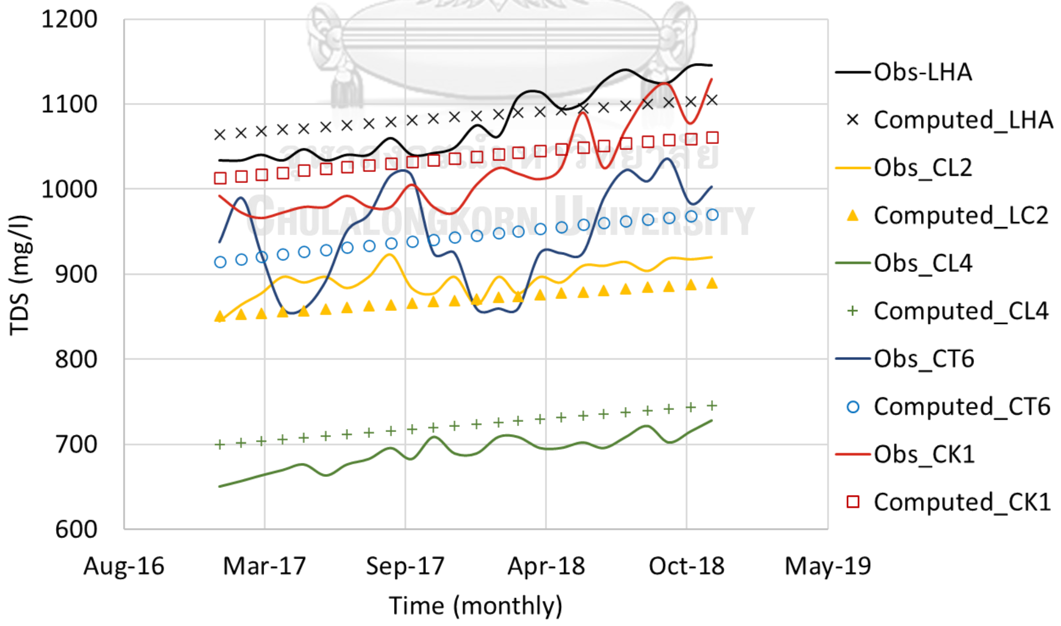


Figure 5.15 - TDS fluctation by computed model and observed data

5.4 Assess impact of GWU

5.4.1 Current situation of GW system by the long-term GWU

Change in GWLs distribution

Figure 5.16 to Figure 5.18 show the differences in GWL between 1994 and 2018 which indicates a drawdown of GWLs in this period. The aquifers qp_{2-3} has the largest declination of GWLs than the other aquifers. Due to small distribution of GWU in the shallowest aquifer (qh), resulting in 3/4 area with drawdown of lower than 4m (Figure 5.16). In the middle zone, GW exploitation is limited in this aquifer, however, a part of the middle zone shows a decrease of GWL by 5m to 7m from 1994 to 2018. The main reason is the high infiltration into below aquifers.

In the qp_3 aquifer (Figure 5.17), over two-thirds of area in the Tra Vinh Province experienced drawdown in the main exploited aquifer (qp_{2-3} aquifer) exceeding 6m (Figure 5.17). The middle zone has larger decrease of groundwater levels than the rest zones, the maximum value of drawdown is 9.0 m and the rate of GWL decline at the center point of depleted cone (coordinate x= is 0.36 m/year). The average rate of drawdown in the northern and middle zone are 0.25 m/year and 0.19 m/year, respectively (Figure 5.17).

In the main abstracted aquifer (qp_{2-3}), the drawdown shows significant values, accounts for over 7 m, locally up to 12 m after 25 years (Figure 5.17). Depleted cones concentrate mainly at GW supply stations of GW production and industrial wells with extensive GW pumping, e.g. Chau Thanh District of the middle zone, and coastal zone. In the northern zone, GWLs maintained highest distribution for all aquifer due to a small amount of GW abstraction. The deeper aquifers also presented a decrease in GWLs in the period from 1994 to 2018 and follow the distribution of qp_{2-3} aquifer due to mainly infiltration to this aquifer.

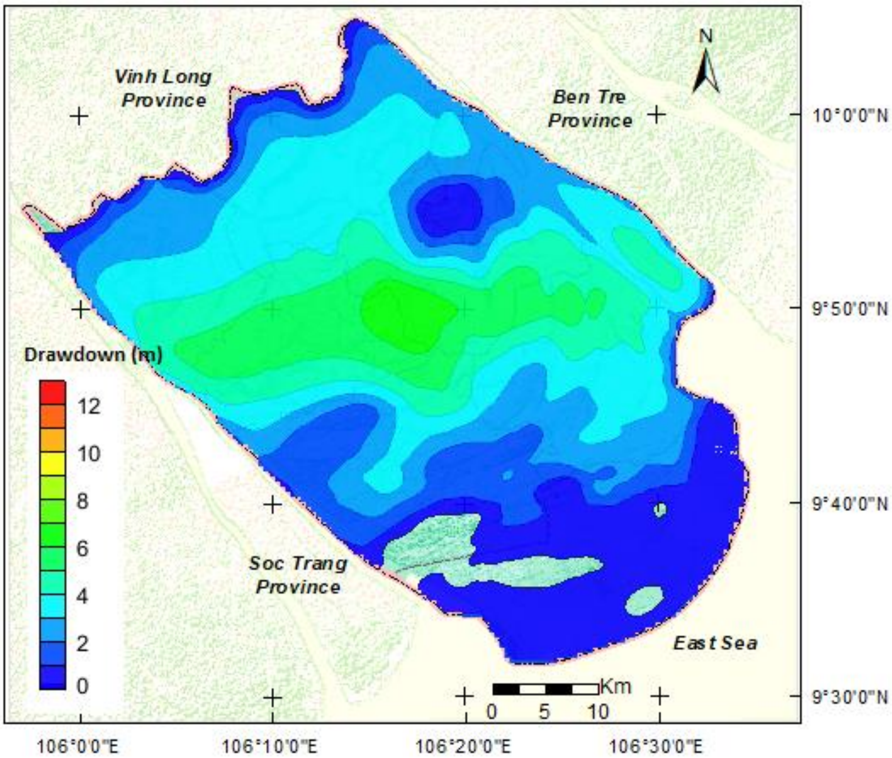


Figure 5.16 - Drawdown map of qh aquifer after 25 years of GW exploitation

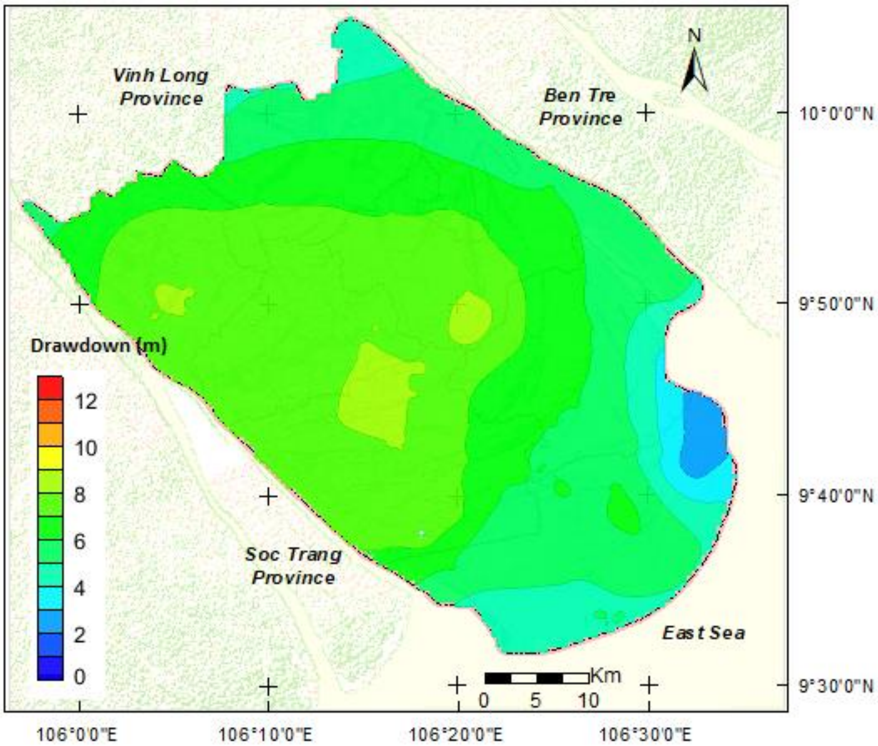


Figure 5.17 - Drawdown map of qp_3 aquifer after 25 years of GW exploitation

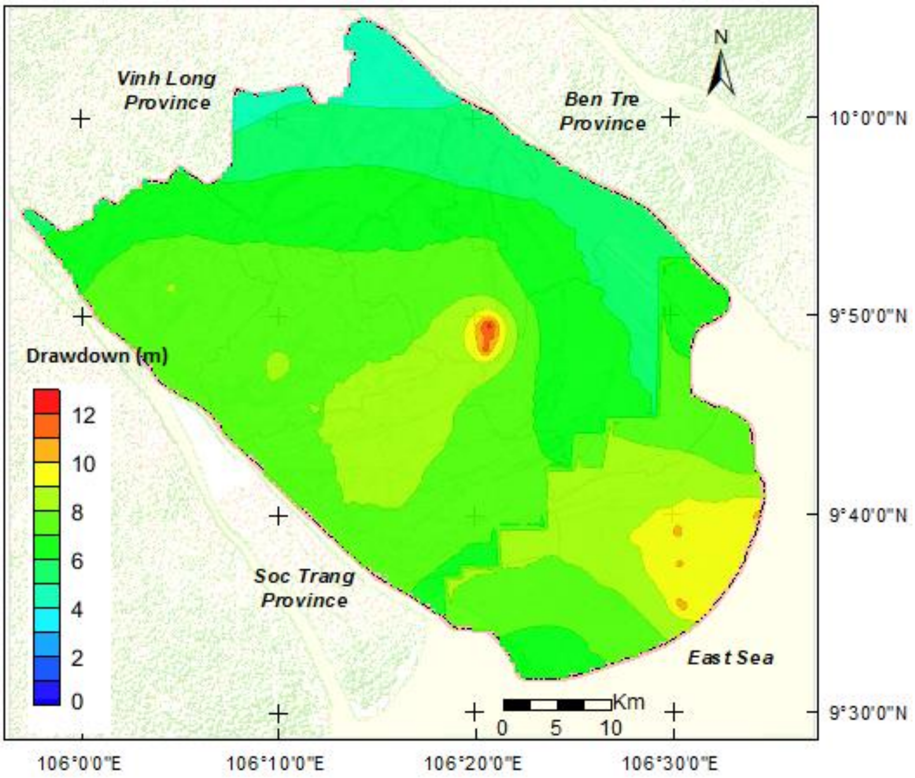


Figure 5.18 - Drawdown map of $qp_{2\text{-}3}$ aquifer after 25 years of GW exploitation

Change in saline GW distribution

Figure 5.19 presents the increasing area of saline GW and rate of the increasing area of saline GW of qp2-3 aquifer between 1994 and 2018. The results indicate that there is an increasing saline GW area most aquifer, except for only qh aquifer. In the Holocene aquifer (qh), saline GW is distributed in the most area and GW abstraction is limited in the fresh-water lenses as sand dune areas. Salinity concentration of the qh aquifer fluctuated by seasonal due to directly recharge from rainfall. For both Upper Pleistocene aquifer (qp_3) and Upper - Middle Pleistocene aquifer ($qp_{2\text{-}3}$), saline GW is distributed in the northern zone (Figure 5.19). Saline GW area has a tendency of expanding from the north (source of salinity) to the south, especially is area of depleted cone area near the fresh/saline interface. The average rate of saline movement in $qp_{2\text{-}3}$ aquifer was 0.32 km^2/year during the period of 1994 and 2018 (Table 5.9). The rate of increase in these areas is largest for $qp_{2\text{-}3}$ aquifer and are almost the same for deep aquifers from qp_1 to $n_{1\text{-}3}$ aquifer.

Table 5.9 - Extension of saline GW area between 1994 and 2018.

Increasing saline GW by:	Aquifer						
	qh	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3
Area (km^2)	0	15	34	6	5	4	6
Average rate (km^2/year)	0.4	0.68	1.36	0.32	0.2	0.16	0.24

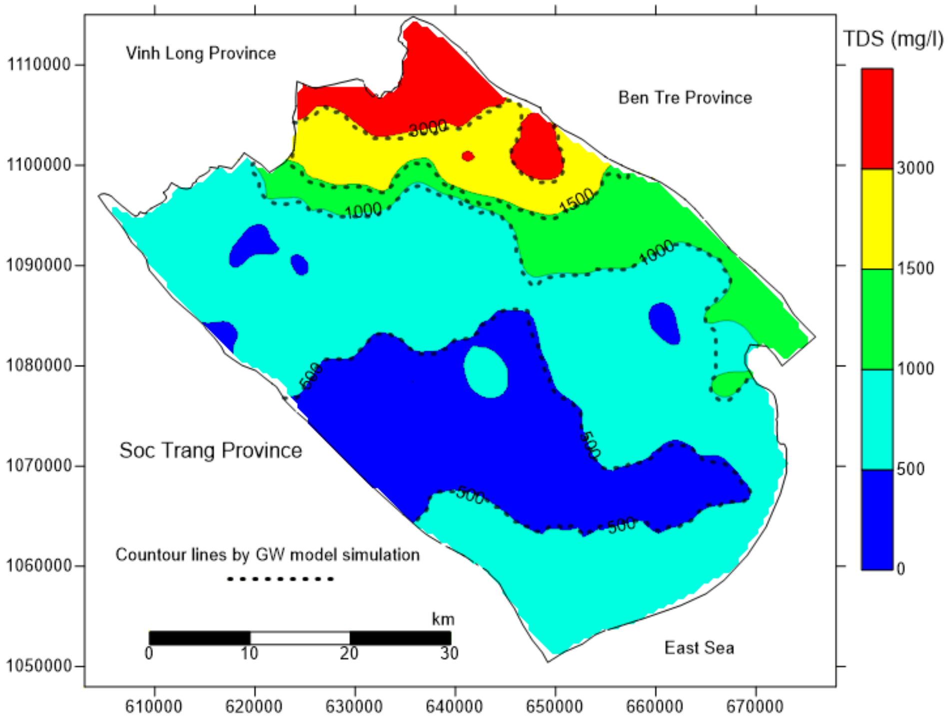


Figure 5.19 - TDS distribution of qp_{2-3} aquifer in March 2018

Change in GW storage

GW budget of the GW flow model is used to estimate inflow and outflow component. A water balance of three shallowest aquifer is shown in to understand the gaps between inflow and out flow components of the aquifer system in the study area (Figure 5.20). Recharge from the sandy areas is the most important water resources to leakage to the lower aquifers contributes to GW abstraction in the upper Pleistocene aquifer (qp_3) (Figure 5.20). In additional, aquifer qh also absorbed total of river leakage of the whole study area. Total outflow including GW abstraction and filtration to below aquifer (qp_3 aquifer) is approximated total inflow of aquifer (river leakage and land recharge), about 128,320 m^3/d. It means that the changing storage of qh aquifer is very low and it also explained by the stable fluctuation of GWLs of this aquifer in duration from 1994 to 2018 (Figure 5.14). In qp_{2-3} aquifer (main abstracted aquifer), 82 percentage of inflow is leakage flow with lower and upper aquifer. Based on the estimated GW budget in 2018, there is 35% of GW abstraction comes from GW storage.

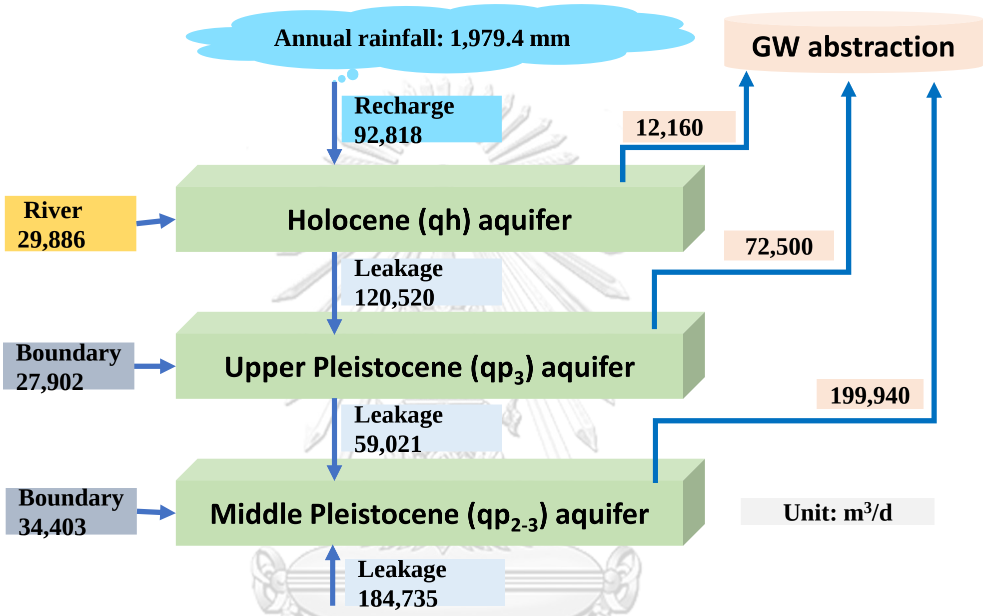


Figure 5.20 - Annual GW balance in 2018 of three shallowest aquifers

The rainfall recharge was mainly dependent on rainfall distribution and showed a stable trend in the period from 1994 and 2018 with an average annual recharge is about 83,546 m^3/d (Figure 5.21). Sum of lateral flow and river leakage occupied only 40% total inflow in 2018 and two these components show a similarity by increasing slight since 2006. The annual change in storages in all aquifers except the aquifer qh are of negative values, meaning that groundwater is being depleted. Changes of GW storage in 1994 of the Tra Vinh Province area were around -4 mil.m^3 and that of 2018 is -44 mil.m^3 (Figure 5.21) resulting the mean rate of depleted GW storage is -1.6 mil.m^3/year. Captured storage has been increasing dramatically since 2008 to catch up with the significant growth of GW abstraction. In other words, the over GW pumping exhausts the storage of the aquifer system and induces the decrease of GWL seriously in the period of 25 years. In these situations, knowledge of GW storage is important for managing GW development and for assessing sustainable yield.

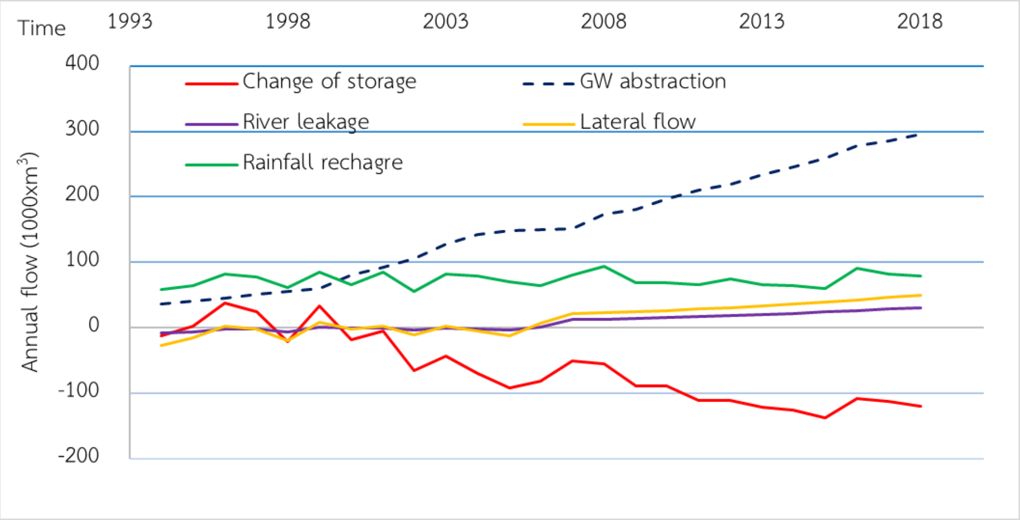


Figure 5.21 - Time series of GW budget of the aquifer system in Tra Vinh Province

5.4.2 Identify GWU issues via survey

From the field survey, a number of surveyed households in middle and coastal zones had to add reinforce tube to increase pumping capacity and other households had to drill deeper wells to access GWL due to drop of GWL in the peak time of dry season (Table 5.10). These issues mainly occurred in the irrigation area with high rate of groundwater pumping in a short duration. For example, in order to cope with high temperature and salt water intrusion, farmers had been pumping GW in 15 to 30 consecutive days to maintain salinity concentration in farming pond. Some tube-wells, which were used for domestic use, also faced the same issue during the dry season (Table 5.10). In the northern zone, the main issue is the distribution of saline GW. More than half of surveyed HH cannot access to fresh GW to supply for domestic use. Most of HH store rainwater to satisfy domestic demand and some HH even had to use water from ponds or canals. Most of GW users faced issue with taste or smell of GW via tube wells. Normally, local people have to make depostion of GW for some days before use. In general, drop of GWLs most commonly occurs because of a long-term pumping of water from the ground. Groundwater is continuously pumped from aquifers, with little or limited recharge (Danh 2008). Saline intrusion mainly occurred in the shallowest aquifer during the dry season due to high pumping for irrigation at sand dune areas. The source of saline water is mainly from canal/river network. However, some households found the saline instrusion from shallow aquifer to deep aquifers.

Table 5.10 - Summary of GWU issues via survey

Zone	Domestic use		Agricultural use	
	Issues	Coping methods	Issues	Coping methods
Northern zone	1. bad taste 2. saline GW	1. Deposition or only use for washing 2. Store more rainwater	1. saline GW distribution	1. Store more surface water
Middle zone	1. bad taste 2. intermittent supply or low pressure	1. some use deposition 2. install reinforce pipes, improve pump capacity, construct deeper wells	1. GWL levels drop	1. install reinforce pipes, improve pump capacity, construct deeper wells
Coastal zone	1. bad taste 2. intermittent supply or low pressure	1. some use deposition 2. install reinforce pipes, improve pump capacity, construct deeper wells	1. saline intrusion in the shallow aquifer 2. GWL levels drop	1. Using other deeper wells 2. install reinforce pipes, improve pump capacity, construct deeper wells

5.5 Findings

Dependency on GW in each zone is different and increased from north to south. In the coastal zone, tube-wells is main supply method for domestic use and agriculture during dry season. In dry season of 2018, GWU is estimated 346,279 m^3/d in which the middle zone occupied about 67 percent. Land surface temperature (LST) presented a good correlation with GWU distribution in term of extrapolation of non-data areas. In future, the technique can be applied to estimate GWU in other area and in regional scale with similar characteristic of GWU. Seasonal GWU pattern from 1994 to 2018 is estimated based on availability of freshwater. The results show a much higher GWU distributed in the dry season due to higher demand and less availability of rainwater and fresh surface water.

Groundwater models in the period of 1994 and 2018 showed that GW system in Tra Vinh Province has moved from a pristine system to a developed system then become a depleted system at present and the existing development of groundwater resources is unsustainable. The impacts of groundwater abstraction to groundwater resources is significant through the following indexes including decrease of GWLs, changes of groundwater storage and increasing area of saline GW. Drawdown of the GW table caused land subsidence and salt intrusion in this period. The accumulative changes of groundwater storage in Tra Vinh Province is -1,545 mil.m^3, and the average decreasing rate is 1.6 mil.m^3/year during 25 years of GW exploitation. Saline GWU mainly expanded from north towards the depleted areas with highest rate in the qp_{2-3} aquifer, approximately 0.32 km^2/year.

Chapter 6 – ASSESSED SUSTAINABLE YIELDS OF THE AQUIFER SYSTEM

The first section of this chapter describes the estimation of sustainable yields by development of sustainable model and concept/criteria of sustainable yield (section 6.1). The sustainable yield estimation included four main sub-sections: 1) development of sustainable models 2) sustainable yield by equilibrium state, 3) sustainable yield by controlling saline movement and 4) Groundwater balance analysis. Besides, this chapter also presents estimation of GW demand in next decade by different scenarios of socioeconomic and climate change (section 6.2). Comparison of sustainable yield and GW demand projections are also carried out to understand gaps of GW supply in next decade under different expectation of socio-economic development and climate change effect.

6.1 Estimation of sustainable yield

6.1.1 Development of sustainable models

In the last chapter, impact of the long-term GWU was assessed by using simulation of GW flow and salinity transportation model. The results showed that storage depletion and saline movement have been happening with a high rate. Sustainable yield of the aquifer system not only depends on GW pumping network but also climate change effect and other factors (management factors). In the study area, GW recharge can occupy around 8% to 12% of annual rainfall at potential areas of recharge, however these areas distributed less than 10% of study area. Therefore, total recharge of study area is lower than 30% of current GW exploitation in 2018. In addition, other studies resulted gradual decrease in GW recharge in VMD over the coming decades, with more decrease over the dry season. In the next decade, GW recharge was projected to reduce less than 1.5mm and 1mm compare with the base year 2010 for RCP 4.5 an RCP 8.5. In the other words, effect of climate change on GW recharge in the study area is not worth considering in the next decade.

Sustainable models of this study aim to investigate sustainable yield of the aquifer system until 2030 based on current distribution of GWU. Calibrated models of flow and salinity transportation was used to develop sustainable models by expanding simulating time until December of 2030. All value of input parameters was kept same as the base year (2018), except only GW abstraction. GW abstraction of 2019 and 2020 was repeated as GW abstraction in 2018, then started to reduce since 2021. Two criteria of sustainable yield were applied into sustainable models including new equilibrium state and control saline movement. In term of GW flow model (MODFLOW), GWLs at important points (depleted cone, coastal area, center of each zone) was checked until the GWLs reach the new equilibrium level. In addition, more reduction of GW abstraction in saline prone areas were to maintain area of saline GW by checking movement of TDS contour (1,000 mg/l) which represent the fresh/saline GW in this study.

6.1.2 Estimation of sustainable yield by criterion of equilibrium state

In term of maintaining the rate of GW abstraction from 2018 to 2020, the GWL decline continued 80 cm (Figure 6.2) for all three observed points of the qp_{2-3} aquifer (Figure 6.1). The amount of GW abstraction was adjusted gradually since January 2021 in order to the GWL decrease is smaller and reaches to a stable state. The simulated result of the qp_{2-3} aquifer showed that steady-state of GWLs was 12 m-MSL at two depleted cones in the middle zone.

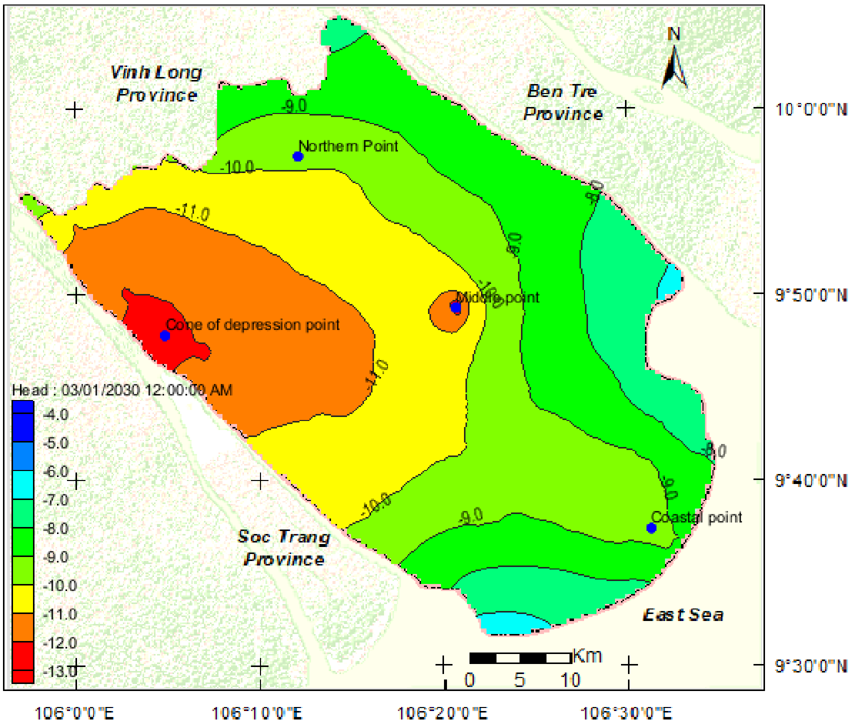


Figure 6.1 - GWLs distribution of qp_{2-3} aquifer in March 2030

While the stable GWLs were 8.7 m-MSL and 9.8 m-MSL in the coastal and northern zone, respectively (Figure 6.2). In the steady-state, low GWLs of the qp_{2-3} aquifer distributed mainly in the middle zone, especially in some districts (Cau Ke, Tieu Can district) closed a other high GW abstraction area of Soc Trang Province (Figure 6.1). The northern and coastal zone distributed high GWLs about 7 to 8 m-MSL and decreased toward the middle zone.

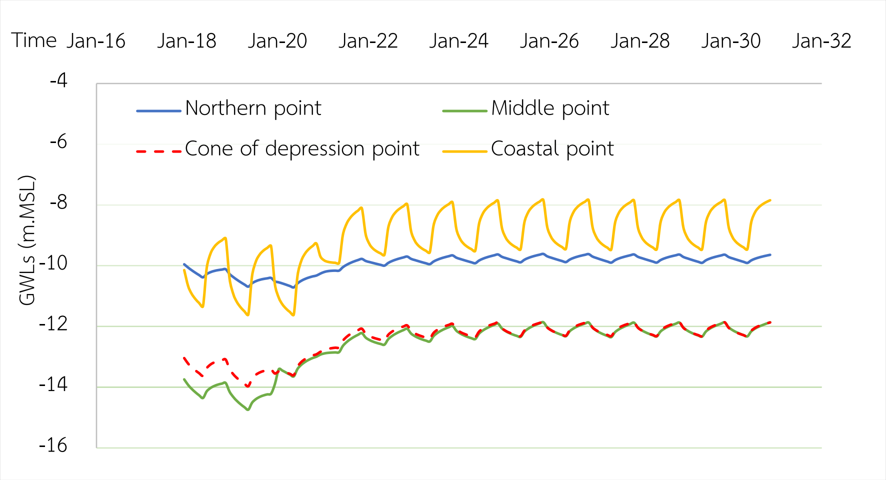


Figure 6.2 - Time series of GWL fluctuation at some points of qp_{2-3} aquifer

The simulation results corresponding to sustainable criterion of equilibrium state were as follows: If the the GW abstraction rate is 195,000 m^3/d since January 2020, the decline in storage has been decreasing and stabilizing since from March 2024 (Figure 6.3). This means that the inflow into the aquifer is in equilibrium with the extraction. This amount of GW abstraction can be called as the “sustainable safe yield” for the aquifers.

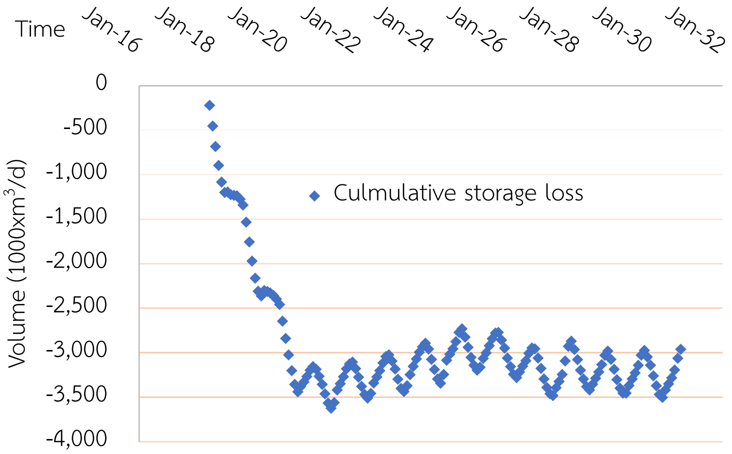


Figure 6.3 - Cumulative storage loss chart of the equilibrium state

6.1.3 Estimation of sustainable yield by criterion of saline controlling

Reducing GW abstraction to reach the equilibrium state also lessened an amount of inflow from the saline source in the north, northeast of the study area and from the coastline. It means the risk of saline movement for aquifers was also reduced. However, the simulation of TDS transportation model presented a large extension of saline GW area (TDS > 1,000 mg/l) in the northern zone and depleted area in the middle zone (Figure 6.4). So as to limit the extension of saline GW in the study area, GW abstraction continued to reduce at some parts along with the fresh/saline interface. By decreasing GW abstraction rate about 20,000 m^3/d in these parts, the area of saline GW was maintained similarly as the one in 2018 for the qp_{2-3} aquifer (Figure 6.5).

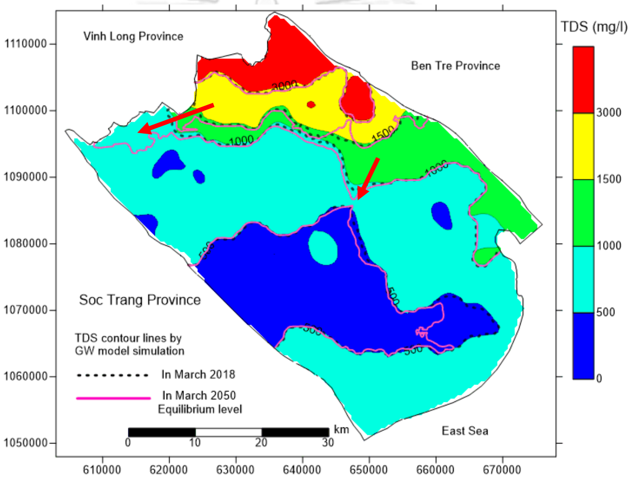


Figure 6.4 - TDS distribution of qp_{2-3} aquifer in March 2030 by in equilibrium state

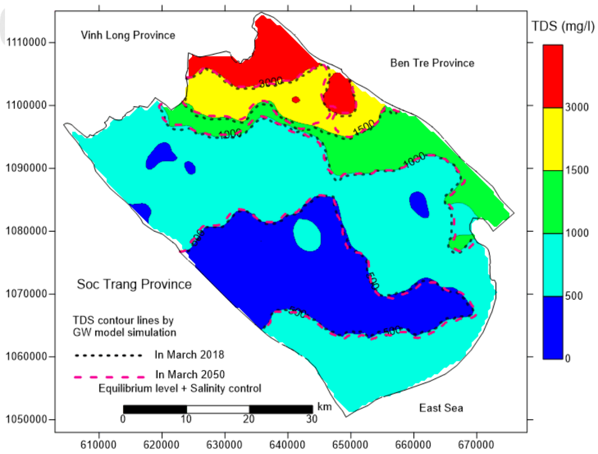


Figure 6.5 - TDS distribution of qp_{2-3} aquifer in March 2030 by in saline controlling

6.1.4 GW balance analysis

The water balance (Figure 6.6) shows that when the volume of GW decreases to about 175,845 m^3/d, the recharge from rainfall and leaky from rivers and streams is almost unchanged; the boundary inflow and change of storage are decreases.

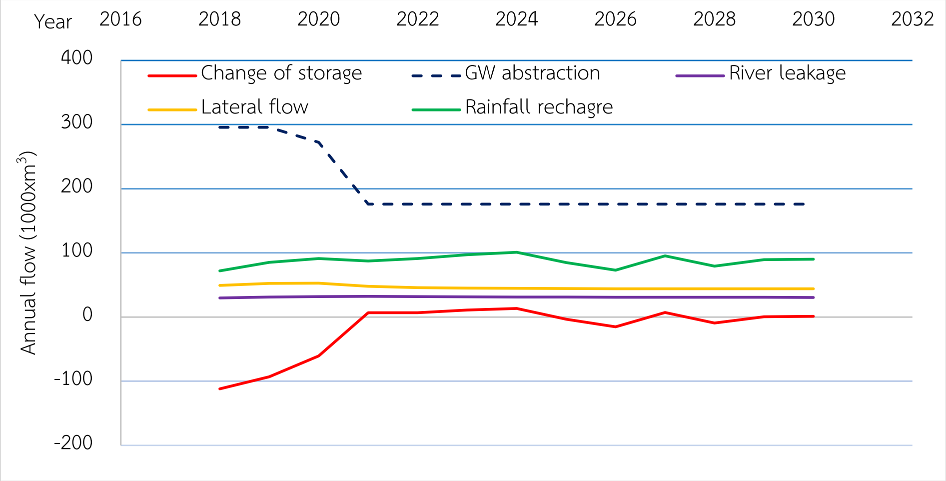


Figure 6.6 - Water budget chart by applying sustainable criteria

The results of the sustainable model show that when the exploitation is reduced equitable for all wells by 34% compared to the current exploitation (corresponding to the exploitation rate is 195,745 m^3/d, the GW system reaches an equilibrium state. The reduced percentage of GW abstraction was 36%, 34% and 32% in the northern, middle and coastal zone, respectively. In order to control saline movement as present, GW abstraction needs to be reduced more in some saline prone areas. In total, 41 % of current GW abstraction needs to be further reduced to limit the saline GW area in 2030 not expand more 5 % than the current one in 2018. The reduced GW abstraction mainly focused on the northern zone with 66 %, and 40 % for the middle zone. There was no decreasing in GW abstraction of the coastal zone due to far distance from the salinity source. See more detail amount of sustainable yields in the Table 6.1.

Table 6.1 - Comparison of sustainable yields and current GW abstraction

Zone	Current GW abstraction (2018)	Sustainable yield estimation			
		Equilibrium state (m^3/d)	Reducing percentage	Saline controlling (m^3/d)	Reducing percentage
Northern zone	24,380	15,711	36%	8,224	66%
Middle zone	213,437	140,485	34%	128,350	40%
Coastal zone	57,977	39,271	32%	39,271	33%
Total	295,794	195,466	34%	175,845	49%

6.2 Estimation of groundwater demand in the future

6.2.1 Estimation of freshwater availability under climate change scenarios

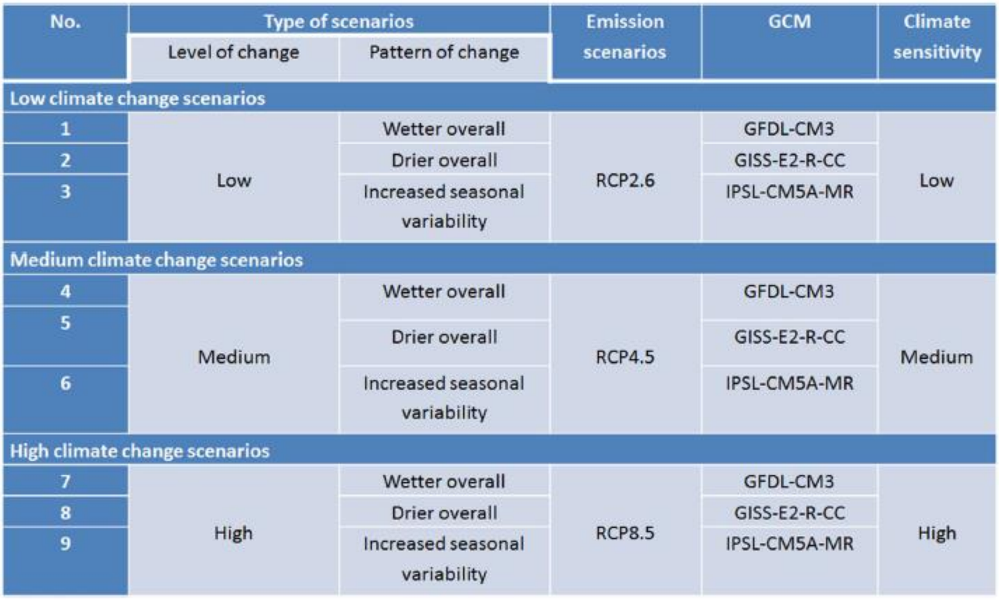
Selection of climate change scenarios

The VMD region locates in one of the highest vulnerable areas by effects of climate change in combination with sea-level-rise over the world (Syvitski et al. 2009, Murray et al. 2012). As the results of the last chapter, GW played a very important role in supplying water for domestic use of Tra Vinh Province. Furthermore, GW was also considered as an alternative source for irrigation due to not available fresh surface water, especially in the dry season. The irrigation demand for GW presented a correlation with availability of fresh surface water during the dry season. So, the application of climate change scenarios needs to represent a range of different climate change projection on the duration of fresh surface water availability in the study area. Three scenarios represent three Global Circulation Models (GCMs) of medium emission of Representative Concentration Pathway (RCP 4.5) for the whole Mekong Basin to 2030 and 2060 (Table 6.2). Three selected climate change scenarios consist of:

- Medium climate scenario is scenario of increased seasonal variability by using GCM model (IPSL-CM5A-MR) and it predicts wetter and drier in wet and dry season, respectively. It is the change simulated from this GCM that is used in the main M3CC simulations.

- Upper climate scenario is scenario of wetter overall as the ‘upper’ bound of projected future impacts by using GCM model (GFDL-CM3) in most of the Lower Mekong Basin (LMB), this model gives a projection of wetter overall conditions).
- Lower climate scenario is scenario of drier overall as the ‘lower precipitation’ bound of projected future impacts by using GCM model (GISS-E2-R-CC). It projects a decrease in wet season flow which it will be a big concern for Mekong River Commission (MRC) member countries);

Table 6.2 - Climate change scenarios for basin-wide assessments (MRC 2017b)



No.	Type of scenarios		Emission scenarios	GCM	Climate sensitivity
	Level of change	Pattern of change			
Low climate change scenarios					
1	Low	Wetter overall	RCP2.6	GFDL-CM3	Low
2		Drier overall		GISS-E2-R-CC	
3		Increased seasonal variability		IPSL-CM5A-MR	
Medium climate change scenarios					
4	Medium	Wetter overall	RCP4.5	GFDL-CM3	Medium
5		Drier overall		GISS-E2-R-CC	
6		Increased seasonal variability		IPSL-CM5A-MR	
High climate change scenarios					
7	High	Wetter overall	RCP8.5	GFDL-CM3	High
8		Drier overall		GISS-E2-R-CC	
9		Increased seasonal variability		IPSL-CM5A-MR	

Projection of the duration without freshwater

The study area locates in the coastal estuaries of the VMD so the freshwater regime is strongly dependent on the inflow from upstream (Dang et al. 2019). Dang 2019 used salinity measures from 1996 to 2017 from 18 monitoring stations throughout the VMD coastal region to explore freshwater regimes the coastal estuaries of the VMD. The study demonstrated that the average discharge at Tan Chau in the dry season (January to May) had a tight relationship (R^2=0.80) with the duration without freshwater at Tra Vinh. Accordingly, when the average dry season discharge at Tan Chau is greater than 5,000 m^3/s, freshwater is available for all days at Tra Vinh. When, the average dry season discharge is lower than 3,000 m^3/s, the duration without fresh water can last 80 days.

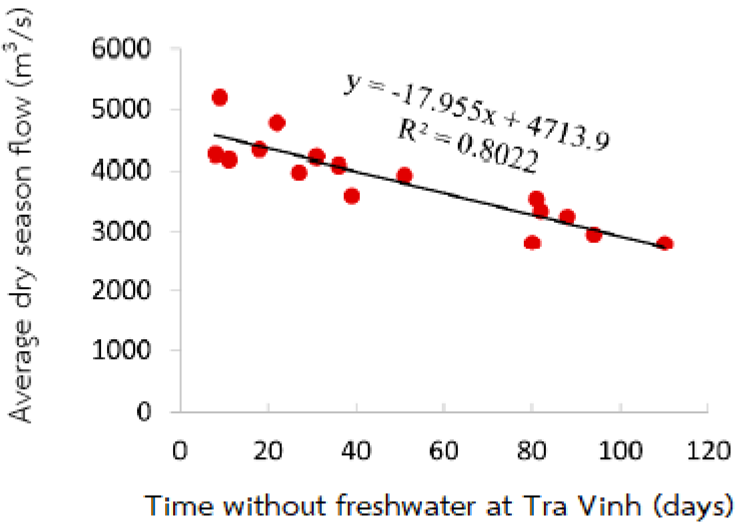


Figure 6.7 - The relationship between mean dry season flow at Tan Chau and the duration without freshwater at Tra Vinh (Dang et al. 2019)

Based on the identified correlations with discharge in upstream (Tan Chau), the duration without freshwater can be predicted in the estuaries (Tra Vinh). The correlated function is converted to estimate the duration without freshwater at Tra Vinh (Dnf) by various projections of the mean dry season flow at Tan Chau ($Q_{dry\text{-}TC}$) as below:

$$D_{nf} = -\ Q_{dry\text{-}TC}*0.0557 + 262.5 \text{ (days)}$$

These results of climate change scenarios show that generally the great impacts in upstream discharge are due to climate change. At the Tan Chau station (Figure 3.3), average dry season flow is projected to change -25%, 8% and 30% compare with base period (1995-2004) for lower, medium and upper of climate change scenarios in the period of 2021 and 2030, respectively.(Table 6.3). The average of dry season flow of base period is 3,729 m^3/s. The study project that in lower precipitation scenario, average dry season flow in Tan Chau will decrease to 2,789 m^3/s in next decade. In medium and high precipitation scenario, it will be 4,027 m^3/s and 4,848 m^3/s, respectively. By projection of upper scenario, there is no days without saline water at Tra Vinh (Figure 3.4) due to high average dry season flow in the next decade (2021-2030). In this period, duration without fresh water is projected as 38 days and 107 days for medium and upper precipitation scenarios, respectively.

Table 6.3 - Estimation of duration without freshwater at Tra Vinh in next decade

Climate scenario	Average dry season flow in Tan Chau (1995-2004) m^3/s	Projected ratio in RCP 4.5 %	Average dry season flow (2021-2030)	Duration without freshwater at Tra Vinh (days)
Lower	3729	-25%	2,797	107
Medium	3729	8%	4,027	38
Upper	3729	30%	4,848	0

6.2.2 Estimation of water demand under socio-economic scenarios

Selection of socio-economic scenarios

Scenarios of socio-economic (SSE) are always considered as an important tool for investigating the consequences of climate change that will impel adaptive strategies (Kriegler et al. 2010). In previous studies, projections of GW demand were developed by increasing or decreasing proportion of current GWU by without linking with any scenarios of socioeconomic (Vuong 2013, Minderhoud et al. 2017, Nam 2017). In this study, SSEs have been applied for estimating GW demand by different purposes and to various zones, typically closely linked with different prediction of climate change.

Total water demand or GW demand of each sector or a certain area is always under the influence of two main components including climate parameter and socioeconomic conditions. Both climate parameter and socio-economic condition vary by spatial and temporal. Change in socio-economic condition includes population growth, land-use change, technologies and institutions. (IPCC AR4). The first SSE was proposed to be business as usual (BAU) that is to are mainly based on the existing tendency of socio-economic conditions in the study area. The BAU scenario is mainly referred from the local plan next 2030 (PPC-TV 2015). The annual average GDP growth rate will reach 9 % during 2021-2025 and 13% during 2026-2030; to restructure the economy in the direction of quickly raising the proportions of industry and services, striving for the target that the proportion of industry - construction, services, agriculture - forestry - fisheries in the GDP will be 28.05%, 33.87% and 38.08% by 2025, and 36%, 34% and 30% by 2030, respectively. In the agriculture sector, rice planting is still the main crop in the next 10 to 15 years, however, the growth rate of expanding aquaculture and forest is intensified 2.5 % per year. The natural population growth rate is maintained at around 4 to 6 % per year. The percentage of poor households will drop 2-3% annually, and by 2030, the percentage of poor households will be equal to the average percentage of the whole VMD region.

Another SSE is applied to follow the strategy of the Mekong Delta Plan (MDP), which aims to sustainable and prosperous development in the far vision of the VMD (MIE 2013). In the MDP scenario, develop strategies is associated with achieving optimum utilization of natural resources, especially is saline water resource. The scenario seems to be under more uncertainty however it can achieve a stipulated level or value in the objective of sustainable development. Apart from the effectiveness in government incentives, the plans on land and water resources are the key to success of this socio-economic scenario.

By following the MDP, Tra Vinh Province is targeted to have a new land structure to maximize the efficiency of saline water resource of a coastal province (Figure 6.8). Mangrove forests are proposed to protect against storm surges and to create a healthier brackish water environment. Integrated shrimp and fish farming, in addition to renewable energy production in mangroves would be encouraged, as opposed to exclusively shrimp farming. Restoration of coastal mangrove belts would include the planting of numerous native species, including many plants with uses and applications in medicine. As a low growth rate of the population was considered in this scenario based on the official Vietnam projections and current trends. In the MDP scenario, the population is projected to be around 30 million in 2030 and then rapidly decrease to 15 million in 2050.

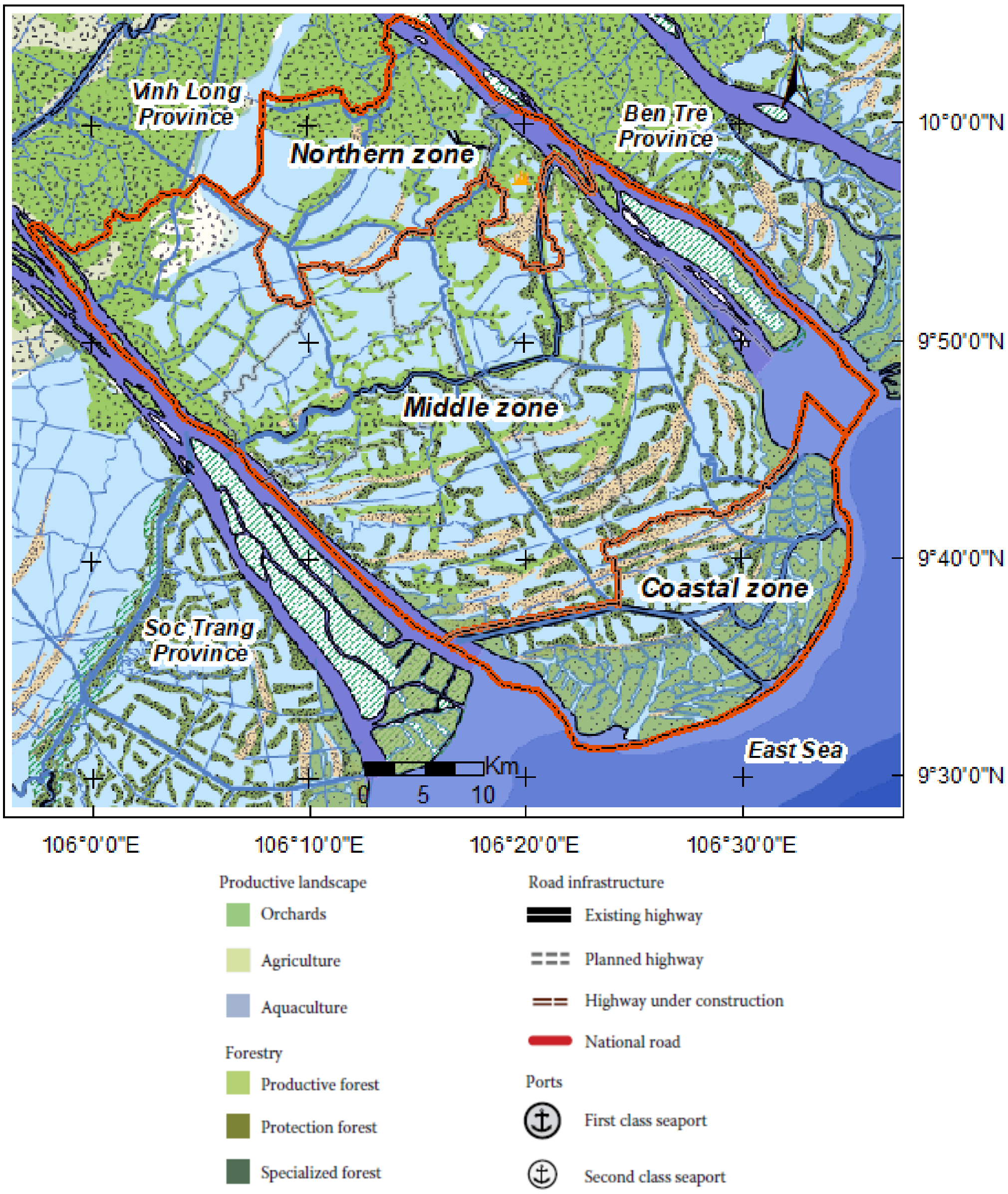


Figure 6.8 - Extract of land use planning of Tra Vinh Province from the MDP

Projection of population growth and land use change

The population of the province is projected to increase by 1.46 million and 1.06 million persons in the next 10 years by BAU and MDP scenarios, respectively. The growth rate was assumed to be the same for all three zones (Table 6.4). There was a difference in changing proportion between agricultural production and aquaculture land. While the BAU scenario showed a lightly increasing percentage of agricultural production land from 62 to 67%, aquaculture land proportion reduced from 13 % to 11% by 2030. In contrast, aquaculture land was expanded significantly and occupied to 20% total land area, especially the model of aquaculture-forest was planned to be 11 % (Figure 6.8). The other kinds of land use showed a small percentage and change by 2030.

Table 6.4 - Population projections by two scenarios

Zone	Population (person)		
	Baseline (2018)	BAU	MDP
Northern zone	254,700	379,500	268,000
Middle zone	684,200	909,500	687,000
Coastal zone	105,100	177,500	105,000
Whole province	1,044,000	1,466,500	1,060,000

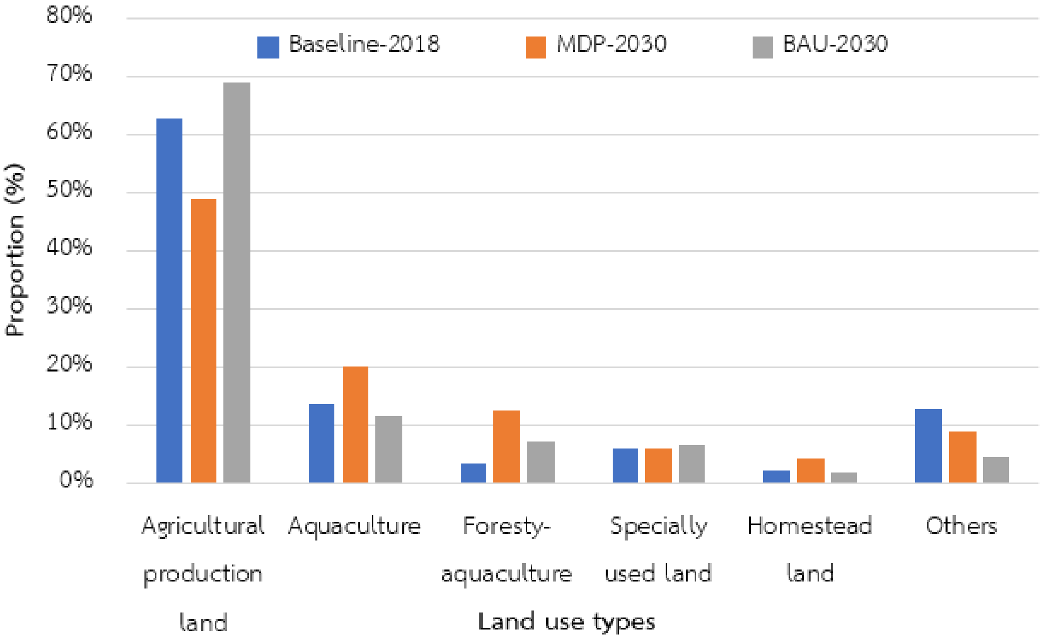


Figure 6.9 - Land use projections by proposed scenarios

Water demand estimation

In the study area, the users of water consist of domestic, industry, rice planting, other crops, livestock, and aquaculture. The calculated water needs were made for northern, middle, and coastal zones. The results have been calculated using statistical data in

2018 and projected data in 2030. The water demand was calculated for categories: domestic, industry, agriculture (food crops, other crops, livestock) and aquaculture. Where:

- The water demand is estimated for food, annual and perennial crops by using the irrigation guideline (TCVN 8641:2011).
- The water demand is estimated for livestock by using the drinking standard for livestock (TCVN 4454-1987)
- The water demand is estimated for freshwater aquaculture by assuming 21,250 m^3/crop (interview and calculation)
- The water demand is estimate for domestic activities by following water supply standard for the VMD until 2030 (No.2140/QD-TTg)
- The water is estimated for industry by following the standard of indutrial water demand (TCXDVN33:2006), accounted fro 25-45 m^3/ha/day

Figure 6.10 illustrates the estimation of 6 categories of water demand in Tra Vinh Province in the dry season of 2018. In particular, food crops are the largest using sector of water, accounting for 81%, which was followed by other crops including annual, perennial crops and orchards at 15% (Figure 6.10). Domestic requires about 104,000 m^3/d of water supply. And only 1% of total water demand consisted of industrial use due to a small proportion of this sector in the study area (Figure 6.10).

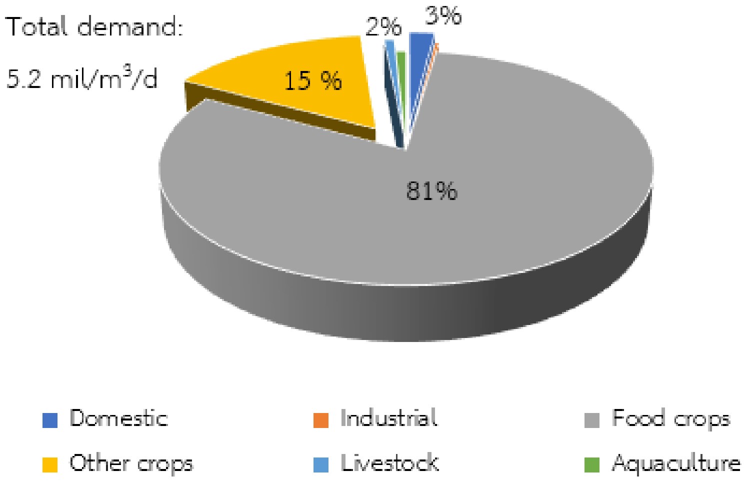


Figure 6.10 - Average water demand of Tra Vinh Province in dry season, 2018

The changes in water demand of three zones by different socio-economic scenarios for the next decade since 2021 is shown in Figure 6.11. In general, all three zones except hobbies book showed a rising trend in water demand over the period by BAU scenario. The increasing water demand of the middle zone is the highest due to expanding of food crop area in this zone while those of the northern zone was the lowest. In particular, water demand projection by BAU scenario in the dry season of 2030 will be 1.1 mil.m^3/d, 5.6 mil.m^3/d and 0.22 mil.m^3/d for the northern, middle coastal zone, respectively (Figure 6.11).

In contrast, water demand (WD) projections by MDP scenario showed a similar pattern of a decrease. The northern zone will decline slowly from around 1.08 mil.m^3/d in 2018 to just under 0.5 mil.m^3/d in 2030 while that for middle and coastal zone went through a similar declination from approximately 4.2 mil.m^3/d to 1.6 mil.m^3/d and 0.17 mil.m^3/d to 0.08 mil.m^3/d in the same period (Figure 6.11). The main reason of significant decrease in water demand of three zones are changing of food plant to other crops as saline/brackish aquaculture, forest and salt-tolerance crops with much lower demand of freshwater.

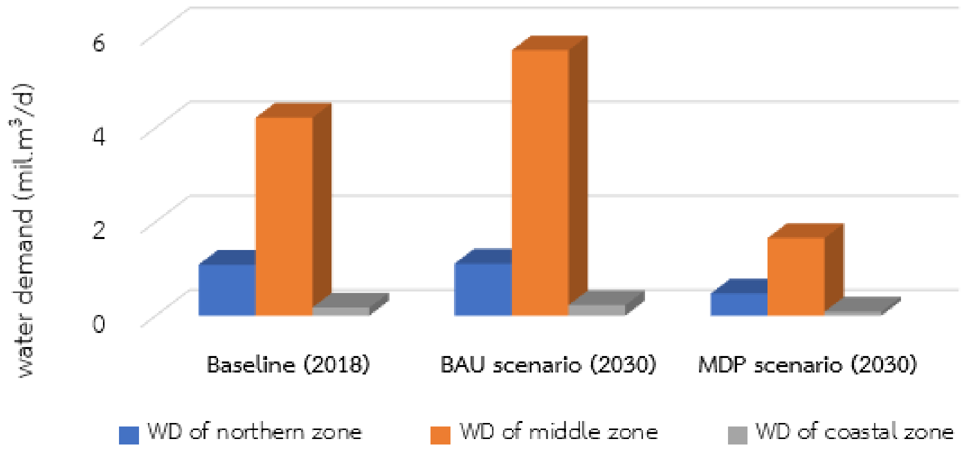


Figure 6.11 - Water demand projections by different scenarios.

6.2.3 Groundwater demand estimation

Proportion of GWU

In order to estimate GW demand, proportion of GWU in the dry season is defined by two categories of water demand. The first category includes domestic and industrial demand which is projected by considering proportion of GW demand equal ratio of

GWU for domestic in the base year (2018). GW is assumed to occupy 44%, 67% and 87% total water demand of domestic and industry in next decade for northern, middle and coastal zone, respectively. The second category are agricultural and aquaculture water demand in which the estimation of GW demand does not cover water demand for food crops (mainly paddy planting) due to strong dependence on surface water supply of these crops. If the dry season is considered from 1 January to 31 May, the proportion of GW for these demands in the middle and northern zone is estimated by comparing the duration without freshwater at Tra Vinh and the whole dry season (151 days).

In the next decade, 71%, 25% and 13% of these demands are GW demand by lower, medium and upper scenarios for the middle zone (Table 6.5). The percentage of the northern is assumed by a half of the middle zone due to around 50% of northern zone can access to fresh surface water throughout the year. In the coastal zone, the whole dry season is considered to depend completely on groundwater so the proportion of GW demand is 100 % (Table 6.5).

Table 6.5 - Identification of GW demand proportion

Zone	Proportion of GWU in dry season				Ratio of GWU in wet season/dry season (%)
	In domestic and industrial demand	Agriculture and aquaculture demand (except food crops)			
		Lower scenario	Medium scenario	Upper scenario	
Northern zone	44%	35%	13%	6%	54%
Middle zone	76%	71%	25%	13%	63%
Coastal zone	87%	100%	100%	100%	74%

Table 6.6 shows the results of the baseline/future scenario for the GW demand. In general, the baseline of GW demand in 2018 shows a higher value than the GWU estimation base on the survey data for all three zones. Total GWU estimation in Tra Vinh Province occupies was 86% of that of GW demand estimation in the base year (2018). Besides, two scenarios of socio-economic development (water demand estimation) and three scenarios of climate change (duration of available freshwater) are combined to carry out 6 scenario of groundwater demand. In general, GW demand is projected much higher in BAU scenarios than MDP scenarios. It can be observed that among 6 scenarios, the highest GW demand for the Tra Vinh Province is presented by lower climate scenario in considering development of socio-economic as usual (BAU scenario), accounting about 73.7 mil.m^3 and the smallest one is only 22.7 mil.m^3 by following the MDP and expectation of upper climate model (Table 6.6). In next decade, GW demand is distributed mainly in the middle zone, represents more than 60% of total GW demand of the study area for all scenarios. By following MDP scenario, GW demand shows a declination in the coastal zone from 13.8 mil.m^3 in 2018 to 7.5 mil.m^3, 4.9 mil.m^3 and 3.7 mil.m^3 by lower, medium and upper climate scenarios, respectively (Table 6.6).

Table 6.6 - Projections of average dry season GW demand in next decade

Zone	GWU estimation in 2018	Average annual groundwater demand in next decade (mil.m^3)						
		Baseline in 2018	Business as usual (BAU)			Following Mekong Delta Plan (MDP)		
			Lower	Medium	Upper	Lower	Medium	Upper
Northern zone	2.8	4.3	6.4	5.5	4.3	4.5	3.7	3.1
Middle zone	28.5	31.1	53.0	34.2	32.6	32.1	16.8	15.9
Coastal zone	10.6	13.4	14.2	12.3	11.4	7.5	4.9	3.7
Total	**41.8**	**48.8**	**73.7**	**51.9**	**48.3**	**44.2**	**25.3**	**22.7**

6.2.4 Gaps in groundwater supply to cope with sustainable yield

GW seems to be required more in the next decade by various scenarios of climate change and socio-economic development. The difference between the sustainable yield of the aquifer system and GW demand projections carry out the gaps of GW supply in the future. Based on that, the alternative method of water supply will be proposed to fulfil these gaps to meet sustainable yield. Table 6.7 shows significant comparison of gaps in GW supply by different scenarios of Tra Vinh Province in next decade. In term of considering development of socio-economic as usual in next decade, sustainable yield of the aquifer system can only satisfy less than 50% in three zones for all three climate scenarios. Proportion of gaps of GW supply by three CC scenarios are 70%, 58% and 55% for lower, medium and upper climate scenarios, respectively (Table 6.7). The northern zone also shows a high percentage in gaps of GW supply (75% on average) in case of following the projections of Mekong Delta Plan. However, sustainable yield of the aquifer system is closed with GW demand in the coastal zone, accounting only 4% in proportion of gap of GW supply. GW demand projections by medium and upper climate scenarios are evenly higher than 5% and 29% of sustainable yield in the coastal area (Table 6.7). Overall, it is important to note that, in next decade, proportion of gaps of GW supply will increase significantly in BAU scenarios and in contrast with MDP scenarios.

Table 6.7 - Projections of gaps of GW supply in next decade

Zone	Sustainable yield (m^3/d)	Gaps in GW supply (m^3/d)					
		Business as usual (BAU)			Following Mekong Delta Plan (MDP)		
		Lower	Medium	Upper	Lower	Medium	Upper
Northern zone	8,224	85%	82%	78%	79%	74%	69%
Middle zone	128,350	70%	54%	52%	51%	6%	1%
Coastal zone	39,271	64%	58%	55%	32%	-5%	-40%
Total	175,845	70%	58%	55%	51%	14%	4%

6.3 Findings

The concept for sustainable yields in both quantity and quality, in the long run, was determined by equilibrium state and maintaining of the distribution of fresh GW. The results of the sustainable model indicate that the current annual GW abstraction (2018) needs to be reduced 49% (175,845 m^3/d) (Table 6.1) to cope with sustainable yield of the aquifer system in Tra Vinh Province in the next decade (2021 - 2030).

GW demand in dry season is projected to increase in BAU scenarios, however, the rate of GW demand is projected to be reduced significantly under DAM scenarios (Table 6.6). By the end of next decade, annual GW demand simulated under MDP scenarios is expected to be about 37.6 mil.m^3 with expectation of high precipitation, accounting less than by nearly 21.7 mil.m^3 in comparison with the one of 2018 (Table 6.6). Comparing between sustainable yield and GW demand, gaps of GW supply almost need to be filled throughout to meet sustainable yield in the next decade under all scenarios, except only following the change of Mekong Delta Plan (MDP scenario) and expectation of wetter climate in the next decade.

CHAPTER 7 - PROPOSED ADAPTIVE MEASURES FOR SUSTAINABLE GROUNDWATER DEVELOPMENT

This chapter aims to propose adaptive measures with additional guidelines from governmental proposal and reviews. First, from the reviews, the adaptive measures for sustainable GW development were separated by three aspects as supply, demand and management. For supply sided, a review of water supply plans was identified by location, capacity and purpose assess how much gaps of groundwater (GW) supply can be reduced. The key idea is in the demand side with an application of the Fogg Behavior Model (FBM) to analyze the different distribution of behavior factors in term of changing agricultural activities to cope with climate change. Adaptive Behavior Models are conducted and applied to propose additional recommendations each zone to cope with sustainable development of GW. For the management side, design of GW monitoring networks of both quantity and quality was proposed to improve management ability of the government and local authorities.

7.1 Review of adaptive measures for GWU

GW is an essential source of freshwater, is an important water supply source for domestic and agricultural activities in Tra Vinh Province. However, GW resources are being rapidly used up at an alarming and unsustainable rate, accounting over 34 %. Reduced precipitation and combined with GW over-exploitation are having direct impacts on aquifers recharge, discharge, storage and saline movement. These circumstances call to adaptive strategies from not only groundwater users but also government or stakeholder with the preservation and sustainable management of GW resources. These circumstances call to adaptive strategies from not only GW users but also government or stakeholder with the preservation and sustainable management of GW resources.

In one hand, it is important to improve the conservation of groundwater reservoirs, limiting water use and optimizing water reuse first. The Mekong Delta Plan (MIE 2013) is considered as an adaptive measure to reduce freshwater demand. In the study area, land use is planning to change to saline aquaculture and combined with mangrove or production forest in the coastal zone (Table 7.1). On the other hand, annual crops are shifted to salt-tolerant crops. The average dry season GW demand can be reduced in a range of 44% and 72% in comparison with the baseline (2018) by next decade. For the middle and northern zone, the average dry season GW demand also shows a significant declination due to agriculture restructuring, accounting by 12% and 31% on average in next decade, respectively.

In the supply side, this shall be pursued through an integrated approach to water management also considering alternative sources of freshwater. Complementary to this, the availability of Managed Aquifer Recharge (MAR) (Dillon et al. 2009, Ngo et al. 2015) to restore and even increase the natural infiltration capacity of freshwater into the aquifer is growing, including rainwater harvesting (collection and store of rainwater otherwise lost due to runoff) and use of river water (Table 7.1). The study area should have solutions to store water by ponds or canals and wait for the rain to start the crop (Table 7.1). This solution is planned to apply in the northern and middle zone due to the more availability of freshwater in these zones. While MAR should be implemented in sand dunes area of coastal with high potential of recharge and reduce the risk of saltwater intrusion into aquifers in the future (IUCN 2010).

For management side, monitoring is anyhow required to assess the compliance with normative standards (van Bracht et al. 1985, Zhou et al. 2013). In Tra Vinh Province, GWLs have been monitored since 1994 as the groundwater started to be exploited in the VMD. Currently, there are only six groundwater monitoring stations consisting of 13 monitoring wells (Figure 5.13) operated by the National Center of Water Resources Planning and Investigation (NAWAPI) to observe both quality and groundwater level of different aquifers in Tra Vinh Province. The existing GW monitoring network can't provide a comprehensive overview of movement in both GW quality and quantity, so it leads to a considerable shortcoming in the overall management cycle of the study area. A design preliminary monitoring networks for groundwater level and salinity monitoring need to be proposed in Tra Vinh Province to provide important information required for managing and developing the sustainability of the groundwater resource (Table 7.1).

The GW system is greatly impacted by location-specific land use in the study area. By restructuring of land use in the study area, GW demand could cope with a sustainable yield of the aquifer system in next decade. However, not the entire local communities will change their current agricultural activities to follow the design of the new system. In term of persuading, the incentive and training require a wide understanding of adaptive behavior of local people due to changing agricultural activities to cope with climate change impact in the past (Table 7.1).

Table 7.1 - Summary of adaptive measures for sustainable GW development

Zone	Review adaptive measures for sustainable GW development		
	Supply side	Demand side (following MDP)	Management side
Northern zone	1. Store water by ponds/canals 2. Divert surface water from upstream	1. Change to perennial crops 2. Change tolerant crops and orchards	1. Design of monitoring networks (GWLs and salinity) 2. Additional incentive and training
Middle zone	1. Store water by ponds/canals 2. Divert surface water from upstream 3. Managed Artificial Recharge (MAR)	1. Change to saline aquaculture 2. Change to aquaculture-forest, orchards	1. Design of monitoring networks (GWLs and salinity) 2. Additional incentive and training
Coastal zone	1. Store water by ponds/canals 2. Managed Artificial Recharge (MAR)	1.Change to saline aquaculture 2. Change to aquaculture-forest, mangrove forest	1. Design of monitoring networks (GWLs and salinity) 2. Additional incentive and training

7.2 Reduction of gaps of GW water supply

During dry season, the increasing frequency of drought and water shortage in the Tra Vinh Province tracks closely to the increasing the disputes and conflicts in water utilization in the upstream of Mekong Delta. A range of gaps of GW supply to cope with the sustainable yield varies by different scenarios of socio-economic development and climate change (section 6.2.3). In order to reduce these gaps, Vietnamese government and local authorities plan alternative methods of water supply for domestic and agricultural activities to reduce pressure on the GW system. In order to expand alternative sources of water supply, the government planned to construct couple storage ponds in northern and middle zone to reduce a portion of water shortage or gaps of GW supply in the estimation of this study. Two ponds include:

- Don Chau Pond: The pond locates in Don Chau commune of Tra Cu district with its surface covering 299 ha. The pond can store 5,220,000 m^3 to supply water for domestic use and irrigation of coastal zone (Duyen Hai district) and some districts of the middle zone (Tra Cu, Cau Ngang district) about 4 to 5 months of the dry season. This pond will reduce the pressure on increasing GW abstraction during the dry season in the middle and coastal zone.
- Lang The pond: The pond locates in the northern zone (Tra Vinh city) with its surface 38 ha. The pond volume is around 1.9 million m^3, with the main purpose to replace a proportion of GW supply for domestic water in Tra Vinh city.

In addition, managed aquifer recharge (MAR) is also proposed in the coastal zone to ensure adequate supply water for domestic use in this zone. Furthermore, MAR also has a role to maintain salinity concentration of GW due to risk of saline intrusion. In case of successful implementation of storage ponds or MAR, GW abstraction can meet sustainable yield of the aquifer system in the DAM scenario. In term of the BAU scenario, reducing percentages of GW are 15%, 5% and 15% in the northern, middle and coastal zone, respectively. See more detail in Figure 7.1.

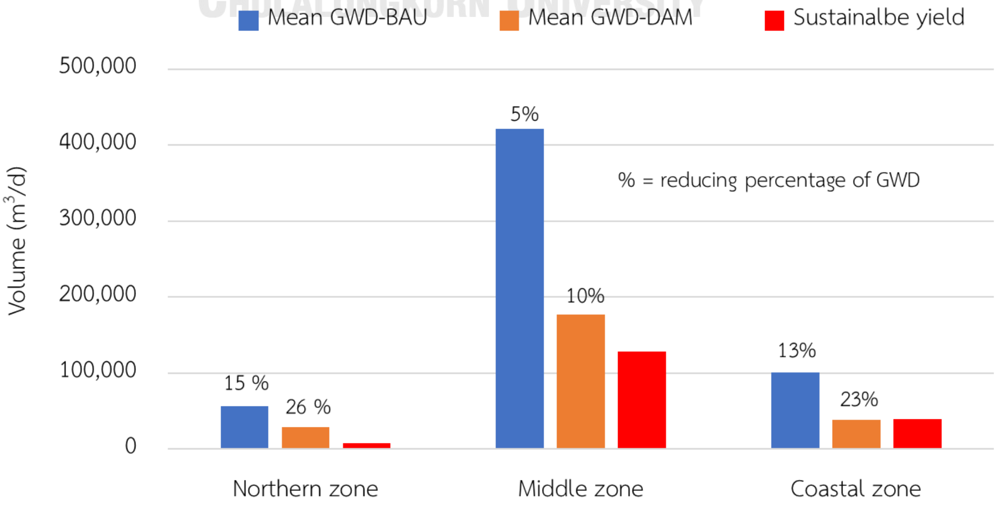


Figure 7.1 - Additional water supply plan and reducing proportion

7.3 Behavior analysis of climate change adaptation

7.3.1 Natural conditions of climate change adaptation

The covering/land use area statistical classification and results in Tra Vinh Province, Vietnam in 2000 and 2015 are shown in the Figure 7.2. In 2000, the rice cultivation and aquaculture seafood area accounting for 51% and 10% total province area, respectively. In addition, the paddy land and aquaculture areas mainly attributed in the lowlands. Total rice area decreased from 108,711 hectares to 89,790 hectares in 2000 and 2015, respectively. From Figure 7.2, it can be seen that the wet cultivation area dropped to 42% while aquaculture area increased to 13% of province area. From 2000 to 2015, the perennial crops are slightly increased from 31% to 33%.

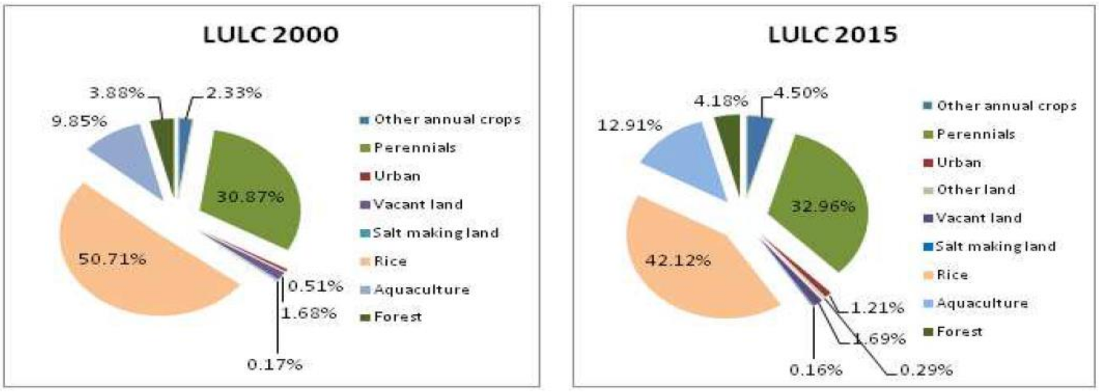


Figure 7.2 - Structure of the Land Cover/Main Land use in 2000 (left), 2015 (right) in Tra Vinh Province

7.3.2 Analysis of surveyed data

Based on the survey results, there was 44% of total respondent changed their own agricultural activities to others in the whole province. Another 44% and 11% were non-changing agricultural activities and changing to off-farm, respectively. The coastal zone showed a highest percentage of changing agricultural activities, about 55%. While people used to maintain their own agricultural activities, occupied only 58 % instead changing to other ones, approximately 28%. See detail in Table 7.2.

Table 7.2 - Statistics of local people’s decision in CC adaptation

Zone	Total surveyed HH	Changing agricultural activities		Non-changing agricultural activities		Changing to off-farm	
		Number of surveyed HH	%	Number of surveyed HH	%	Number of surveyed HH	%
Northern zone	140	69	49%	63	45%	8	6%
Middle zone	139	39	28%	81	58%	19	14%
Coastal zone	140	77	55%	44	31%	19	14%
Total	419	185	44%	188	45%	46	11%

7.3.3 Development of adaptive behavior models

The farmers are more likely to concern about market price than other motivation factor. In other words, the market input/output is main constraint to farmer’s decision to change or not change their own agricultural activities. The strength of belief in the reality of climate change impact can motivate farmer’s decision. Access to available water supply is main factor of ability group, it occupied 90 % of total surveyed respondent. If farmers cannot see a stability in accessing water supply, most of them don’t change their own agricultural activities. Nowadays, access to information of climate change or adaptive measures seems to be not a big issue. Farmers can access this information via internet, TV, friends and propaganda by local authorities. Access to new technologies and capital showed a close percentage of total surveyed respondent, around 75 %

Table 7.3 - Estimation of behavior coefficient

Zone	Motivation coefficient		Ability coefficient			
	a_1	a_2	b_1	b_2	b_3	b_4
Northern zone	0.48	0.52	0.23	0.28	0.31	0.20
Middle zone	0.44	0.56	0.17	0.30	0.31	0.22
Coastal zone	0.40	0.60	0.17	0.30	0.35	0.16

In the northern zone

Figure 7.3 show the scattered plots of motivation and ability factors in the northern zone. It indicates that a separated distribution of variation farmer's decision by changing or non-changing their agricultural activities (trigger point) can be explained by significant variables of behavior factors. Motivation weight is divided by three levels including low motivation, moderate motivation and high motivation. For surveyed respondent with low motivation, the decision was to not change their own agricultural activities to adapt to climate change impact although ability shows a high value (0.7 to 1) in some surveyed respondent (Figure 7.3). There is a separated decision-making in term of changing or non-changing agricultural activities by the moderate motivation group. In case of changing agricultural activities, ability weight shows a range of 0.69 to 1, except only two surveyed respondents (Figure 7.3). The range represents for respondents which can be easy to access irrigation, capital and additional technologies or climate change information. With ability weight lower than 0.6, there is only two surveyed respondents decided to change their agricultural activities for moderate motivation group. Only four respondents show high motivation in the northern zone decided to not change their agricultural activities due to low ability weight (Figure 7.3). In other words, these respondents can’t access to any ability component or only access to capital/credit.

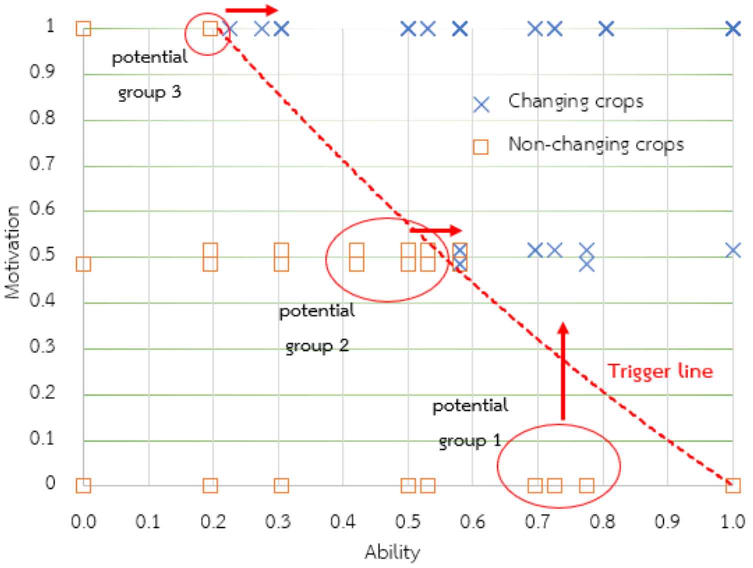


Figure 7.3 - Adaptive behavior model of changing or non-changing agricultural in the northern zone

In the middle zone

Figure 7.4 shows the scattered plots of motivation and ability factors in the middle zone. It indicates that a separated distribution of variation farmer's decision by changing or non-changing their agricultural activities (trigger point) can be explained by significant variables of behavior factors in this zone. This zone shows a lower number of surveyed respondents who changed their agricultural activities to cope with climate change impact than the northern zone. These respondents also show a range of ability weight between 0.6 and, except only five respondents with high motivation and one respondent with moderate motivation (Figure 7.4). There is only one respondent with changing the agricultural activities under low motivation. For moderate motivation group, more than a half of surveyed respondents can only access to one or two ability components including (assess to climate change information, access to technologies, access to irrigation and access to capital/credit). (Figure 7.4) It can lead to their decision to not change their agricultural activities to cope with climate change. The remaining respondents carried out the decision to change their agricultural activities due to availability of climate change information, technologies, and irrigation (0.7 to 0.85 of ability weight) (Figure 7.4).

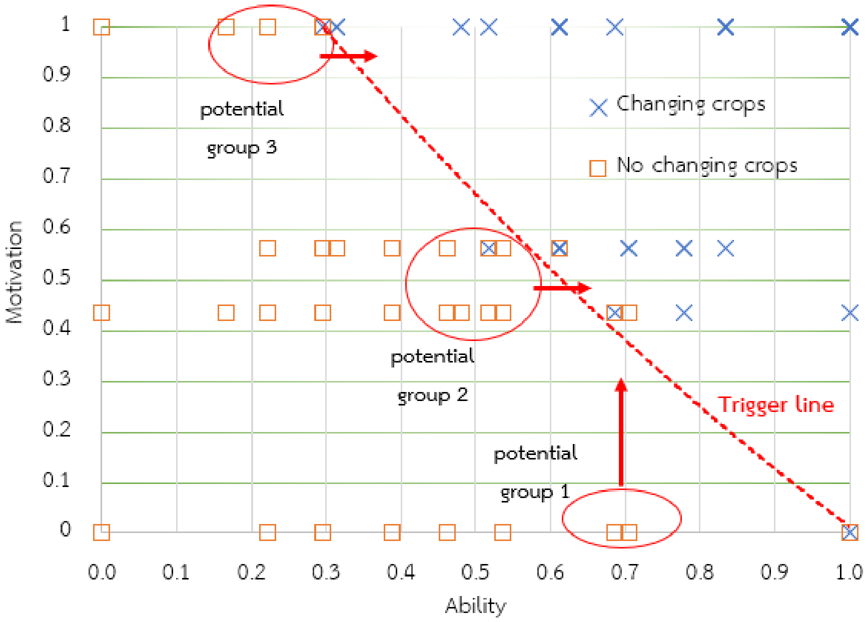


Figure 7.4 - Adaptive behavior model of changing or non-changing agricultural in the middle zone

In the coastal zone

Figure 7.5 shows the scattered plots of motivation and ability factors in the coastal zone. It indicates that a separated distribution of variation farmer's decision by changing or non-changing their agricultural activities (trigger point) can be explained by significant variables of behavior factors in this zone. The coastal zone also presents a highest number of respondent (Table 7.2) in term of changing agricultural activities to cope with climate change in the past. Similar in the northern zone, respondents did not change their agricultural activities with low motivation for the coastal zone. For high motivation group, three respondents do not change their agricultural activities due to low ability weight (less than 0.3) (Figure 7.5). It means these respondents can access to only one ability component (climate change information or technologies or capital/credit). Other remaining respondents in high motivation group can access at least two ability components, and it led to the decision of changing their agricultural activities. Most of respondents with moderate motivation changed their agricultural activities if they can access to irrigation and technologies or more than that (ability weight is higher than 0.6), except only a respondent with ability weight lower than 0.6 (Figure 7.5). Other respondents who can’t access irrigation or technologies, do not change their agricultural activities, accounting by ability weight lower than 0.5 (Figure 7.5).

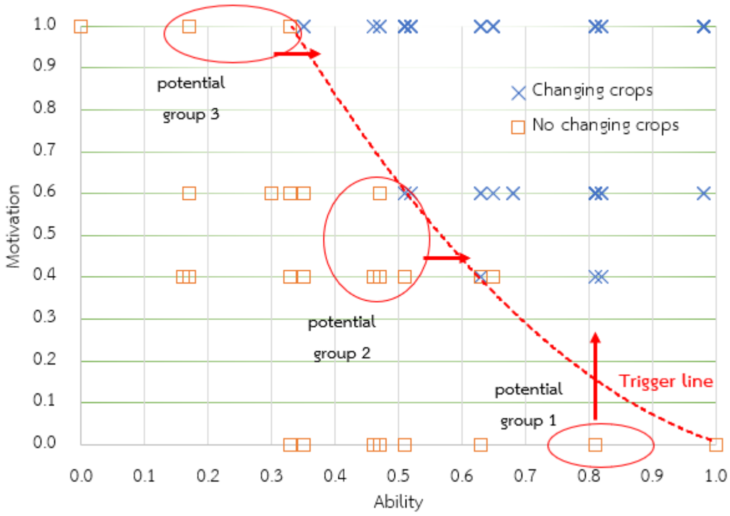


Figure 7.5 - Adaptive behavior model of changing or non-changing agricultural in the coastal zone

7.3.4 Additional recommendations from ABM

However, most of the respondents show moderate motivation and varies of ability weight in all three adaptive behavior models (ABM). In order to be more successful in the implementation of the Mekong Delta Plan (MDP) with many changes of agricultural activities, additional recommendations need to be proposed for each specific zone. For each zone, the recommendations focus on three potential groups which distribute closely with trigger lines. The first group is defined by low motivation and high ability. For all three zones, this group need to be improved awareness of climate change impact and sustainable effectiveness of new crop planning by demand or price of crop products. The second group is defined by moderate invitation and moderate ability. In the coastal and middle zone, respondents in this group used to face issues with irrigation water and capital/credit. In order to bring this group passing trigger lines of ABM, it should add more ability to make the decision in changing agricultural activities by ensuring the supply of irrigation water and supporting bank loans. In the northern zone, paddy was changed to perennial plants and orchards by a large proportion of this zone for long term ago, so farmers show a habit with existing agricultural activities. There is also a gap in knowledge of new technologies of the respondents in the second potential group. Therefore, by conduct more meeting or training about new technologies or new crops, ability weight of this group can be improved to move this group passing the trigger line. It means respondents of this group can change their decision to follow the MPD if they can have more training or guideline to apply new technologies on different agricultural activities. The third potential group is defined by high motivation and low ability. In general, respondents of this group are much easier to adjust their decision. With high motivation, respondent of this group needs to be only supported only one or two resources to bring their behavior target (changing agricultural activities) to successful part of ADMs. In the middle and coastal zone, government or local authorities should pay more attention on reducing shortages of irrigation water and productive support credit to make farmers feel easier to make the decision to change to other agricultural activities. In addition, it is essential that information of climate change and new technologies need to be supported more frequency in the northern zone in term of persuading farmers to change their agricultural activities.

Table 7.4 - Additional recommendations via behavior analysis

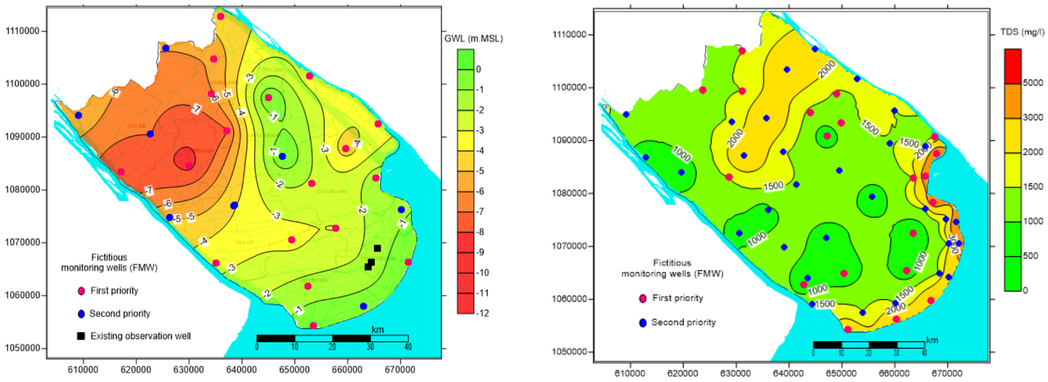
Zone	Additional recommendations		
	Potential group 1	Potential group 2	Potential group 3
Northern zone	Disseminate widely effect of climate change Ensure outcomes of new agricultural products	Conduct more training, guidelines of new technologies in different agricultural activities	Update timely information of climate forecast
Middle zone	Disseminate widely effect of climate change Ensure outcomes of new agricultural products	improve capacity of irrigation water supply & productive support credit	improve capacity of irrigation water supply & productive support credit
Coastal zone	Disseminate widely effect of climate change Ensure outcomes of new agricultural products	improve capacity of irrigation water supply & productive support credit	improve capacity of irrigation water supply & productive support credit

7.4 Design of GW monitoring network

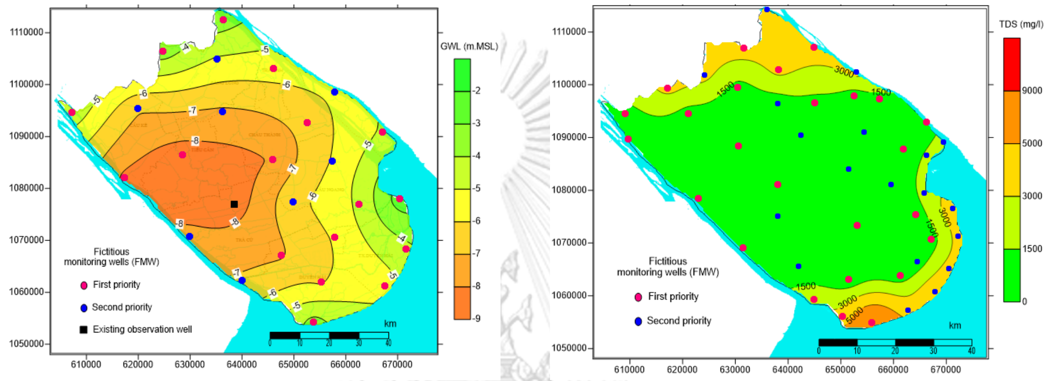
In order to improve sustainable yield management, preliminary monitoring networks for GWLs and salinity monitoring are designed for three shallowest aquifers in Tra Vinh Province. The GW flow and salinity transport models are applied to produce contour maps of GWLs and TDS distribution for three important aquifers in a coastal province of Mekong Delta due to limitation of actual observations. Secondly, maps of GWL and salinity distribution are used to select locations and numbers of monitoring points based on monitoring criteria. Kriging interpolation method is applied to reproduce GWL and TDS contour maps based on the proposed monitoring networks. Kriging standard deviation was also used to evaluate proposed monitoring network as wells. Finally, a priority list of monitoring wells are recommended for monitoring network implementation and management.

Through a number of trial-and-error iterations, the final selected monitoring wells are 24, 25 and 25 for the Holocene aquifer (qh), Upper Pleistocene aquifer (qp_3) and Upper-Middle Pleistocene aquifer (qp_{2-3}), respectively. The developed contour maps of GWLs by Kriging method show a similarity with the simulated map of GW flow model (Figure 7.6). The standard deviation of interpolation error (KSD) is less than 1.0 at most areas. Therefore, these selected monitoring wells consist of a good preliminary GWL monitoring network for Tra Vinh Province

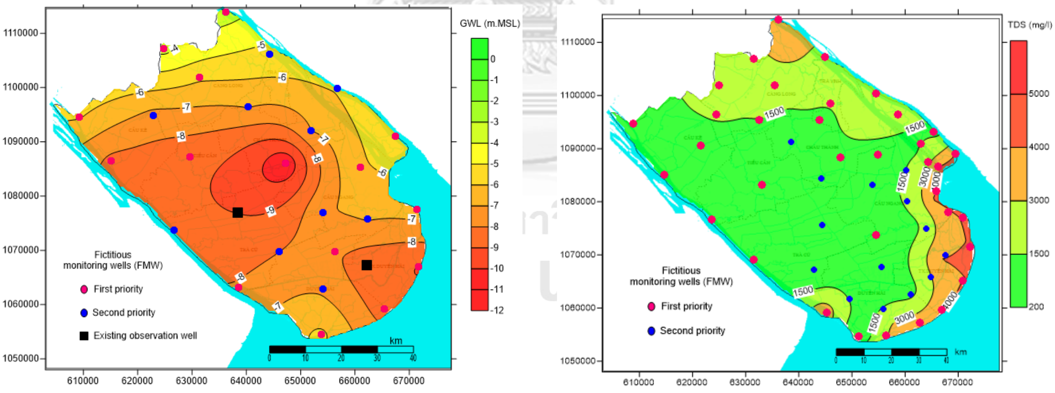
The developed contour maps of TDS by Kriging method show a similarity with the simulated map of the MT3DMS model (Figure 7.6). Through a number of trial-and-error iterations, the final selected monitoring wells are 44, 46 and 45 for the Holocene aquifer (qh), Upper Pleistocene aquifer (qp_3) and Upper-Middle Pleistocene aquifer (qp_{2-3}), respectively (Figure 7.6). In most areas, the standard deviation error of Kriging interpolation (KSD) is lower than 500 mg/l in qp_3 and qp_{2-3} aquifers, and more than 1,000 mg/l in large areas in the Holocene aquifer due to heterogenous distribution of fresh/saline of this aquifer. However, this aquifer accounts for less than 8% total GWU of the Tra Vinh Province, a high error of Kriging interpolation can be accepted. Therefore, these selected monitoring wells consist of a good preliminary salinity monitoring network for Tra Vinh Province. Since installation of GW monitoring wells is very costly, so monitoring wells were divided in two priority categories following monitoring criteria to be more efficiently implemented (Figure 7.6). For GWL monitoring network, the focus areas is depleted cones and boundary areas. For salinity GW monitoring network, the focus areas are transition zones between fresh/saltwater and seawater intrusion areas.



a) Holocene aquifer (qh)



b) Upper Pleistocene aquifer (qp_3)



c) Middle Pleistocene aquifer (qp_{2-3})

Figure 7.6 - Desingn of GW monitoring networks: left (GWLs monitoring), right (salinity monitoring)

7.5 Findings

Reviews of Government guidelines explained a detailed plan on demand, supply, management sides to develop socioeconomic associated with sustainable development of groundwater resources. This study can help clarifying additional recommendations to enhance successful implementation of the MDP via each side as below:

- In supply side: Needs more surface storage due to limited GW pumping from sustainable yields of the aquifer system
- In demand side: Propose adaptive measures on agricultural activities to cope with limited resources but need to grow socioeconomic to match with target.
- In management side: Needs to improve monitoring system to control within the sustainable yields. Needs more incentive and technology for change (from FBM analysis) to implement agricultural activities based on the MDP.

Chapter 8 - CONCLUSIONS AND RECOMMENDATIONS

This last chapter presents the overall conclusions and recommendations of this study. The results of three chapters include the role of GWU, impact of GWU, sustainable yields, GW demand, behavior analysis, additional recommendations and proposal of GW monitoring network, which are summarized by linkage with current literature reviews to describe the overall picture of the study. The last section shows the recommendations and limitations of this study and directions for future studies.

8.1 Conclusions

8.1.1 Role of groundwater use

Mean of GWU varied from 0.95 m^3day^{-1} per HH to 1.35 m^3day^{-1} per HH and its trend increases from northern to coastal zone. Mean of GWU for irrigation and aquaculture were 25.7 and 30.8 m^3day^{-1} per ha

In the dry season of 2018, groundwater use is estimated 346,279 m^3/d in which the exploited amount in the northern, middle and coastal zone are 23,822 m^3/d, 23,1608 m^3/d, 90,849 m^3/d, respectively. GW is exploited mainly for domestic use, about 55 % of total GWU in both northern and middle zone. This percentage in the coastal zone is only 29 %, the other remaining percentage is for irrigation and aquaculture use.

LST is proved to be good tools with good correlation with groundwater use (GWU) distribution with adj-R^2 = 0.646. In future, the technique can be applied to estimate GWU in other area and in regional scale.

In Tra Vinh Province, in 2018, water is supplied for domestic use via five supply methods including bottled water, tap water, rain harvest and groundwater well. Percentage of the total surveyed household which are completely dependent on GW source are 66 and 89 % of in the middle and coastal zone, respectively. In two these zones, there is no surveyed household maintained their domestic use without any GW supply. Due to the distribution of saline GW, there is only 33 per cent of the total surveyed households which was partly or completely dependent on GW source in the northern zone.

8.1.2 Impact of GWU

In Tra Vinh Province, groundwater depletion most commonly occurs because of a long-term pumping of water from the ground. Many areas of the Tra Vinh Province are experiencing groundwater depletion, especially at exploited clusters with large production as Chau Thanh, Tieu Can district. In sand dune areas, high GW abstraction for irrigation and aquaculture in a continuous time resulted in GW depletion. The coastal zone is especially in high risk of facing GW depletion during the peak time of the dry season. From our field survey, it was found that local people had to add reinforce tube to increase pumping capacity in the qp_{2-3} aquifer and even drilled new wells to cope with depletion of the shallowest aquifer.

Not like other coastal areas over the world, fresh groundwater is found and exploited in aquifers from 150m up to 500 m below ground surface. In three shallowest aquifers, brackish water is present only in the northern part of the aquifer and a north-south TDS distribution with lower values towards the south where many exploited wells have been operating to supply water for domestic and agricultural use. Salinity concentration grew up in the dry season due to the effect of seawater intrusion through river and canal network in Holocene (qh) aquifer.

The most obvious consequences of depleting groundwater resources are the increased costs of pumping groundwater as the groundwater table decreases dramatically. Because groundwater levels declined too far, then the well owner might have to attempt to lower the pump and add reinforce tube. A percentage of surveyed households can’t use GW from aquifers at certain times of the dry season and they had to construct deeper wells or reduce irrigation amount and planting area.

This long-term extensive exploitation has depleted groundwater resources and caused several problems. In some places with heavy GW withdrawal, the water table dropped from 5 m below the ground surface in 1994 to 15 m below the surface in the early 2018s. Based on the estimated GW budget in 2018, there was 35% of GW abstraction comes from GW storage. Captured storage has been increasing dramatically since 2008 to catch up with the significant growth of GW abstraction. In other words, the over GW abstraction reduced the storage of the aquifer system and induced the decline of GWL significantly in the period of 25 years. The results demonstrated that GW system in Tra

Vinh Province has moved from a pristine system to a developed system then become a depleted system at present. This raises the concern that present GWU is already depleting a limited aquifer, and that further intensification of this GWU in future is unsustainable.

8.1.3 Sustainable yields

To analyze sustainable development of GW system in Tra Vinh Province area, a concept of equilibrium state and controlling saline GW movement is proposed and proved to improve both quantity and quality management. A three-dimensional GW numerical modelling (MODFLOW-SEAWAT) is used to meet equilibrium state and for controlling saline GW movement. The model result shows that the sustainable yield is 175,845 m^3/d, about 59 % of current GW abstraction. Especially, the sustainable yield is only one-third of the current pumping in the northern zone.

By reducing GW abstraction is 195,000 m^3/d since January 2020, the decline in storage has been decreasing and stabilizing since early 2024. However, saline GW area still expanded toward some of depleted cones. So as to satisfy the concept of sustainable yield, the volume of GW decreases to about 175,845 m^3/d, the recharge from rainfall and leaky from rivers and streams is almost unchanged; the boundary inflow and change of storage are decreases.

8.1.4 Groundwater demand

After proposing socioeconomic growth and climate change scenarios, the analysis of the unmet water demand and per cent coverage of the GW demand to cope with the sustainable yield for the period of 2020 and 2030 was computed. By scenarios of following the master plan of VMD, the estimated GWDs are closed with the sustainable yield of aquifer due to low-outlook in population growth and changing agriculture activities to adapt with saline water. If population growth and land use pattern are still maintained as usual, the demand of GW will be higher 2.5 times than sustainable yield on average of three scenarios of climate change.

8.1.5 Behavior analysis

Behavior analysis provides a different view on looking on adaptation parameters to cope with new changes from the Master Plan of VMD. From our field survey and analysis, it was found that the motivation factors and ability factors significantly influence the farmer's decision in changing or not changing their own agricultural activities to others. In other words, if farmers perceive high effectiveness for changing their agricultural activities (reduce damage or higher price) and their ability is good enough, they are more likely to intend to change to other agricultural activities. In the middle and coastal zone, paddy or food crops was changed to aquaculture, annual crops and orchards. While there was 55 % of total surveyed HH changed their own agricultural activities in the coastal zone, the percentage in the middle zone is only 28%. This difference can be explained by more difficulty in accessing source of water supply and capital in the middle zone. The northern zone showed a high percentage in changing agriculture activities with mainly changing to perennial crops (coconut, sedge). A high concern about the impact of climate change and market price motivated farmers to change their own agricultural activities (paddy food crops).

8.1.6 Additional recommendations

Government proposals for sustainable GW development are intended to inform and assist adaptive measure in three aspects including demand, supply and management. They are illustrative and are presented to help local authorities consider possible ways to address anticipated current and future threats resulting from the changing climate and socio-economic development. However, the strategies presented are not a comprehensive in term of convincing local people changing their agricultural activities to cope with climate change impact. Fogg Behavior Model indicated some improvement via motivation and ability factors. The additional measures should be prepared for implementing the new plan of VMD. In the northern zone, information about climate change and new technologies need to be supported more frequency. While government or local authorities should pay more attention to improve capacity of irrigation water supply and productive support credit to make farmers feel easier to change to other agricultural activities in the middle and coastal zone.

8.1.7 Proposal of GW monitoring network

Preliminary monitoring networks have been designed using contour maps of groundwater levels and TDS distribution from GW flow and saltwater transport models as a reference. Because of limitation in number of GW monitoring wells, preliminary GWL monitoring networks need to be implemented with a series of piezometers to observe GWLs and salinity concentration in main exploited aquifers. Time series data of monitoring GWLs will carry out efficiency determination on the direction and velocity of GW flow through aquifers and improvement in simulations or projections of three-dimensional GW flow patterns in Tra Vinh Province. In addition, monitor and map of TDS should be used to identify saline prone areas that help lessen or prevent future increase in salinity GW. The proposed monitoring networks need to be improved to support the government or local authorities in term of control freshwater availability of both river and groundwater system with the consideration of sustainable yield proposed.

8.2 Recommendations

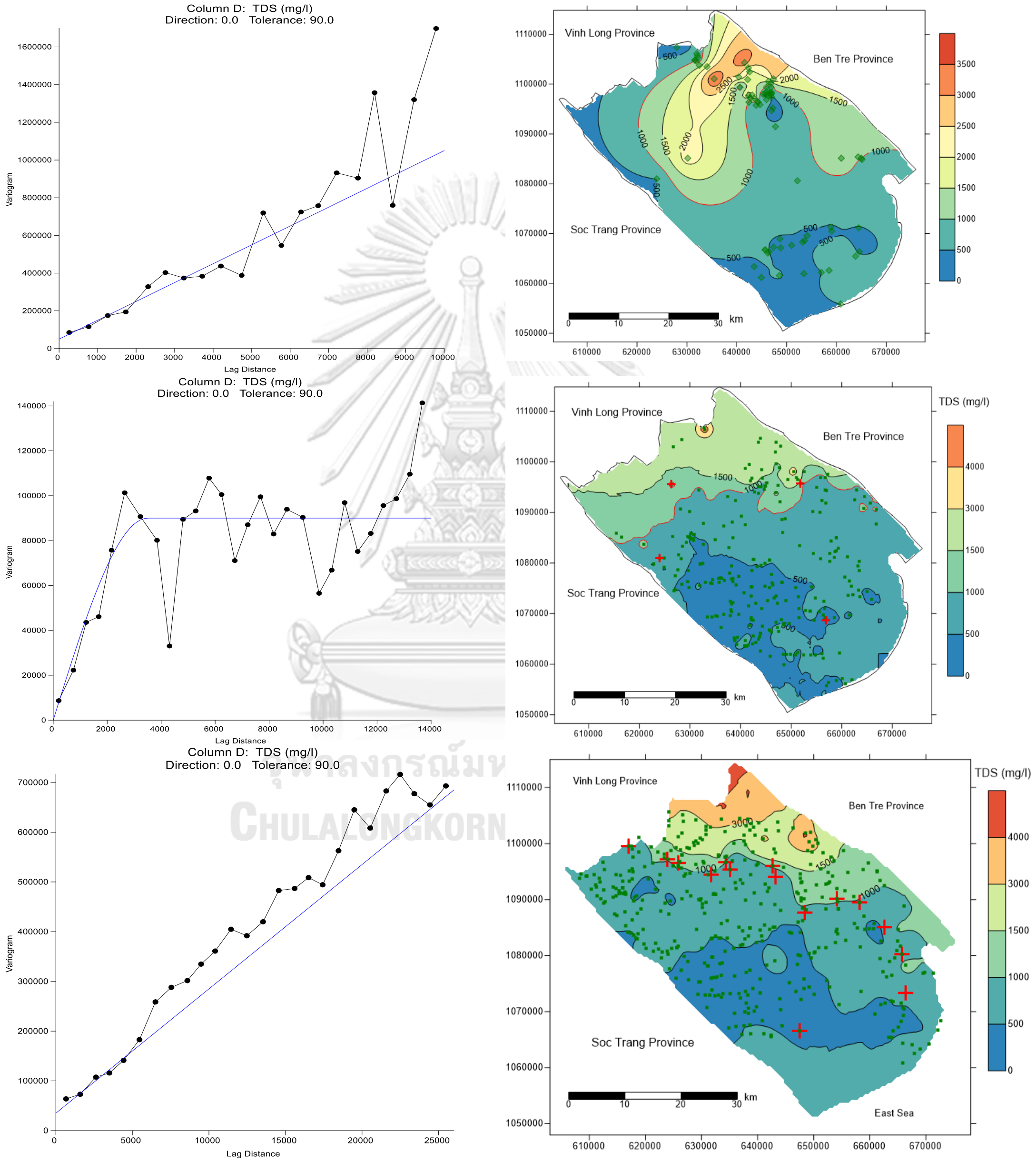
The thesis deals with socioeconomic survey, GW modelling and behavior analysis in adaptive measures proposed. The sample screening was carefully and scientifically conducted to ensure the representative samples, while the field survey was carried out with great caution. In this study, the sample size was selected and analyzed in the regional scale, so future studies for implementation should be conducted in more details in the local scale (e.g. commune or district only). That would help to generate further useful insights for local authorities as well as more detailed implications for the national government in implementation of the Mekong Delta Plan. In addition, it must be demonstrated that survey and model developed in this study are successful in the initial trial, though not completely sufficient to deal with these implementation challenges. It can be seen that the GW survey and models were efficiently developed as suitable tools for assessing GWU and its impact, there are still outstanding issues which need to be considered in further studies:

- More salinity monitoring/measurement to confirm the salinity distribution location/pattern which will affect the sustainable yield estimation and GW recharge locations
- Fresh GW distribution of aquifers in the coastal zone should have more study to confirm the volume and location of this freshwater aquifer.

APPENDIX

APPENDIX 1 - TDS interpolation using Kriging Method (Surfer 11).

Left: three variogram models of three aquifers. Right: TDS distribution of three aquifers. Top: Holocene aquifer (qh). Middle: Upper Pleistocene aquifer (qp_3). Bottom: Upper-middle Pleistocene aquifer (qp_{2-3}).

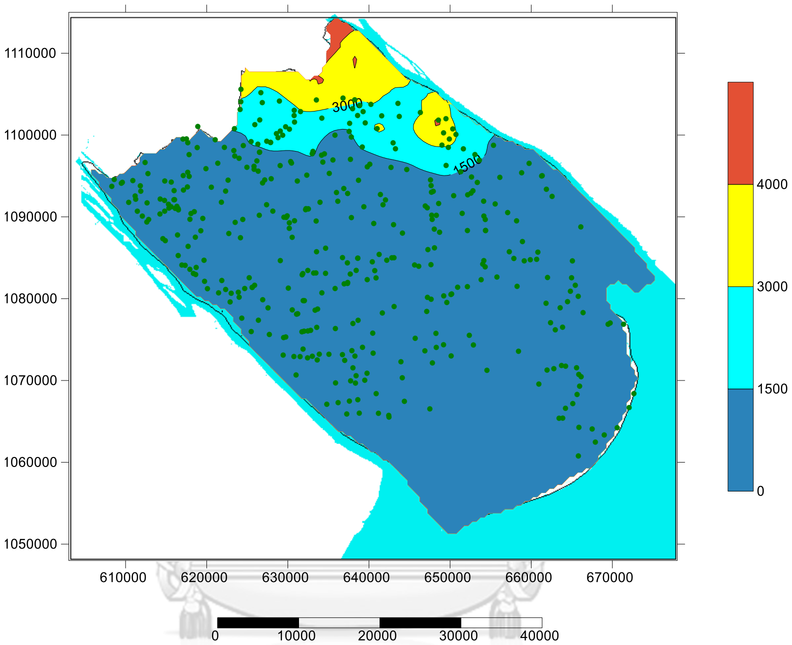


APPENDIX 2 - Commune selection for the socioeconomic survey

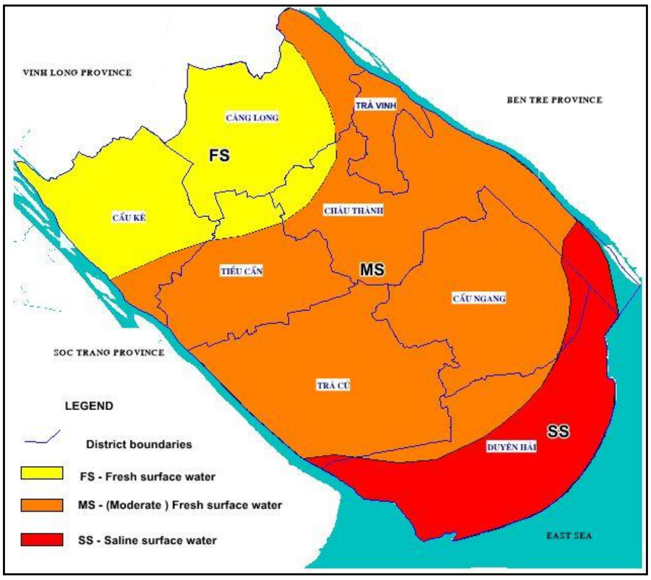
Criterion 1: Potential of freshwater distribution of groundwater and surface water

1) Northern zone: Easy to improve surface water + Fresh/saline groundwater (FSBG)
2) Middle zone: Hard to improve surface water + Fresh groundwater (BSFG)
3) Coastal zone: Saline surface wall seasons + Fresh groundwater (SSFG)

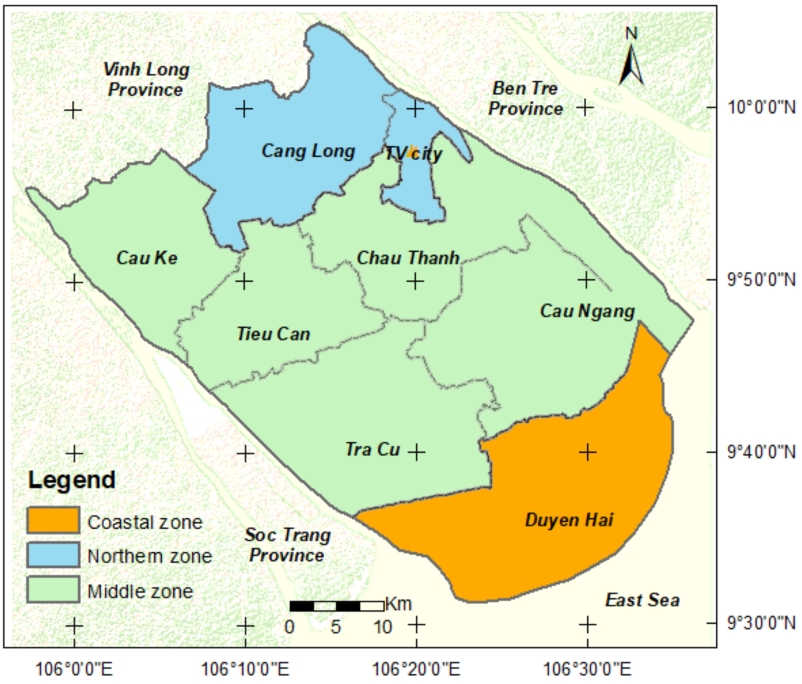
2.1 Representative state of existing saline groundwater in Tra Vinh Province



2.2 Extracted map of saline intrusion in the Vietnam Mekong Delta (Scarrott 2009)



2.3 Identification of three zones in the Tra Vinh Province



Criterion 2: Sample screening by selecting surveyed communes based on GDP per capital assessment

2.4 General information of selected communes.

Zone	Commune	Population	Area	GDP/capita	Potential of WR	
		person	ha		Surface water	Groundwater
Northern zone	My Cam	11,832	2,298	High	Fresh	Saline
	Huyen Hoi	14,244	3,473	Moderate	Fresh	Fresh/Saline
	Dai Phuoc	9,520	2,008	Low	Fresh + Saline	Saline
Middle zone	Dinh An	5,444	592	High	Fresh + Saline	Fresh
	Thanh Son	9,592	1,415	Moderate	Fresh + Saline	Fresh
	Ham Giang	2,488	1,591	Low	Fresh + Saline	Fresh
Coastal zone	Long Huu	10,862	3,623	High	Saline	Fresh
	Truong L.H	5,560	3,751	Moderate	Saline	Fresh
	Dan Thanh	7,069	4,134	Low	Saline	Fresh

APPENDIX 3 - Survey implementation

3.1 General information of surveyed households

Component		Northern zone	Middle zone	Coastal zone
Respondent age	20-30	3%	1%	5%
	30-45	19%	19%	28%
	>45	79%	80%	67%
Number of family member	1-2	6%	7%	8%
	3-5	59%	79%	74%
	>5	33%	14%	18%
Education level	None	3%	9%	5%
	Primary-high school	91%	86%	89%
	University/vocation	6%	6%	6%
Economical activities	Paddy	44%	60%	13%
	Aquaculture	0%	18%	57%
	Other crops	68%	24%	50%
	Non-agriculture	11%	18%	14%
Household income	<40 mil.vnd/year	44%	64%	31%
	40-100 mil.vnd/year	41%	23%	38%
	>100 mil.vnd/year	15%	13%	31%

3.2 Some photos of surveyed implementation

a) Group discussion

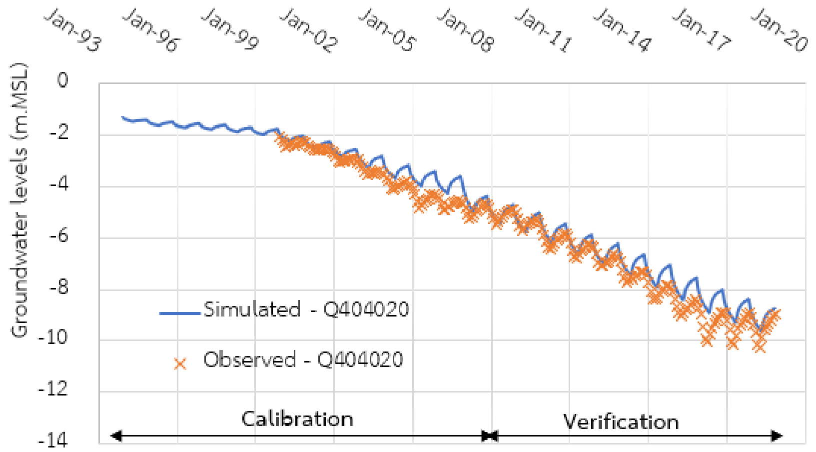
b) Interview respondent

c) GW pumping for irrigation

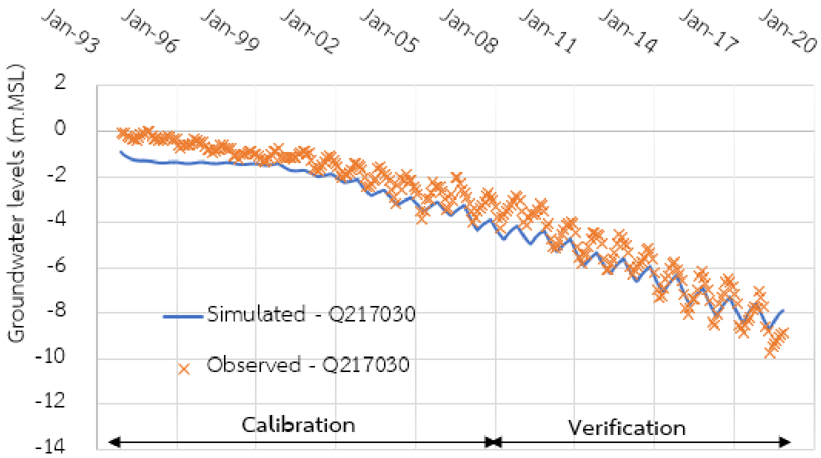
d) GW pumping for aquaculture

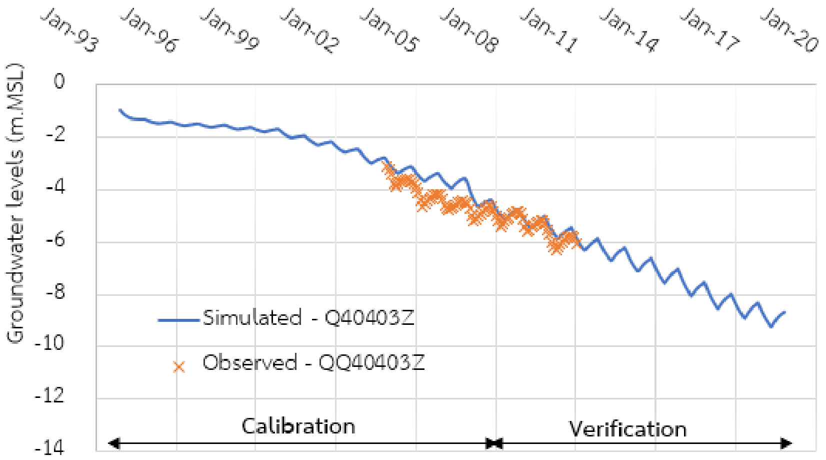
APPENDIX 4 - Calibration results of groundwater flow model

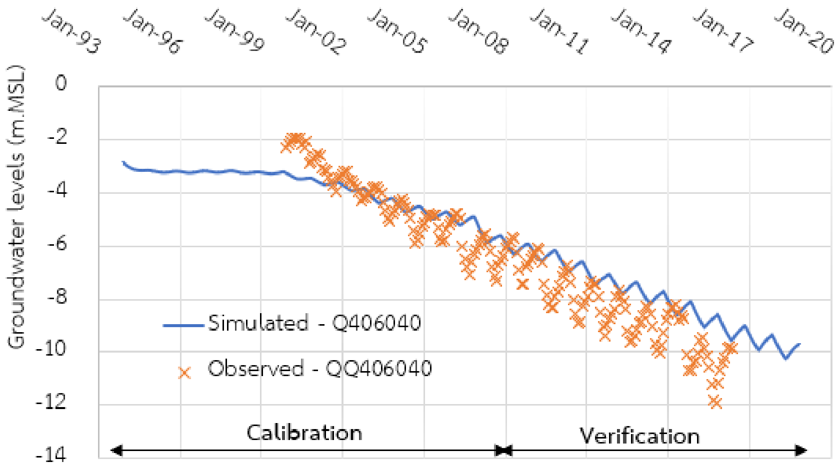
4.1 Comparison of simulated and observed GWLs of qp_3 aquifer (observation well Q404020)



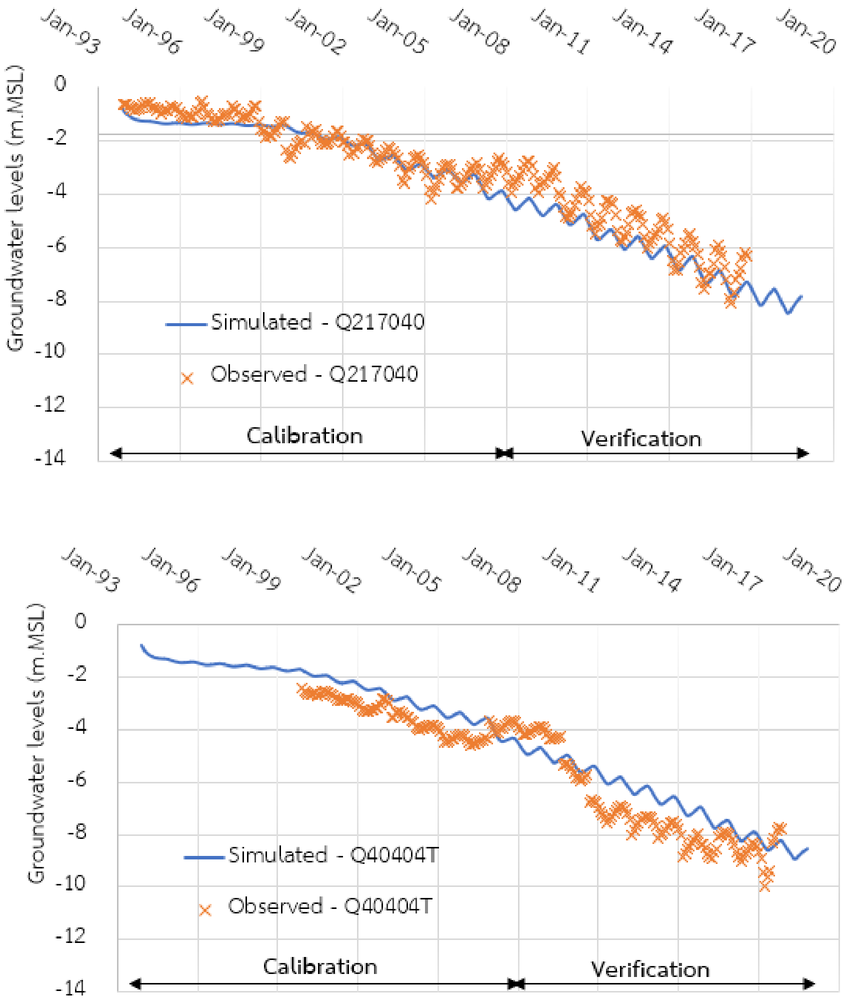
4.2 Comparison of simulated and observed GWLs of $n_{2\text{-}2}$ aquifer (observation well Q217030, Q40403z, Q406040)

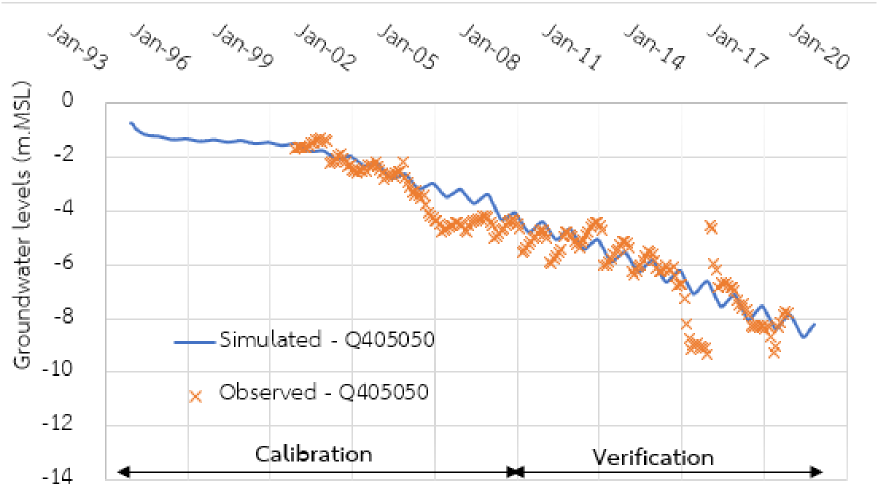




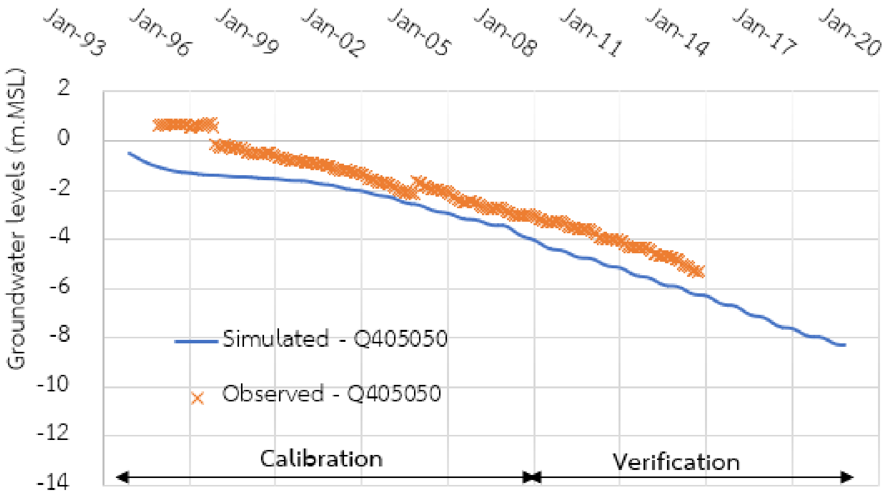


4.3 Comparison of simulated and observed GWLs of n_{2-1} aquifer (observation wells: Q217040, Q40404T, Q405050)





4.4 Comparison of simulated and observed GWLs of n_{1-3} aquifer (observation well Q405050)



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