SURFACE WATER-GROUNDWATER INTERACTION PROCESSES FOR GROUNDWATER PUMPING MANAGEMENT IN SAIGON RIVER BASIN

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A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Engineering in Water Resources Engineering
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กระบวนการปฏิสัมพันธ์ระหว่างน้ำผิวดินและน้ำใต้ดินสำหรับการจัดการสูบน้ำใต้ดินในลุ่มน้ำไซง่อน

นายลอง ทานห์ ตรัน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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Thesis Title	SURFACE WATER-GROUNDWATER INTERACTION PROCESSES FOR GROUNDWATER PUMPING MANAGEMENT IN SAIGON RIVER BASIN
By	Mr. Long Thanh Tran
Field of Study	Water Resources Engineering
Thesis Advisor	Associate Professor Sucharit Koontanakulvong, Ph.D.

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ลอง ทานห์ ตรัน : กระบวนการปฏิสัมพันธ์ระหว่างน้ำผิวดินและน้ำใต้ดินสำหรับการจัดการสูบน้ำใต้ดินในลุ่มน้ำไซง่อน. (SURFACE WATER-GROUNDWATER INTERACTION PROCESSES FOR GROUNDWATER PUMPING MANAGEMENT IN SAIGON RIVER BASIN) อ.ที่ปรึกษาหลัก : สุจริต คูณธนกุลวงศ์

หลังช่วงปี 1990 การสูบน้ำบาดาลมาใช้ในลุ่มน้ำไซง่อนเพิ่มขึ้นอย่างมาก ตามความต้องการน้ำที่เพิ่มขึ้น ระดับน้ำบาดาลลดตัวลงอย่างมากโดยเฉพาะในพื้นที่ท้ายน้ำ การศึกษาครั้งนี้ได้พยายามพัฒนาแบบจำลองน้ำใต้ดินโดยนำพารามิเตอร์ปฏิสัมพันธ์ของน้ำผิวดินและน้ำใต้ดินเข้าร่วม และยังนำแนวคิดปริมาณสูบที่ยั่งยืนมาใช้ประกอบการจัดการปริมาณการสูบที่เหมาะสมภายใต้ความต้องการใช้น้ำที่มากขึ้น ในลุ่มน้ำไซ่ง่อน

จากข้อมูลการวัดเก็บค่าความชื้นในดินภาคสนาม ทำให้สามารถประเมินค่าอัตราการซึมระดับลึกของน้ำเฉลี่ยรายเดือนของดินทราย ดินเหนียวผสมทราย และดินเหนียว อยู่ในช่วง วันละ 2 – 4.5 มม, 1.5-3.5 มม และ 0.5-2 มม. ในช่วงความเข้มฝน 4-14 มมต่อวัน นอกจากนี้ ยังทำให้รู้ว่า ค่าความนำของท้องแม่น้ำมีค่าเป็นสัดส่วนตามเปอร์เซนต์ของทรายในตะกอนท้องน้ำ ผลของการสูบน้ำอย่างมาก ทำให้ปริมาณการเติมน้ำจากแม่น้ำสู่แอ่งน้ำท้ายน้ำมีปริมาณมากถึง 50 % ของปริมาณน้ำไหลเข้าทั้งหมด แบบจำลองน้ำใต้ดินที่พัฒนาขึ้นพิจารณาพารามิเตอ์ปฏิสัมพันธ์ของน้ำผิวดินและน้ำใต้ดินทีได้ พบว่า อัตราการสูบอย่างยั่งยืนในพื้นที่ท้ายน้ำที่สูบอยู่และพื้นที่ใหม่ด้านเหนือน้ำ เท่ากับ 0.88 และ 1.02 ล้านลบม ต่อวัน ตามลำดับ

ดังนั้น การใช้น้ำร่วมจากทั้งน้ำประปาผิวดินและน้ำบาดาลในลุ่มน้ำไซง่อน มีเพียงพอสำหรับความต้องการใช้น้ำประมาณการบนฐานของการใช้ที่ดิน คือ 4.9 ล้านลบม ต่อวัน โดยจะเป็นการใช้น้ำจากแม่น้ำ 3.5 ล้านลบม ต่อวัน และอีก 1.4 ล้านลบมต่อวันมาจากน้ำบาดาล ในขณะที่ความต้องการใช้น้ำประมาณการของธนาคารโลก จะเพิ่มสูงถึงวันละ 6.9 ล้านลบม เกินกว่าปริมาณน้ำร่วมสูงสุดที่จัดหาได้ โดยใช้น้ำประปาจากแม่น้ำประมาณ 4.2 ล้านลบม และน้ำบาดาลอีก 1.9 ล้านลบม ที่ขาดอีกประมาณ 0.8 ล้านลบมต่อวันจะต้องพัฒนาระบบน้ำประปาจากแม่น้ำเพิ่ม และ/หรือนำเทคโนโลยีการประหยัดน้ำ/การใช้น้ำซ้ำมาช่วยการขาดน้ำปริมาณดังกล่าว

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

5971457021 : MAJOR WATER RESOURCES ENGINEERING
KEYWORD: sw-gw interaction groundwater model sustainable yield optimal pumping Saigon River Basin

Long Thanh Tran : SURFACE WATER-GROUNDWATER INTERACTION PROCESSES FOR GROUNDWATER PUMPING MANAGEMENT IN SAIGON RIVER BASIN. Advisor: Assoc. Prof. Sucharit Koontanakulvong, Ph.D.

Since the 1990s, the excessive extraction of groundwater of Saigon River basin is dramatically increased and groundwater resources of Saigon River basin have been facing dramatically drawdown groundwater level in the downstream area. The study attempted to develop groundwater modeling through employing SW-GW interaction parameters and incorporate the concept of sustainable pumping yield to detect optimal pumping management under growing water demand in Saigon River Basin.

According to field observed soil moisture, the study recognized the average monthly percolation rate of sand clay loam, sand clay, and clay varies 2-4.5 mm/day, 1.5-3.5 mm/day, and 0.5-2 mm/day, respectively to rainfall intensity 4-14mm/day. Besides, the conductance in riverbed is coressponded with the sand percentage of sediment. As consequent of the high pumping rate, the river recharge contributed 50% to groundwater budget in downstream. The developed groundwater modeling through employing SW-GW interaction parameters derived found that the groundwater sustainable yield in existing downstream and in upstream new area are 880,000 m^3/day and 1.02 MCM/day, respectively.

Thus, the conjunctive water supply in Saigon River Basin is sufficient for land use based water demand (4.9 MCM/day), which utilize 3.5 MCM/day from surface and 1.4 MCM/day from aquifers. Meanwhile, water demand, based on World Bank's estimate (6.9 MCM/day) is over the maximum conjunctive water supply of Saigon river basin which includes 4.2 MCM/day from surface river water, and 1.9 MCM/day from groundwater. Hence, Saigon River Basin should improve surface water capacity and/or utilize water saving/recycle technology to cover water shortage of 0.8 MCM/day

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

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Long Thanh Tran

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LIST OF ABBREVIATION

DNRE= Department of Natural Resources and Environment of Binh Duong Province

DWPRIS=Division for Water Resources Planning and Investigation for the South of Vietnam

GDP= Gross Domestic Product

HCMC= Ho Chi Minh City

m. MSL = meters mean sea level

MCM= million cubic meters

SRHMC=Southern Regional Hydrometeorological Center

WB= World Bank

CHAPTER I

INTRODUCTION

1.1 Background and problems

Since 1990s, in line of social and economic growth in the Ho Chi Minh City and nearby provinces, the water demand water was rapidly increased. In 2016, through the survey in whole basin, water demand was estimated to be 4 million m^3/day (DNRE-Binh Duong, 2017; Division for Water Resources Planning And Investigation For The South Of Viet Nam DWPRIS, 2016). However, due to insufficient infrastructure, surface water is not capable to supply fresh water for 17 million population in Saigon River Basin. Therefore, groundwater resources have been exploited to cover 27% of water demand (~ 0.8 million m^3/day). Although the potential groundwater storage was estimated to be 2.5 million m^3/day, the pumping well density distributed unevenly, resulting dramatically drawdown groundwater level (< -35m MSL) (Chan, 2015; Phu, 2008).

In order to preserve groundwater resources in Saigon River, numerous publications attempted to investigate groundwater resources in Saigon River Basin. In 2000, Win Boehmer (2000) developed conductance values for all hydraulic stations of river system utilizing hydraulic conductivity from pumping tests in Nambo Plain, including Saigon River Basin. The calculated conductance coefficients in Saigon River are from 2.2 m/day to 4.4 m/day. In 2010, Chân and Kỳ (2010b) and Ha Quang Khai (2014) accessed potential groundwater recharge via inverse numerical groundwater modeling. The groundwater-river interaction parameters were utilized conductance values from Win Boehmer (2000). The results indicated that the river recharge contributes 20% to 40% of the groundwater budget in Saigon River Basin. Moreover, the river recharge amount has linear relationship with groundwater abstraction. Tuan Pham Van and Koontanakulvong (2018) developed a function of interaction parameters for middle part of Saigon River via piezometric head. However, most groundwater recharge estimation focused on hydraulic conductivity and different piezometric head of aquifers without fully understand the GW-SW interaction process as well as parameters in Saigon River Basin.

The surface and groundwater interactions are the primary source to balance long-term budgets of aquifer systems through precipitation and river (Allen, Mackie, & Wei, 2004; Koontanakulvong & Siripubttichaikul, 2002; Lerner, 2002; Marios Sophocleous, 2002). Somehow, the nonlinear interactions among surface water (both river and precipitation) discharge into aquifers remains challenge tasks on direct measurement and distribution spatial variability for long-term in catchment scale. Since 1980s, numerous methods have been developing to determine the deep percolation as well as river-groundwater interaction fluxes; to quantify the rate of gain and loss through small cross-section riverbed via seepage meters (Lee & Cherry, 1979; Murdoch & Kelly, 2003; Rosenberry & LaBaugh, 2008); to estimate flows in and out at streambed utilizing measurement of piezometric head differences between the river and the subsurface flow via streambed piezometers (Barlow & Coupe, 2009; Fanelli & Lautz, 2008; Lee & Cherry, 1979; Schmidt, Conant Jr, Bayer-Raich, & Schirmer, 2007); soil water balance method (Feltrin, de Paiva, de Paiva, & Beling, 2011; Kumar, 1997; Lal, 1991; Reddy, 1983); infiltration test using single ring, double rings, the well permeameter (Sangbun, Sangchan, & Mekpruksawong, 2014; J. Wu & Zhang, 1994); inverse modeling technique (Ha Quag Khai & Koontanakulvong, 2015; Koontanakulvong & Suthidhummajit, 2015; Tuan Pham Van & Koontanakulvong, 2018); ground water level fluctuation method (Hung Vu & Merkel, 2019; Kumar, 1997; Lutz et al., 2014); identify possible groundwater recharge sites obtained the isotopic characterization of rainfall, surface water, and groundwater (Abdalla, Al-Hosni, Al-Rawahi, Kacimov, & Clark, 2018). Despite advancements in recent numerical modeling, the complexity of surface water and groundwater interaction parameters probably drive to estimate inappropriately groundwater storage. The lithological composition of streambeds and aquifers mostly are considered as static, homogeneous entities. (González-Trinidad, Pacheco-Guerrero, Júnez-Ferreira, Bautista-Capetillo, & Hernández-Antonio, 2017; Partington, Therrien, Simmons, & Brunner, 2017). Thus, the simplified conceptualization of complex surface water-groundwater interactions also produces uncertainty bias for hydrogeology process (Brunner, Therrien, Renard, Simmons, & Hendricks Franssen, 2017; Kosugi et al., 2011). Henceforth, the estimated system parameters without perception of groundwater-surface water interaction mechanism may bring inappropriate inputs into groundwater model solutions, especially in alluvial plain area (Sanford, 2002).

In order to have more robust groundwater sustainable pumping management for socio-economic development, surface – groundwater interaction process showed more intensively under transient conditions. The study attempted to develop groundwater modeling through employing GW-SW interaction parameters and incorporate the concept of sustainable pumping yield to detect optimal pumping management under growing water demand scenarios in Saigon River Basin.

1.2 Objectives

The main objective of study is to develop groundwater resources management to cope with freshwater demand under development scenarios in Sai Gon River Basin.

The specific objectives are:

- To determine function of land recharge and function of river – groundwater interaction via field measurements,
- To determine the surface water and groundwater interaction fluxes exchange via groundwater model development,
- To recommend groundwater pumping management to meet water demand scenarios (based on the master plan of land use and the trending of social-economic growth) by employing the studied surface water and groundwater interactions and obtaining the sustainable yield concept.

1.3 Research approach and scope

1.3.1 Research approach

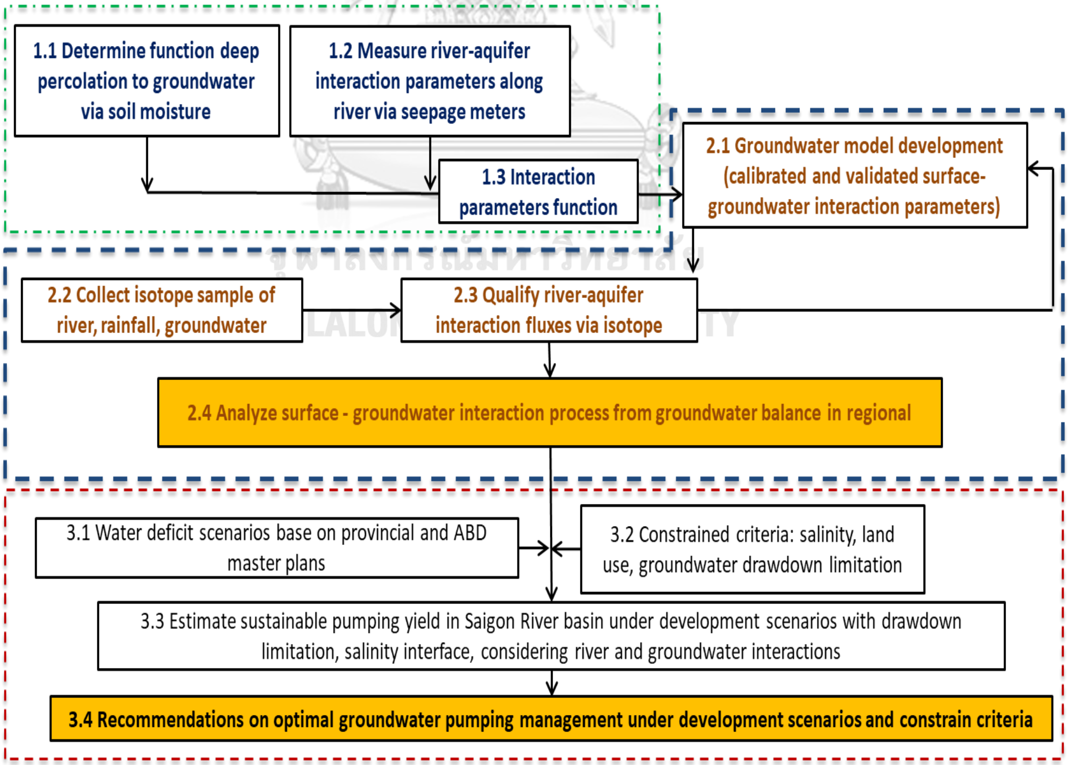


Figure 1. 1: Schematic representation of the study framework

This study proposed a new approach for groundwater pumping management which is more realistic and proactive in the identification of surface – groundwater interaction flux and the demarcation of groundwater pumping yield. Figure 1.1 shown the framework of the study assessment in surface water and groundwater interaction process to recommend pumping management under the sustainable yield concept and development scenarios in the Saigon River Basin. In particular, this integrated approach can be divided into three main parts, i.e., to investigate the characteristics deep percolation and river interaction parameters in Saigon River Basin via the soil moisture monitored and seepage measurements, to determine fluxes exchange (volume and patterns) between surface and groundwater via groundwater modeling and isotope, to recommend optimal pumping management for future water demand scenarios by employing optimal groundwater pumping intensity. The optimal groundwater pumping was estimated from the evaluated interaction flux of surface water and groundwater.

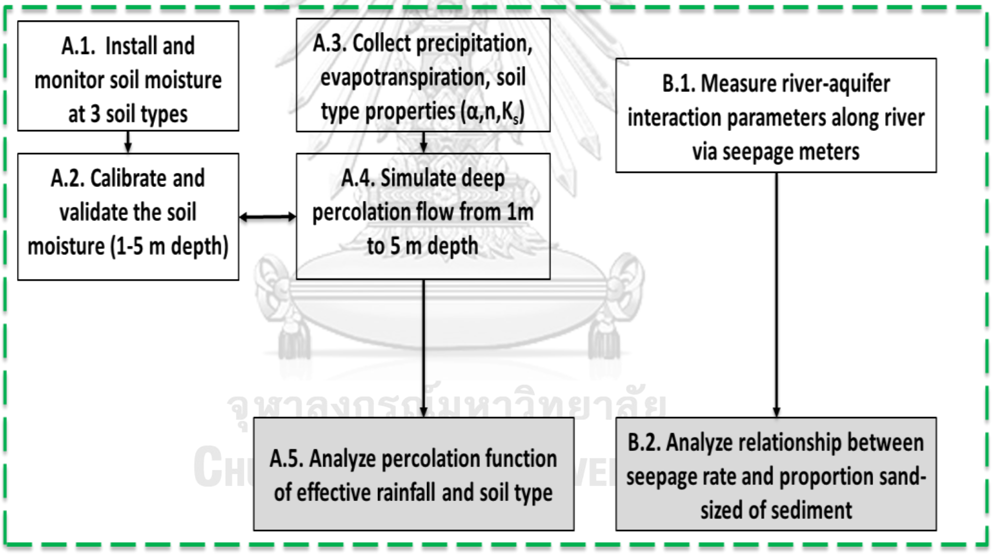


Figure 1. 2: Framework of field measurement of the surface - groundwater interaction parameters (A. Land recharge, B. River seepage)

First, the characteristics of deep percolation function and river interaction parameters were investigated via soil moisture sensor and seepage measurement. In the deep percolation part, the moisture of three soil types in the study area was automatically monitored daily by field soil moisture sensor in 12 months to investigate the characteristics of percolation. Due to the variable of soil moisture, soil properties, and climatic, the percolation flows were simulated via one-dimensional soil water flow model (HYDRUS 1D). The water retention parameters were estimated by inverse modeling utilizing observed soil moisture in the field. The performance of soil moisture simulation is justified due to statistic parameters and the regression coefficient. The functions of percolation rate with effective rainfall (considered as rainfall minus evapotranspiration), rainfall intensity (rainfall/no of days), percolation rate (percolation/effective rainfall) of three soil types were determined. For the river-aquifer interaction parameters part, the seepages of riverbed were measured at five stations along the Saigon River Basin. The sediment of riverbed along Saigon River Basin was collected to analyze relationship between seepage rate and proportion sand-size of riverbed sediment.

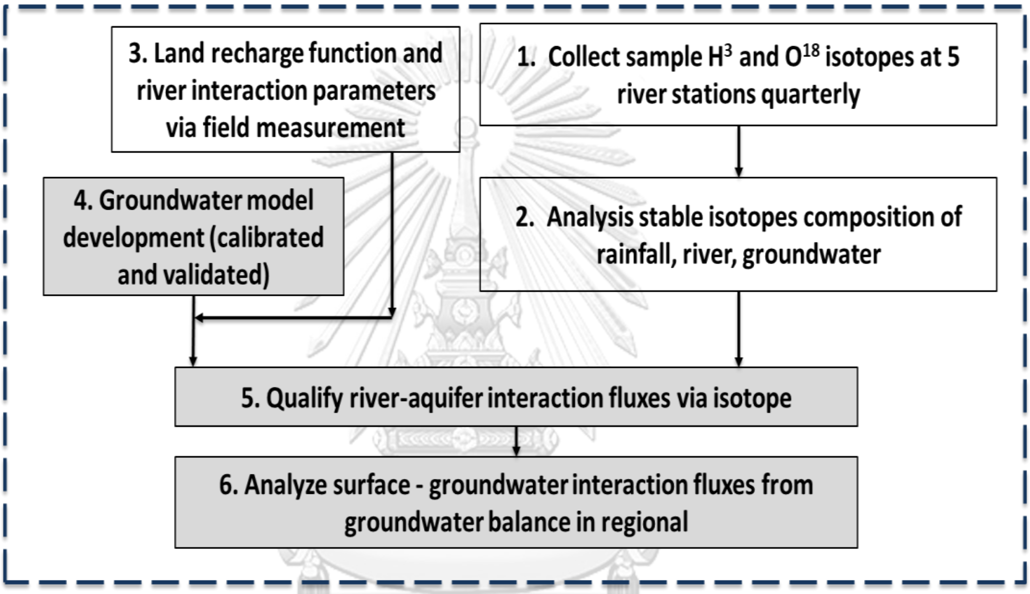


Figure 1. 3: Framework of the surface water and groundwater interaction fluxes exchange

Second, the exchange fluxes between river and groundwater were determined via the water budget of groundwater modeling. The proportion of rainfall, river, groundwater was analyzed from collected H^2 and O^{18} isotope samples at five river stations quarterly. The regional groundwater model was developed by applying surface- groundwater interaction parameters, which were investigated from the field. The land recharge function and conductance of riverbed were calibrated and validated again by inverse modeling obtained piezometric. The performance evaluation based on statistical parameters, namely, the coefficient of determination (R^2), maximum error, minimum error, the standard deviation (SD), the root-mean-square error (RMSE). The proportion sources of groundwater recharge lately were evaluated through isotopes composition of rainfall, river, groundwater. The developed regional groundwater modeling provided insights groundwater and river interaction exchange fluxes in Saigon River Basin.

Third, the recommendation on groundwater pumping management to meet water demand scenarios in the Saigon River Basin was explored from groundwater modeling coupling with the studied interactions of surface water and groundwater .The water deficit scenarios in Saigon River Basin calculated from the projected water demand via land use master plan by provincial, and the projected water demand via Gross Domestic Product (GDP) growth by World Bank (WB), and surface water supply plan by 2035 .Then, the pumping intensity in existing area was analyzed to determine the optimal pumping intensity for the sustainable yield in existing area and new area considering drawdown criteria, gradient at saline interface, and land use. The sustainable groundwater pumping was simulated via “increase pumping step by step” approach with considering drawdown criteria and gradient at salinity interface . The optimal groundwater pumping management) target, area, time, space, vertical (is recommended to meet demand under socio-economic growth and sustainable yield . The simulation was based on the past 20 year climate data.

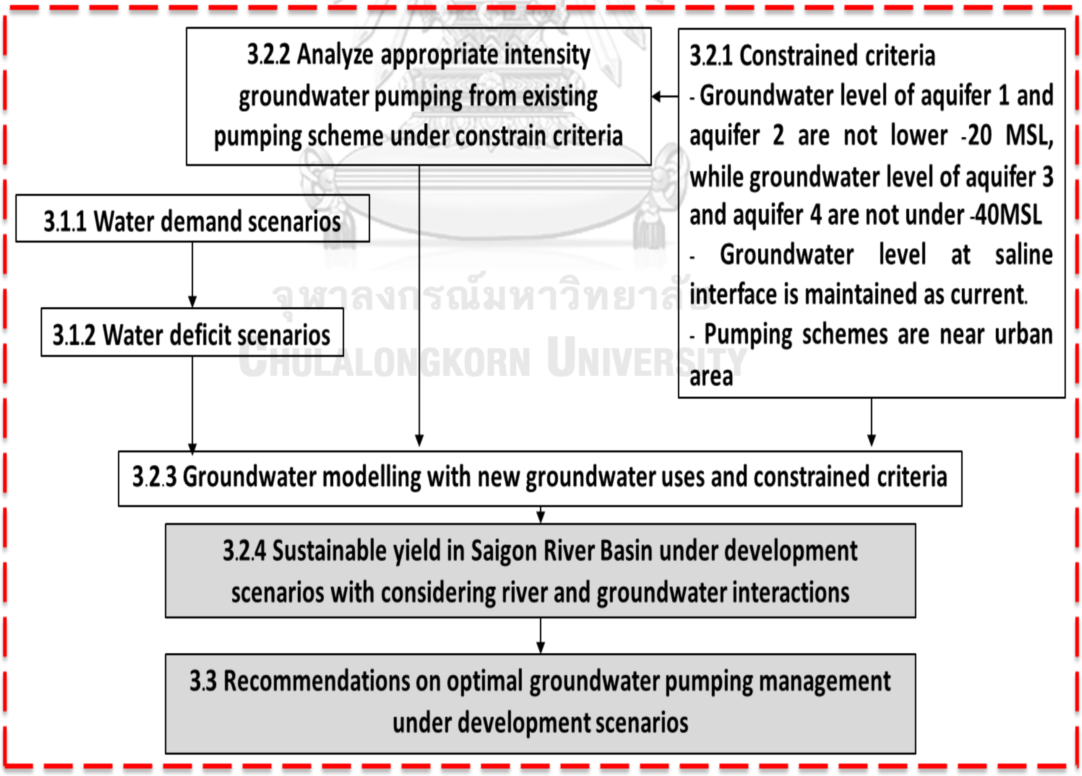


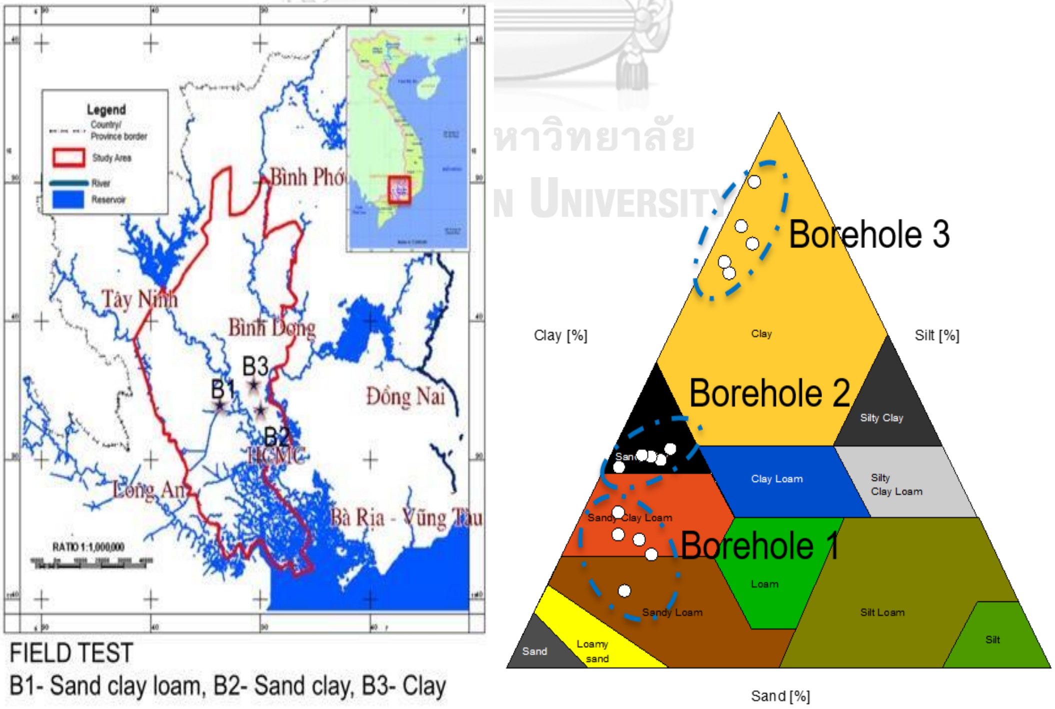
Figure 1. 4: Frameworks of optimal groundwater pumping management for development scenarios

1.3.2 Scope of the study

1.3.2.1 Scope

The scope of this study composes four main components, i.e., the deep percolation process, river – groundwater interaction process, the fluxes exchange between river and groundwater was analyzed via water budget of groundwater modelling, recommend sustainable groundwater yield and optimal pumping management for development scenarios. The details of these components follow as:

1) The deep percolation process in the Saigon River Basin was analyzed through the soil moisture approach. The soil moistures of three soil types in the field were monitored from 1 meter to 5 meters by adapting low-cost soil moisture profile probe and Arduino platform. Figure I-5 indicates the location of the field monitored soil moisture. The monitored soil moisture, rainfall, evaporation was collected daily from Oct 2017 to Dec 2018. As one of the common domains for simulating water movement, the one-dimensional soil water flow model HYDRUS 1D was applied to estimate the percolation flow for each soil type. The water retention parameters were estimated by inverse modelling utilizing collected soil moisture in the field. Then, the percolation function of three soil types was built from effective rainfall and sand percentage. The effective rainfall in this study was considered as precipitation minus evaporation.



FIELD TEST
B1- Sand clay loam, B2- Sand clay, B3- Clay

Figure 1. 5: Location and soil classification of three monitored soil moisture fields

2) The river – groundwater interaction parameters were measured via field measurements. The conductance riverbed was measured at five stations along the Saigon river via seepage meters with a diameter of 572 mm. To measure the fluxes exchange between river – groundwater, the seepage meters were inserted 40 cm to the riverbed. Figure 1.6 presents measured field sites for the interaction parameter along the Saigon River. The relationship between river - groundwater interaction parameters and sand percentage were analyzed to determine the function of the river - groundwater interaction parameters along the Saigon River Basin.

3) The fluxes exchange between river and groundwater was analyzed via the water budget of groundwater modelling. The comprehensive 3D model of 4 aquifers for Saigon River Basin was developed by the GMS-MODFLOW program, incorporating monthly data from Jan 1995 to Dec 2017 on the hydrogeology and the external hydraulic stresses on the aquifer (recharge and pumping rates), utilizing field measurement surface- groundwater interaction parameters. The land recharge function and conductance of riverbed were calibrated and validated again by inverse modelling obtained piezometric. The composition O^{18} and H^{2} of river and groundwater were collected at five stations quarterly and analyzed following SMOW standard. According to the stable isotope composition of the river, groundwater, rainfall, the proportion of fluxes exchange between river and groundwater was calculated following a simple two-component mixing model and qualified with the results from groundwater modelling. The time step simulation is monthly. Then, the results of groundwater flow budget were analyzed in seasonal scale for upstream and downstream zones. Hence, the results of river and groundwater interaction process modelling can provide the insight groundwater budget of each aquifer in Saigon River Basin;

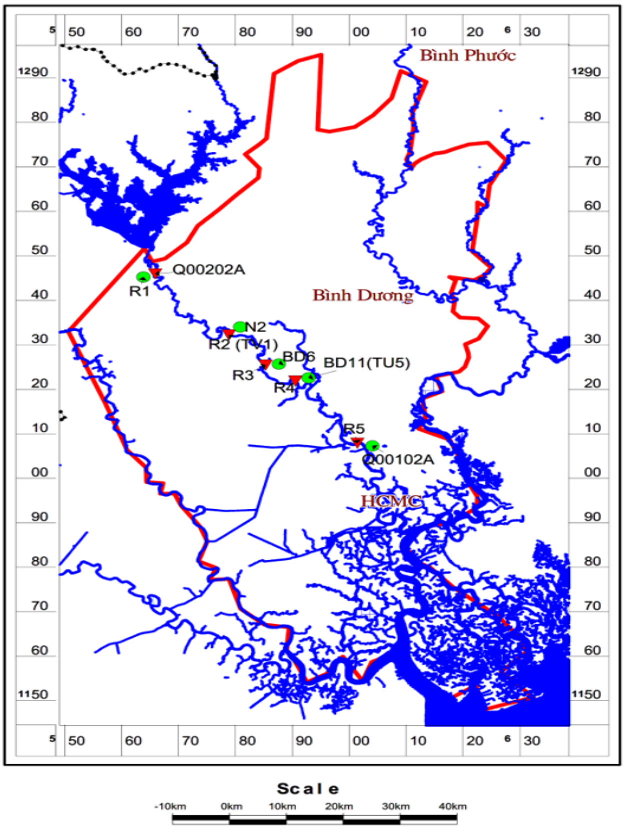


Figure 1. 6: Location of interaction parameter measurements along the Saigon river

4) The sustainable pumping yield and optimal groundwater pumping management were simulated based on developed groundwater modelling on river – groundwater interaction. The water deficits calculated from water demand scenarios from provincial, World Bank and potentially available surface water supply. Optimal pumping in this study considered maximum pumping per square kilometers in four aquifers without bringing negative impacts to aquifers. In order to avoid critical drawdown in the cone of the pumping area, the optimal pumping intensity for regional defined by the pumping intensity analysis in the existing area which are above drawdown criteria. The sustainable groundwater pumping under socio-economic growth scenarios in Saigon River Basin explored via invert modelling. The sustainable pumping yield was estimated with considering drawdown constraint, remained hydraulic gradient at the saline interface, and land use. The simulation inputs utilized the past 20 years of climate data. According to sustainable groundwater budget coupling with the surface – groundwater interaction, the study proposed a recommendation for optimal groundwater pumping management in Saigon River Basin under socio-economic development scenarios.

1.3.2.2 Study area

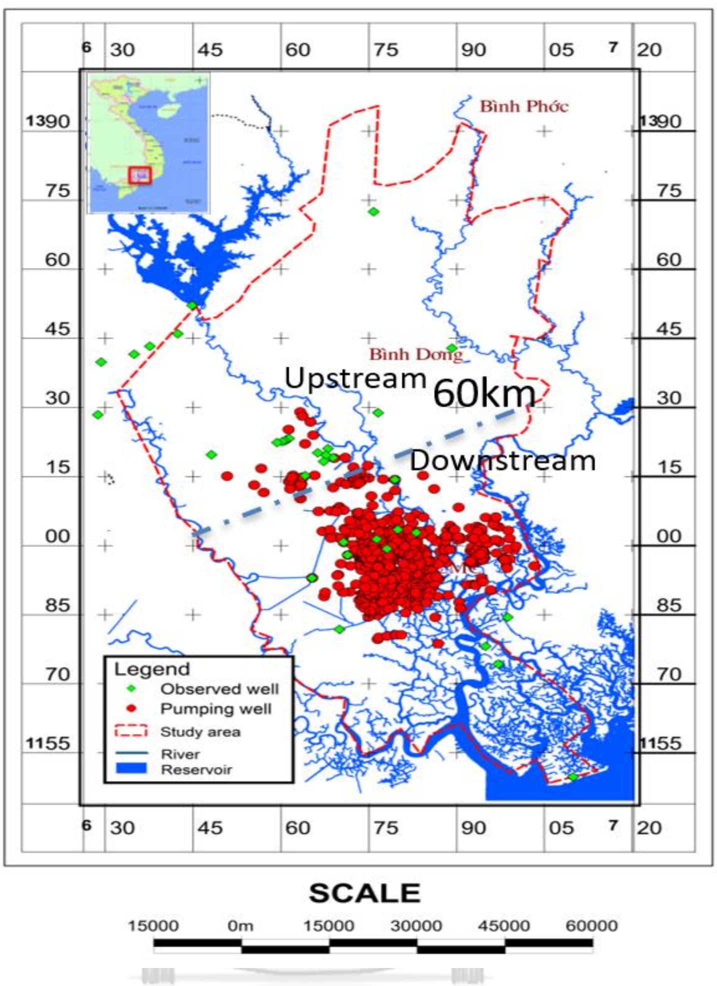


Figure 1. 7: Study area with well locations

The study area stretches from latitude 10.32^{0}N to 11.2^{0}N and from longitude 106.2^{0}E to 107.02^{0}E. It covers an area of 6,640 km^2, including Ho Chi Minh City, Binh Duong, a part of Long an and Tay Ninh Province. This area is the most significant industrial zones and economic zones in Vietnam. Currently, the groundwater pumping operated mainly in the downstream, and drive declining drawdown dramatically. Meanwhile, under low abstraction activities, the groundwater levels of upstream are higher than river stage. The groundwater is higher than river stage in upstream, while the groundwater level is lower than river stage in downstream. The boundary between upstream and downstream considered approximately 60km distance from Dautieng dam. The details of the study and concerned area are shown in Chapter II.

1.3.2.3 Data and duration used

The data collection is summarized as Table 1.1. The collected data are from Southern Regional Hydrometeorology Center Department of Resources and Environmental, Division for Water Resources Planning and Investigation for the South of Vietnam, and fieldwork collecting.

Table 1. 1: Summary of data collection for the study

Data	Number of stations	Period	Sources
1. Precipitation, evaporation, temperature	5	1995-2018	SRHMC
2. Observed groundwater level	35	1995-2018	DWPRIS
3. Observed river stage	5	1995-2018	SRHMC
4. Seepage measurement	5	2018	Field work collection
5. Observed soil moisture	3	2017-2018	Field work collection
6. Hydrogeology map of Saigon River Basin		2017	DWPRIS
7. Bore log data	400	1995-2017	DWPRIS
8. River cross-section	20	2015	SRHMC
9. Stable isotope	5	2017-2018	Fieldwork collection
10. Soil sample testing	8	2017 -2018	Fieldwork collection
11. Well abstraction (pumping rate, location)		1995-2018	SRHMC

The study duration includes 2 periods: historical simulation and future projection. The river – groundwater interaction process was accessed in historical simulation based on climatic data from year 1995 to 2017. The optimal groundwater pumping management was projected to year 2035 utilizing scenarios of provincial land use masterplan, World Bank, and climatic data in the historical period.

1.4 Study procedures

This study composes four main components: the deep percolation function (land recharge) in the Saigon River Basin, the Saigon river – groundwater interaction parameters, surface water, and groundwater interaction fluxes exchange via development groundwater modeling and stable isotope, optimal groundwater pumping management in Saigon basin for development scenarios. The brief study procedures of these components are as follow:

1.4.1 The deep percolation function (land recharge) in the Saigon River Basin

1) Install soil moisture sensor from 1m – 5m depth in the outcrop area of three aquifers. The soil moisture sensor was modified from the low-cost soil moisture sensor of Kojima et al. (2016). The soil moisture was recorded real-time via Arduino board,

2) Collect soil samples at field sites and classify the soil by ASTM standard (2007). The calibration curve of each soil type was built by matching the soil water content via the gravimetric method with resistance read from Arduino sensor,

3) Simulate percolation in each soil type via one-dimensional soil water flow model HYDRUS 1D (Simunek, Van Genuchten, & Sejna, 2005),

4) Analyze the percolation rate of three soil types under rainfall intensity to build land recharge function with effective rainfall and sand percentage.

1.4.2 The river – groundwater interaction parameters were measured via field measurements.

1) Measure the conductance of riverbed at 5 stations along the Saigon river via seepage meters with a diameter 572 mm (Lee & Cherry, 1979). The soil samples of riverbed sediments at 5 fieldworks were collected and classified via ASTM standard.

2) Analyze the relationship between conductance and sand percentage of sediments

1.4.3 Surface water and groundwater interaction fluxes exchange via development groundwater modeling and stable isotope

1) Collect hydrogeology map, results of hydraulic conductivity via pumping test, survey groundwater pumping, observed piezometric head from Division for Water Resources Planning and Investigation for the South of Vietnam (DWRPIS)

and river stage, river cross-section from Southern Regional Hydrometeorological Center (SRHMC),

2) Collect sample stable isotope (O^{18} and H^{2}) of rainfall, groundwater, river at five stations along the Saigon river. The results of stable isotope in water was analyzed following SMOW standard ("Standard Mean Ocean Water" (Craig, 1961a),

3) Develop groundwater modeling by obtaining measured surface – groundwater interaction parameters in the field. According to the hydrogeology map, there are four aquifers interacted with the surface. Hence, the study modeled groundwater systems consist of 4 aquifers. The characteristics of four aquifers followed the condition of hydrogeology map and bore log from DWRPIS. The land recharge function and river recharge fluxes were developed via field measurement of this study. In this study, the monthly observed river stage along the Saigon river basin was input data into groundwater modeling to calibrate the exchange flux between river – groundwater in the region. The calibration and verification of surface water - groundwater interaction parameters based on the best fit of the simulated piezometric head with observation. The statistical goals of model calibration are the residual standard deviation less than 10 percent of total change observed head across the model domain,

4) Qualify proportion sources of groundwater recharge (land recharge, river recharge) from modeling by analysist of composition O^{18} in river, rainfall, groundwater,

5) Analyze the groundwater budget of Saigon River Basin obtaining surface – groundwater interaction process

1.4.4 Recommendation on optimal groundwater pumping management for development scenarios

1) Calculate water deficits under provincial and World Bank scenarios,

2) Analyze appropriate groundwater pumping intensity under drawdown criteria from existing pumping scheme (see detail in Appendix F),

3) Estimate sustainable groundwater yield in the condition of drawdown constraint in the existing area (downstream) and the new area (upstream),

4) Recommend on optimal groundwater pumping management to meet the water demand scenarios and sustainable groundwater yield in Saigon River Basin.

1.5 Expected outcomes

1) Achieving the function of land recharge via soil moisture sensor and soil water balance, and surface water and groundwater interaction parameters,

2) Understanding fluxes exchange between surface water and groundwater via field measurements and groundwater model,

3) Achieving sustainable yield and optimal pumping management to meet water demand scenarios (based on the master plan of land use and the trending of social-economic growth) by applying the studied interactions of surface water and groundwater under sustainable pumping yield

1.6 Research significant

This study approach is to integrate the interaction functions derived from field measurements and the development of water modeling to propose groundwater pumping management under sustainable groundwater pumping yield.

The interactions among surface water (both river and precipitation) discharge into aquifers is a challenging task on direct measurement and spatial distribution variability for long-term in catchment scale. However, most groundwater studies in Saigon River Basin relied on hydraulic conductivity of aquifers and different piezometric heads without considering sediment riverbed properties and evaluating ratio between land recharge and river recharge. Hence, the approach of this study attempted to develop surface – groundwater interaction parameters via field measurements for better understanding the groundwater recharge process in Saigon River Basin. The land recharge movement was simulated via HYDRUS 1D and calibrated with monitor soil moisture. The seepage was measured and analyzed with grain-sized sediment along the Saigon River. Consequently, the field measurement pointed out two function for surface – groundwater interaction parameters: the land recharge function employing effective rainfall and sand percentage, and the conductance function with sand percentage of sediments. Furthermore, the surface water – groundwater fluxes exchange confirmed distinctly via δO^{18} evidence of river, groundwater, rainfall. As results of development groundwater model, the study pointed out the appropriate groundwater pumping intensity for the Saigon River Basin. Moreover, the results also figured out the sustainable groundwater yield and optimal pumping management under development social-economic scenarios via utilizing appropriate intensity and clarified groundwater recharge in Saigon River Basin.

1.7 Limitation of the Study

The limitations of the study describe as follow:

1. The study applied and used the existing dam operation release rule to simulate river - groundwater interaction fluxes for development scenarios, which maintained flow rate at least $20m^3/s$ to control the salinity of 4‰ at Phu An station.

2. On the regional scale, the land recharge function was considered homogeneous in same aquifer.

3. With the limited recorded salinity data, the study assumed that to maintain drawdown groundwater at the salinity interface as existing conditions will avoid more salinity move to the freshwater area.

4. The material sediments of riverbed are considered to be as current situation in the simulations.

1.8 Thesis content

The content of this dissertation is composed of 8 chapters and details of each chapter are as follows:

Chapter I introduction includes background and problems, objectives, research approach and scope, study procedures, outcome expected, research significant and limitation of the study

Chapter II study area includes the characteristic of study area such as the boundary and location, topography, meteorology, hydrology, land use, hydrogeology system, groundwater use, land use and trend of GDP

Chapter III literature review includes percolation estimation, river – groundwater interaction parameters, groundwater resources via stable isotope, groundwater pumping management.

Chapter IV techniques, theories and criteria used include techniques used in soil moisture sensor, river – groundwater interaction, groundwater modeling, groundwater budget, groundwater pumping management.

Chapter V the field measurement of interaction parameters, monitor soil moisture via soil moisture sensor, percolation process, direct measurement of the interaction flux (seepage meters), mass balance of isotopic compositions of groundwater, interpolation method for groundwater parameters distribution, groundwater flow model, groundwater flow budget, criteria used to estimate sustainable groundwater yield.

Chapter VI the surface water and groundwater interaction fluxes exchange, development groundwater modeling, calibration and verification parameters from field measurement, qualification the proportion sources of exchange fluxes by stable isotope composition of groundwater, river, and rainfall, flow budget under surface groundwater interaction

Chapter VII the recommendation on optimal groundwater pumping management for development scenarios, the water deficits under provincial and World Bank scenarios, estimate sustainable yield pumping management considering the limitation of drawdown, saline interface, land use, recommend optimal groundwater pumping management in Saigon basin for development scenarios.

Chapter VIII conclusions and recommendations include the conclusion in each chapter and the recommendations for optimal groundwater water management under sustainable groundwater yield and the next research issues.

CHAPTER II

STUDY AREA CONDITIONS

2.1. Topography

Study area stretches from latitude 10.32^0N to 11.2^0N and from longitude 106.2^0E to 107.02^0E. It covers an area of 6,640 km^2, including: Ho Chi Minh City, Binh Duong, Long an and Tay Ninh Province. Saigon basin topography is gradually lower from the north to the south and from the west to the east (Figure 2.1). Average elevation is from 2 to 5.2 m, except for some high hills in the northern delta province. Along the Saigon River, elevation is from the 0.1 to 6.0 m high, and then lowers to the central plains in the 1.0 to 1.5 m high, and only 0.3 to 0.7 m in the tidal, coastal area. The elevation of upstream varies 30-40 m. MSL and downstream's ranges 0.3-5 m. MSL.

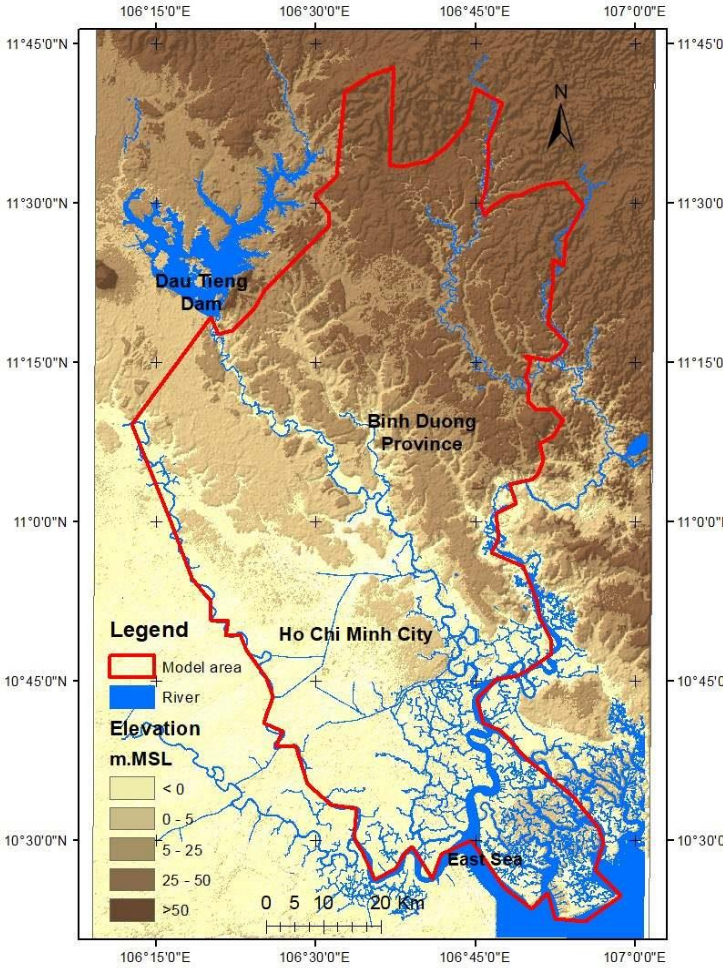


Figure 2. 1:Topography of study area

2.2 Climatic

Since Saigon River Basin located in tropical pacific region, the city has a tropical monsoon climate with wet and dry seasons. The rainy season is from May to November, and the dry season is from December to April of the following year. On average, Ho Chi Minh City has 160 to 270 hours of sunshine a month, the average temperature is 27 ° C, the highest is up to 40 ° C, and the lowest is 13.8 ° C. Every year, the city has 330 days average temperature of 25 to 28 ° C. The average rainfall is 1,949 mm/year, 159 days/year, with the highest rainfall in the months of 5 to 11, accounting for 90%, especially in June and September (General-Statistical-Office-of-Ho-Chi-Minh-City, 2012). This period also coincides with high tide season (Phi, 2007), causing floods in the city.

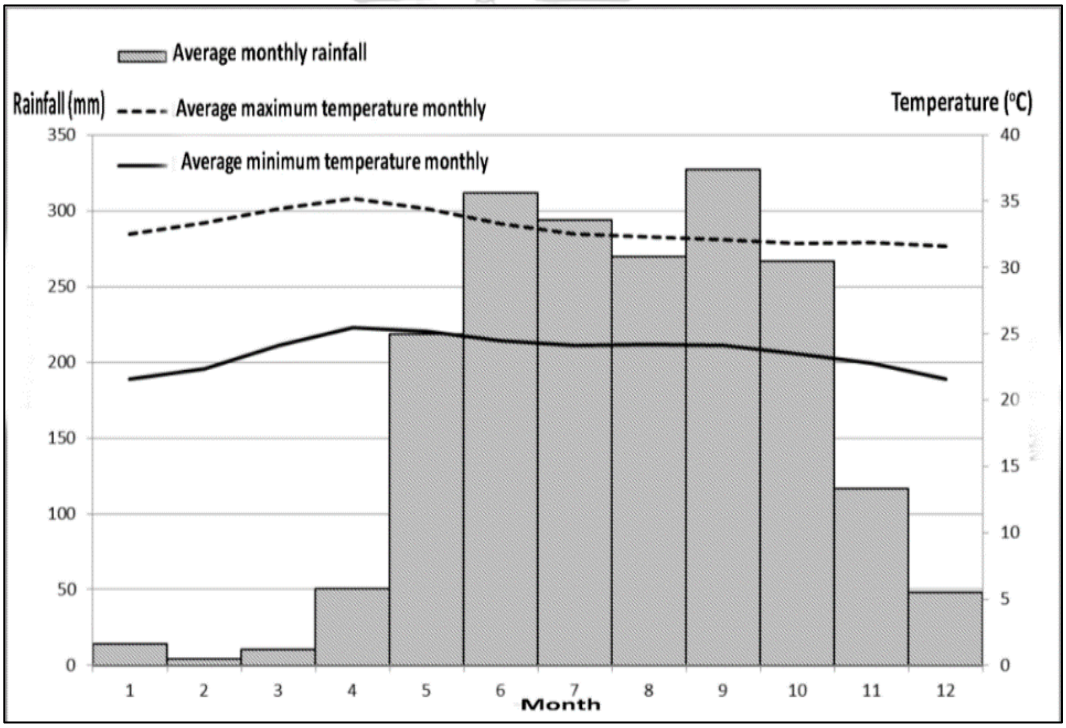


Figure 2. 2: Average monthly rainfall, average maximum temperature monthly, average minimum temperature monthly at Saigon River Basin (General-Statistical-Office-of-Ho-Chi-Minh-City, 2012)

2.3 Hydrology

Saigon River begins in the highland of Loc Ninh, near Vietnam-Cambodia border. The river then flows downstream along the western boundary of Binh Duong before entering the territory of Ho Chi Minh City (Figure 2.3). In Dau Tieng District of Tay Ninh

Province, the river is dammed to create Dau Tieng Reservoir, whose functions are flood control and irrigation for agricultural production in Ho Chi Minh City region. Dau Tieng reservoir affects a large area of Saigon River Basin (2,700 km). Its volume is 105 million m^3. It supplies water for irrigation and clean water supply in Tay Ninh Province (north of Dau Tieng reservoir), Binh Duong Province, Long An Province and Hochiminh City. Moreover, the reservoir also contributes to push back the salinity point because it discharges water to the downstream of Saigon River at a rate of 20 m^3/s to control a salinity of 4% at Phu An station (Dan, Ha, Than, Nga, & Khoa, 2007). For the rest of the year, water elevation of Saigon River is influenced mostly by semi-diurnal tidal, which changes four times a day. Besides tidal influence, flows volume of Dong Nai River also contribute significantly to the variation of water elevations in Saigon River (Phi, 2007).

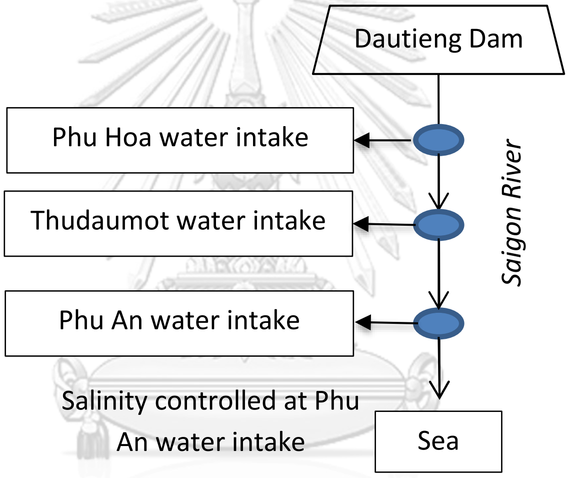


Figure 2. 3: Schematic Saigon River

2.4 Hydrogeology

Due to the soil profiles and distribution of soil types, there are four distinguished aquifers which have flux exchange with Saigon River, namely Upper Pleistocene (qp_3), Upper- middle Pleistocene (qp_{2-3}), Lower Pleistocene (qp_1), and Middle Pliocene (n^2_2). Generally, lithology of each aquifer consists of fine to coarse sand, gravel, and pebble. Figure 2. 4 illustrates 2 cross-sections for overview of the spatial distribution and interconnection of aquifer system in Saigon River Basin. Basically, the aquifer system in Saigon basin has an artesian basin structure. A brief characterization of the aquifers and their composition is summarized below.

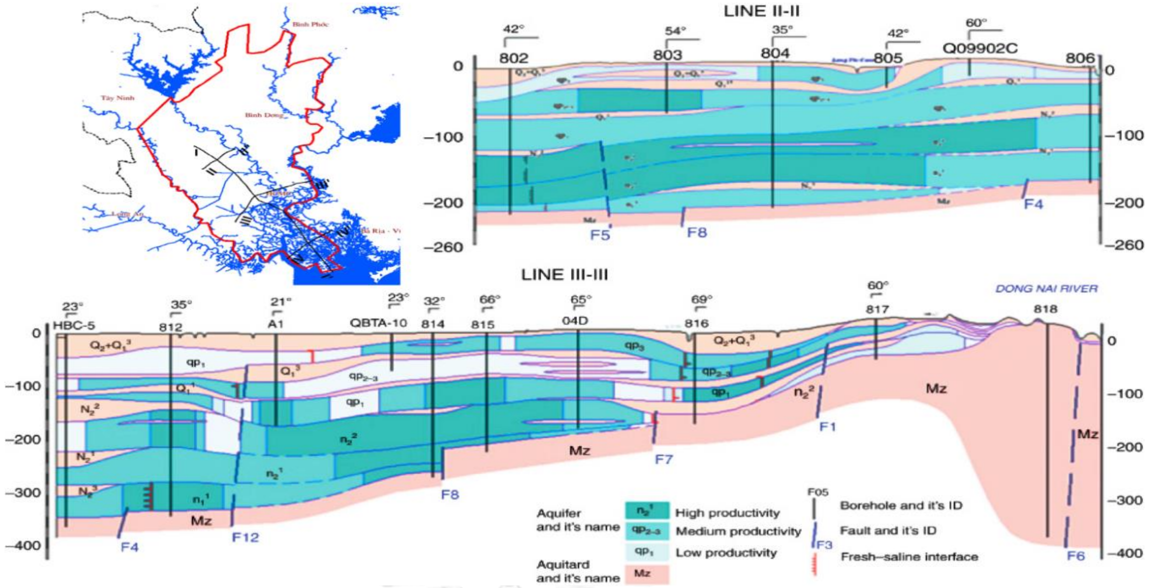


Figure 2. 4: Aquifer System in HCMC, Vietnam (Vuong, 2010)

2.5.1 Intergranular Upper Pleistocene aquifer (qp_3: aquifer 1)

Intergranular upper Pleistocene aquifer (qp_3) area covers 3,153 km^2 (see Figure 2. 5). This aquifer appears at south-west of study area. Top of aquifer is from 0.0 m. MSL to 65.0 m. MSL. The bottom of aquifer is from 6.0 m. MSL to 90.0 m. MSL. The aquifer thickness varies from 2.0 m to 63.0 m.

The main lithological compositions of the aquifer are fine – medium sand, somewhere is coarse sand, silt sand, sand silt.

According to pumping tests of 86 wells, the groundwater yield is poor to high productivity with groundwater discharge range from 0.05 to 11.48l/s, groundwater level drawdown ranges from 0.2 to 19.24m.

Poor productivity area distributes from Cu Chi district to Le Minh Xuan Ward and small area in district 9. Medium productivity area distributes at apart of Cu Chi, Go Vap and Can Gio District. High productivity area distributes at small part in the study area.

Fresh water area is 1,959 km^2 distributed in the north of Saigon River Basin from the center to Cu Chi district. Results of chemical analysis show that total dissolved solids (TDS) range from 0.04 to 0.51g/l (average as 0.1g/l), pH ranging from3.81 to 7.32 (average as 5.99), average hardness is 1.12(mg/L) (soft water) and typical water types are chlorine and bicarbonate.

While, salinity water area is about 1,199 km^2, distributes at the south of the study area including Can Gio and Nha Be district, district 9 and the south of Binh Chanh District. Results of chemical analysis show that total dissolved solids (TDS) range from 1.75 to 21.23g/l (average as 10.60g/l), pH ranging from 3.1 to 7.6 (average as 5.17), average hardness is 81.5(mg/L) (hard water) and typical water types are chlorine and bicarbonate.

In summary, intergranular upper Pleistocene aquifer (qp_3) distributes on shallow area and water in the freshwater area has good water quality. However, thickness is thin, therefore potential of groundwater exploitation of this aquifer seem to be not much, and it can be appropriate only for domestic water supply of household with small capacity. Hence, the piezometric heads of this aquifer have not changed much in decade years. (Figure 2. 9)

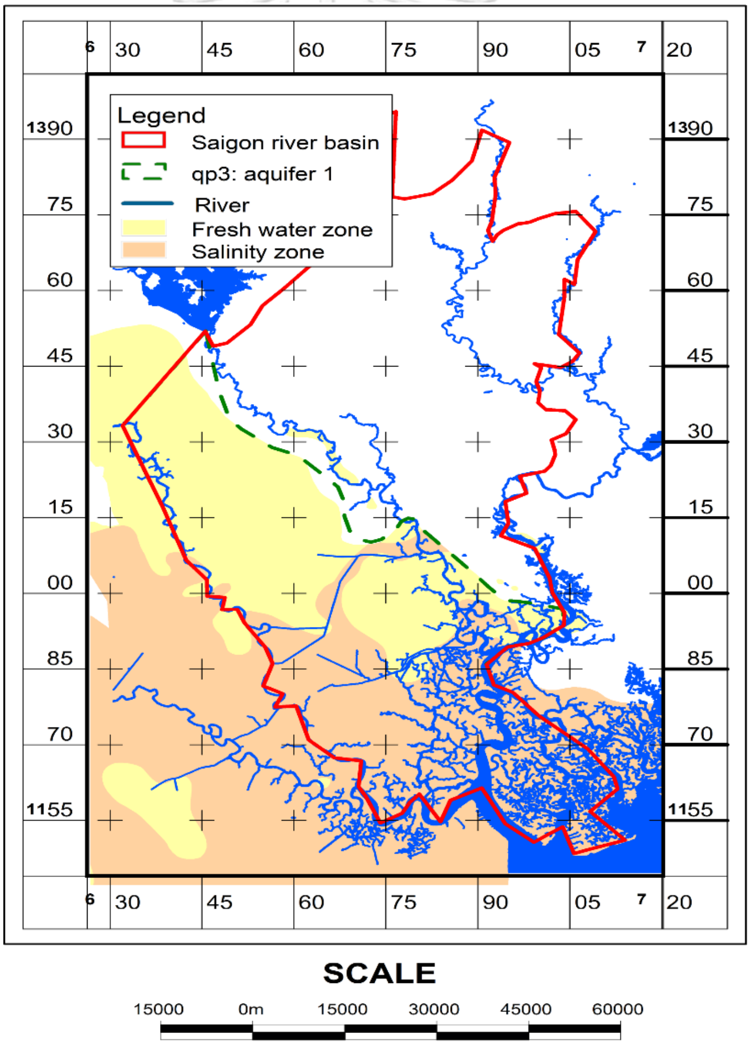


Figure 2. 5: Upper Pleistocene aquifer distribution map (Vuong, 2010)

2.5.2 Intergranular Upper - middle Pleistocene aquifer (qp_{2-3}: aquifer 2)

Intergranular Upper-middle Pleistocene aquifer (qp_{2-3}) area covers 2,620 km^2 (see Figure 2.6). This aquifer appears at south-west of study area. The top of aquifer is from 0 m. MSL to 120.0 m. MSL. The aquifer bottom is from 4.0 m. MSL to 155.0 m. MSL. The thickness varies from 4.0m to 84.0 m

The main lithological composition of the aquifer is fine to coarse sand.

According to pumping test results of 112 wells, the groundwater yield is from poor to high productivity with groundwater discharge range from 0.34 to 36.1 l/s, groundwater level drawdown ranges from 0.19 to 20.94 m.

Poor productivity area distributes at Cu Chi district, the City Centre area and district 9. Medium productivity area distributes on western apart of Cu Chi and Binh Chanh district and eastern part of Thu Duc district and Can Gio district, Binh Duong province. High productivity area distributes at district 12, 7, Hoc Mon, Binh Chanh and a small part in Cu Chi district.

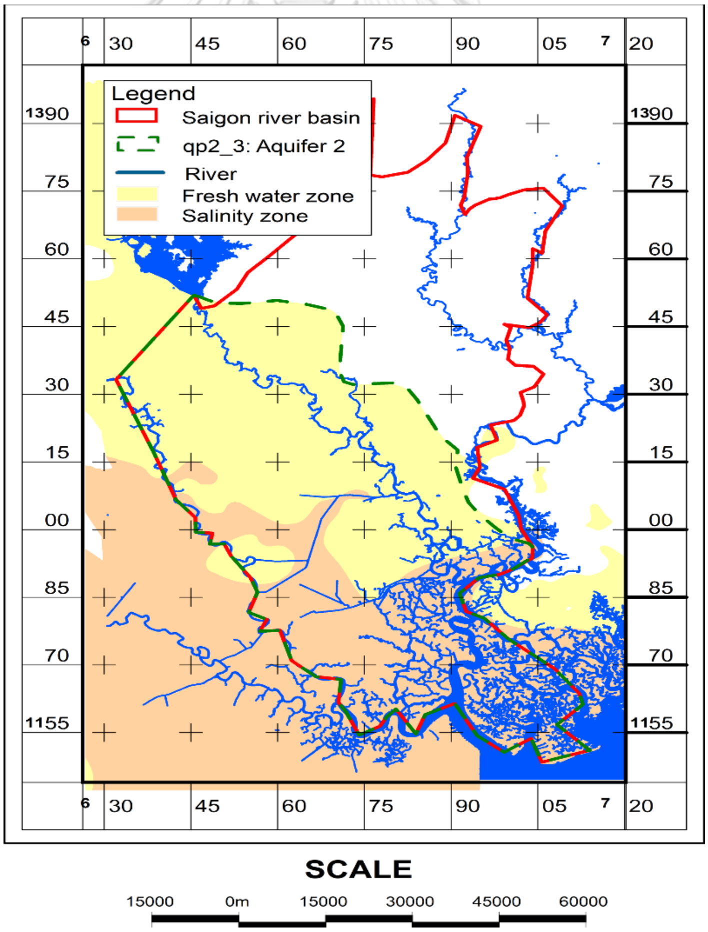


Figure 2. 6: Upper - middle Pleistocene aquifer distribution (Vuong, 2010)

Fresh water area distributes on 1,430 km^2 at Cu Chi, Tan Phu, Binh Tan, Hoc Mon, District 12, Go Vap and Thu Duc. The water quality in the area is as follows: total dissolved solids (TDS) ranging from 0.03 to 0.83g/l (average 0.10g/l), pH ranging from 3.52 to 7.80 (average 6.58) and average hardness 0.42(mg/L). Typical water types are: chlorine, chlorine - bicarbonate, chlorine – sulfate and bicarbonate - chlorine.

While, salinity water covers on area 1,190 km^2, including District 9, Nha Be, Binh Chanh, and Can Gio district. Total dissolved solids (TDS) are from 1.75 to 8.65 g/l (average 3.71g/l). pH is from 2.80 to 4.80. Average hardness is 33.80 (mg/L). The typical water type is chlorine.

In summary, potential groundwater exploitation of this aquifer seemed to be good, due to the fresh water distribute on the large area of 1,430 km^2. As shallow aquifer, the aquifer was mainly exploited for household. Moreover, the abstraction is growing every year. Therefore, this aquifer is facing dramatically declining groundwater levels (see Figure 2.9).

2.5.3 Intergranular Lower Pleistocene aquifer (qp_1: aquifer 3)

Inter-granular Lower Pleistocene aquifer (qp_1) area covers 4,442 km^2 (see Figure 2. 7). According to, the results of 302 wells, the aquifer top depth varies from 11.0 to 160.0 m and bottom depth varies from 25.0 m to 195.0 m, and average thickness is about 27.1 m.

The main lithological composition of the aquifer is fine to coarse sand, gravel sand. According to pumping tests results of 54 wells, the specific yield is poor to high productivity with groundwater discharge range from 0.52 to 39.77 l/s, groundwater table drawdown is in the ranges from 1.0 to 25.0 m and specific discharge is in the range from 0.014 to 5.560 l/s.

Poor productivity area distributes at Cu Chi district, Tan Phu District, district 2 and district 9 of Hochimnh City. Medium productivity area distributes on western apart of Cu Chi, Binh Chanh District, the City Centre, and Can Gio District. High productivity area distributes at District 12, 7, Thu Duc, Hoc Mon, Binh Chanh and a small part in Cu Chi District.

Fresh water area which covers 3,285 km^2, distributes at the north of Saigon River Basin. Total dissolved solids (TDS) is in the range 0.04 to 0.73g/l (average 0.17g/l), pH ranging from 3.25 to 8.32 (average 6.48), and average hardness is 1.56(mg/L). The typical water types are chlorine, chlorine – bicarbonate and bicarbonate.

Saltwater area is approximate 1,157 km^2. The salinity area distributes at western part of Cu Chi district, Binh Chanh district, Nha Be district, district 7, and Can Gio district. Total dissolved solids (TDS) are from 1.82 to 14.21g/l (average 7.27 g/l). pH is from 3.50 to 7.50 (average 4.75). Average hardness is 42.15 6(mg/L). The typical water type is chlorine.

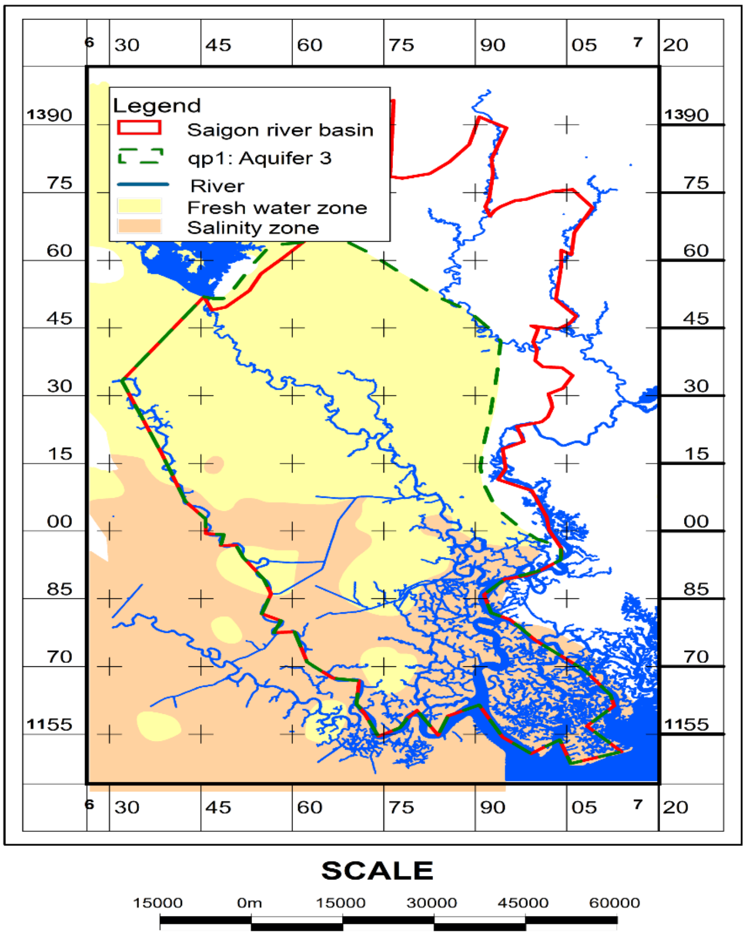


Figure 2. 7: Lower Pleistocene aquifer distribution (Vuong, 2010)

In summary, freshwater area of this aquifer distributes on large area of 3,285 km^2. This aquifer is mainly supplied for domestic use purpose. However, due to narrow thickness and high wells density in Ho Chi Minh City, this aquifer is also facing dramatically declining groundwater level under cause exceed abstraction (Figure 2.9).

2.5.4 Inter-granular middle Pliocene aquifer (n_2^2: aquifer 4)

Inter-granular middle Pliocene aquifer (n_2^2) covers on the area of 6,640 km^2 (see Figure 2. 8). The top aquifer is from 34.0 m to 209.0 m. The bottom aquifer varies from 55.0 to 236.0 m. The thickness is from 10 m to 85.0 m.

The main lithological composition of the aquifer is fine sand somewhere is coarse sand and gravel sand.

According to pumping tests results of 100 wells, the groundwater yield is poor to high productivity with: groundwater discharge ranges from 0.12 to 28.57 l/s, groundwater table drawdown ranges from 0.15 to 35.00 m and specific discharge range from 0.012 to 3.47 l/s.

Poor productivity area distributes on small area. Medium productivity area distributes on northern apart of Cu Chi and Hoc Mon district, district 9, district 7 and Can Gio district, Tay Ninh province. High productivity area distributes at district Cu Chi district and center of Ho Chi Minh City, Binh Duong Province.

Fresh water is located from Cu Chi district to the City Centre and Ben luc District on area of 5,728 km^2. Results of 24 chemical analysis show that total dissolved solids TDS is in the range from 0.02 to 0.96 g/l (average 0.22 g/l), pH ranging from 4.75 to 8.34, and average hardness is 1.652 (mg/L). Typical water types are chlorine, chlorine - bicarbonate, bicarbonate, and bicarbonate - chlorine.

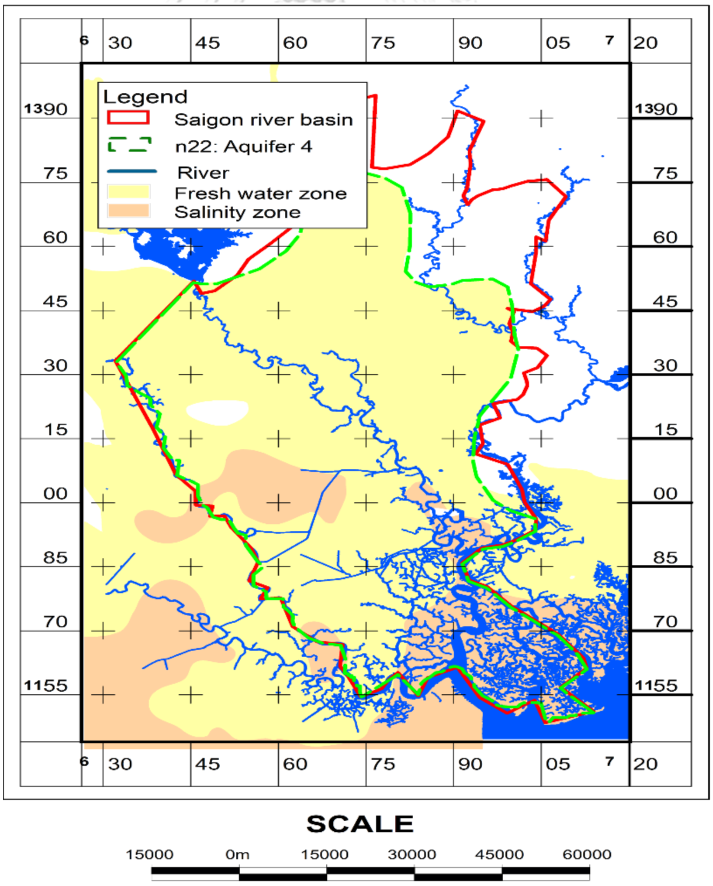


Figure 2. 8: Middle Pliocene aquifer distribution (Vuong, 2010)

Saltwater is located at the southern part of the Saigon River Basin near the coastal on area of 912 km^2. Results of 14 chemical analyses show that total dissolved solids are in the range from 1.39 to 51.00 g/l (average 14.79 g/l). pH is from 1.39 to 8.30. Average hardness is 74.69 (mg/L). Typical water types are chlorine, and chlorine – bicarbonate.

In summary, this aquifer is medium depth and freshwater area is large. Water quality is good. In currently, this aquifer is main target of abstraction wells for domestic and industrial. Hence, this aquifer is also facing declining groundwater level problem. The drawdown is low down more than 20m for over 20 years (Figure. II-9).

The areal extent and main parameters of the aquifer system are summarized in Table 2. 1.

Table 2. 1: The main parameters of the aquifer system in Saigon River Basin (Vuong & Long, 2016)

Parameters	Aquifer 1 (qp_3)	Aquifer 2 (qp_{2-3})	Aquifer 3 (qp_1)	Aquifer 4 (n_2^2)
Distribution area (km^2)	3,158	4141	4983	6,640
Saline GW area(km^2)	1199	1190	1157	912
Fresh GW area (km^2)	1,959	2,951	3,826	5,728
Average thickness	22.6	27.2	27.1	37.6
Head above the top of aquifer (m)	8.83	35.59	72.44	111
Specific yield (μ)	0.255	0.261	0.258	0.258
Specific storage (μ^*)	0.00901	0.00227	0.00133	0.00066

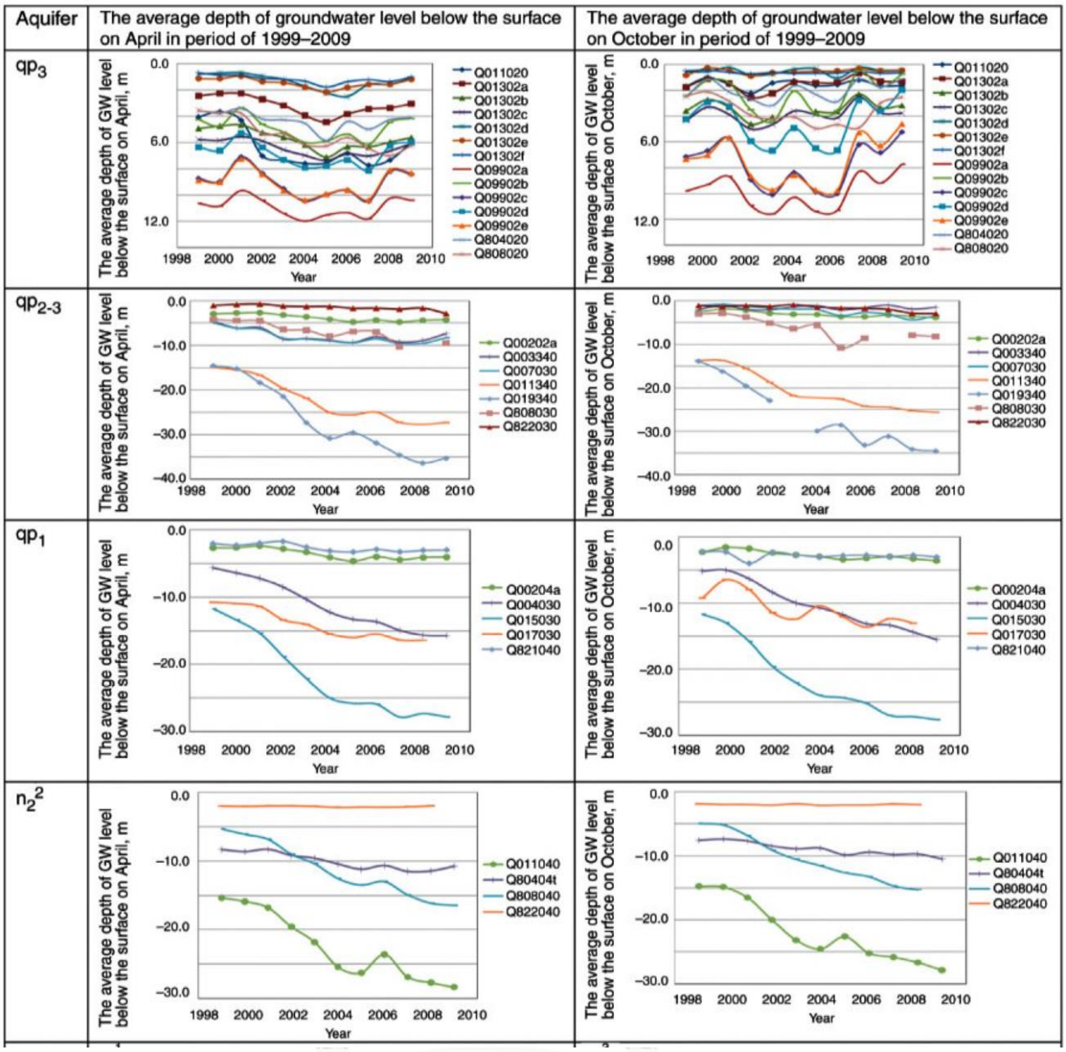


Figure 2. 9: Average depth of groundwater level below the surface for April in the period 1999 –2009 at monitoring wells in center part of Saigon River Basin (Vuong & Long, 2016)

2.5 Land use & salinity

According to planning land use by 2030 report by Ministry Of Natural Resources And Environment Vietnam (2013), the agriculture cover 50.1% of total land use, which is 3,335 km^2; the urban area distribute in the center of the basin with 3,265 km^2. In general, the urban located mainly in downstream Saigon River Basin as Hochiminh City and Binh Duong Province. In the 10-year period, agricultural land of Hochiminh City reduced by 6 % while non-agricultural land increases by 7%. Likewise, Binh Duong Province will decrease agricultural land 1% and increase non-agricultural land 1% yearly. Table 2. 3 indicates the officially master plan land use for Binh Duong between the years 2015 and 2020. Table 2. 3 highlights the officially documented land-use changes in HCMC between the years 2000 and 2010.

Table 2. 2: Master plan of land use for Binh Duong province (Vietnam Government, 2018)

	2015		2016		2017		2018		2019		2020	
Criterion	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
Agricultural land	207.61	65	207.45	64	204.20	63	195.79	60	194.662	60	190.535	58
Non-agricultural land	61.85	19	62.02	19	65.26	20	73.74	23	74.802	23	78.929	24
Urban land	51.47	16	52.29	16	53.10	16	54.73	17	56.369	17	58	18

Table 2. 3: Documented land-use changes in HCMC (Ministry Of Natural Resources And Environment Vietnam, 2013)

	2000		2005		2010	
Criterion	ha	%	ha	%	ha	%
Agricultural land	130,720	62	123517	59	118052	56
Agriculture	91139	70	77955	63	72143	61
Forestation	33472	26	33858	27	34117	29
Aquaculture	4149	3	9765	8	9441	8
Salt marsh	1959	2	1471	1	1943	2
Other agricultural land	0	0	468	0	408	0
Non-agricultural land	74294	36	83774	40	90868	43
Residential land	16686	22	20521	25	23666	26
Public land	19602	26	28535	34	32974	36
Religious land	0	0	400	1	410	1
Cemetery	998	1	925	1	951	1
Rivers & lakes	36163	49	33250	40	32813	36
Other non-agricultural land	919	1	143	0	54	0
Unused land	4414.5	2.1	2263.7	1.1	635.5	0.3
Total land	209501.8	100	209554.5	100	209554.9	100

Groundwater in the central and the northern areas are fresh water with TDS concentrated <1,000 mg/L, whereas groundwater the southern area, part of the western area, defined as saline water due to higher TDS concentrations. The salt intrusion in groundwater are mainly from seawater (Ngo, Lee, Lee, & Woo, 2015). Figure 2 shows 10 demonstrated land use in the study area.

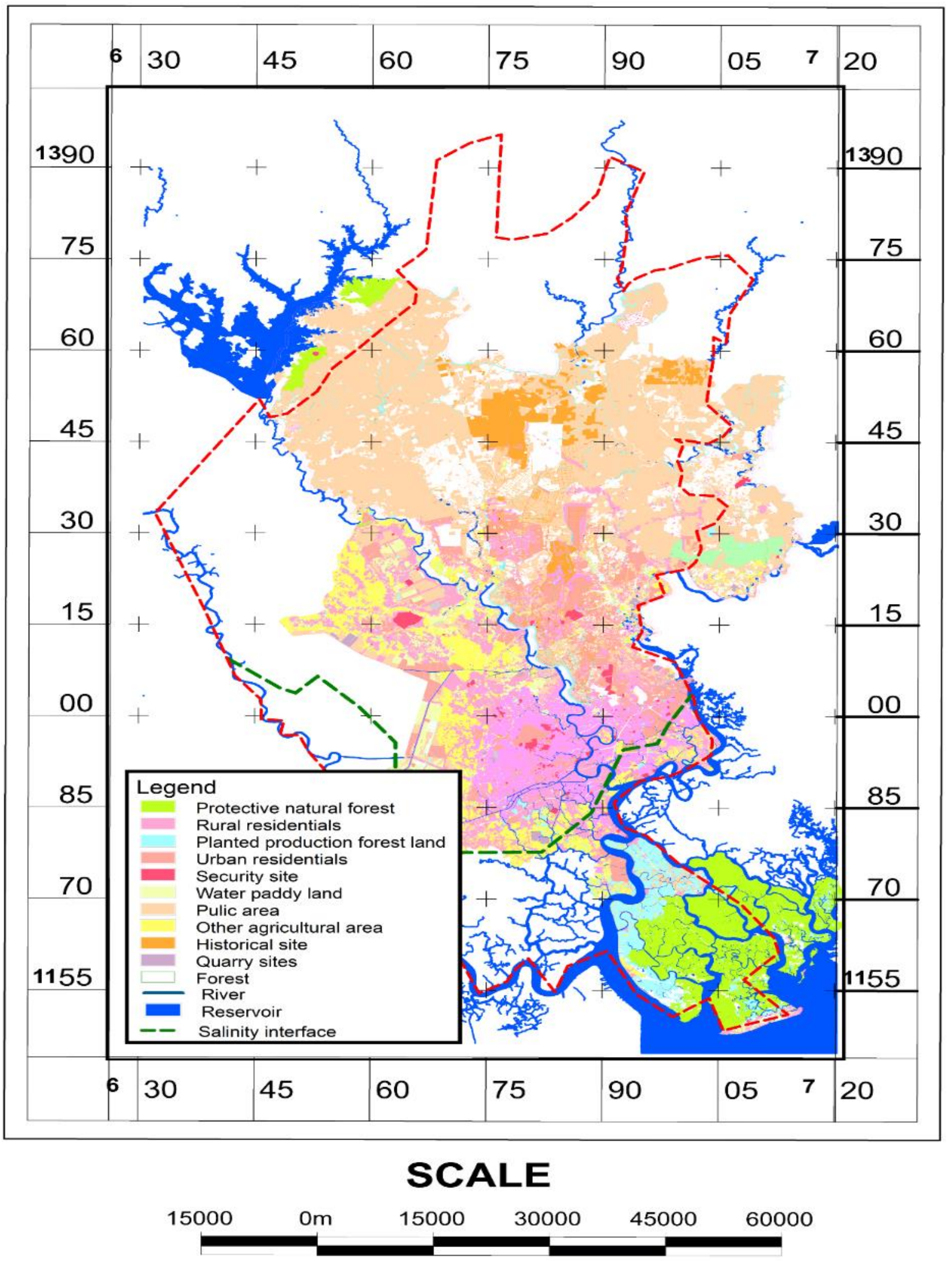


Figure 2. 10: Land use map (Ministry Of Natural Resources And Environment Vietnam 2013)

2.6 Current groundwater use

Since 1920, groundwater has been used as a source of water supply in Ho Chi Minh City. Under pressure of expanding industrial and urbanization, water demand has been increasing since 1990 when the economic development policies of Viet Nam have been adapted. However, the developing of surface water infrastructure in HCMC has not met growing water demand. Besides, the free of charge groundwater resources has also led the increasing abstraction in center part of Saigon River. According to survey report from Division for Water Resources Planning And Investigation For The South Of Viet Nam DWPRIS (2000), Nga (2006), Division for Water Resources Planning And Investigation For The South Of Viet Nam DWPRIS (2019), the groundwater exploitation was increased from 267,066 m^3/day in 1995 to 883,135 m^3/day in 2017. Because of large thickness, the groundwater pumping was proceeded mainly in aquifer 2 (qp_{2-3}) and aquifer 4 (n_2^2). At the current, 55% of groundwater was exploited for households, while the industries employ 45% of groundwater abstraction in the region for their activities. Details of groundwater abstraction in 4 aquifers were shown in the Figure 2. 11.

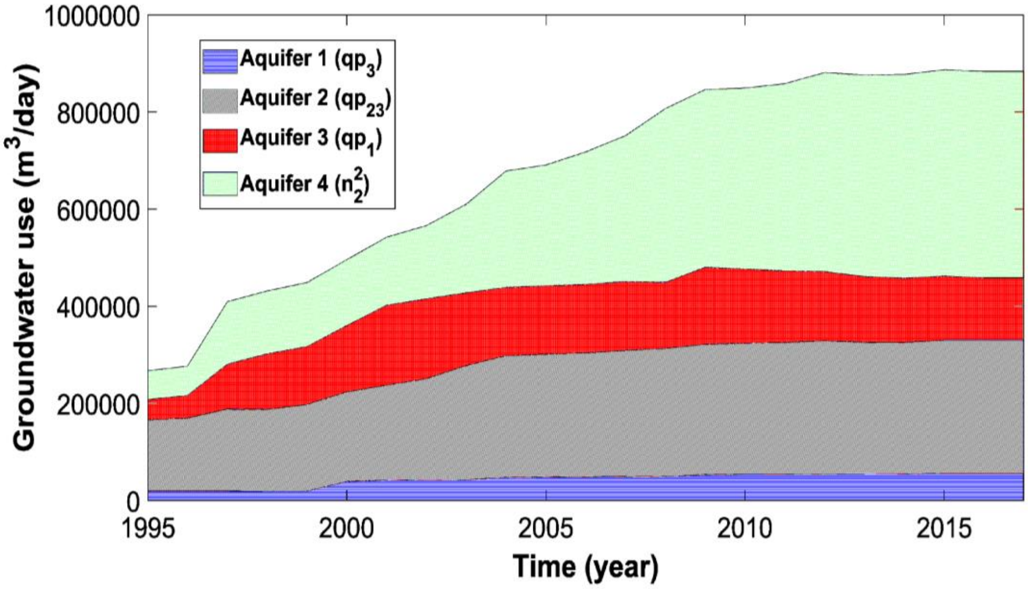


Figure 2. 11: Groundwater abstraction of 4 aquifers from 1995 to 2017 (DWPRIS ,2019)

2.7 Trend of GDP

Saigon River Basin include 2 big industry areas of Vietnam: Hochiminh City and Binh Duong Province. Ho Chi Minh City is a delta city and the largest conurbation in Viet

Nam. In 2016, GRDP of Ho Chi Minh City achieved USD45.29 billion with the growth rate of 8.05% annually. In particular, the service sector was the dominant contributor with USD24.8 billion, comprising 54.8% of the city's economy, followed by the industrial & construction sector and the agriculture-forestry-fishery sector, accounting for 0.84% and 28.76% respectively. The city has a population of approximately 8.5 million projected to increase to 10 million by 2025 and is the economic hub of Viet Nam with an estimated gross domestic product (GDP) of USD43.7 billion. The Binh Duong Province's GDP grew by 8.5 percent in 2016, higher than the national average of 6.2 percent. The average GDP per capita in the province was US$ 4949.56 (VND108.6million), more than twice the national GDP per capita at US$ 2,215 (VND48.6 million). Currently, industry accounts for 63 percent of the economy, while services and agriculture account for 23.5 percent and 4.3 percent respectively. Within the general growth of region, the industrial and construction sectors increased at 9.1% – the leading rate among the sectors. The service sector and the agro-forestry-fisheries sector kept their momentum with upsurges of 6.9% and 2.2%, respectively. According to GDP growth rate, the water demand increase rate of irrigation sector, industry sector, and household was projected 1% annual increase, 7% annual increase, and 4% annual increase, respectively. (World Bank, 2017)

CHAPTER III

LITERATURE REVIEW

Both groundwater and surface water are the fundamental sources of many natural processes and human activities. As part of the hydrological cycle, both groundwater and surface water interact in a variety of physiographic and climatic landscapes, and thus, should be treated as one entity (McCallum, Andersen, Giambastiani, Kelly, & Ian Acworth, 2013; Marios Sophocleous, 2002; T. C Winter, Harvey, Franke, & Alley, 1998). Understanding of these processes is the key to evaluating the ecological structure of groundwater resources systems and their management, especially under pressure of pumping rate. In spite of numerous archiving methods to estimate percolation, to determine river recharge, to investigate sources of recharge, these methods somehow remain restraint on the monitored duration and on evaluating the proportion of exchange flux between surface water – groundwater. This study pursues approach which included daily monitored field, isotope analysis, monthly groundwater modeling to clarify interaction fluxes between surface water and groundwater in the Saigon River Basin. To develop groundwater management, this approach pointed out the appropriate intensity groundwater pumping for Saigon River Basin. Table III-1 summaries conventional methods for estimating exchange fluxes of the groundwater – surface water interaction. Moreover, the results also figured out the sustainable groundwater yield with drawdown criteria and optimal pumping management under development social-economic scenarios via utilizing appropriate intensity and clarified groundwater recharge in Saigon River Basin. The section below brief conventional methods for estimating fluxes at the groundwater – surface water interface and groundwater pumping yeild and management.

Table III- 1: Summarized conventional methods for estimating exchange fluxes of the groundwater – surface water interaction

Method	Sources	Deep percolation	Riverbed's conductance	Investigated the sources of recharge	Duration	Dimensions measure	Results
Zero flux plane	Khalil et al. (2006)	X			Every 5 days	10-100cm depth 1 mx1 m cross-section	Percolation rate of sandy clay soil: 2.4 cm/day.
Water-Table Fluctuation	Nimmo, Horowitz and Mitchell (2015)	X			1-40 days	Top aquifer depth in local scale	Ratio land recharge and rainfall 0.19-0.42
Water balance + lysimeter	Upreti and Ojha (2015)	X			Daily	10-100cm depth 1 mx1 m cross-section	Percolation rate of sandy loam: 0.4-0.7 mm/day.
Vertical hydraulic gradient	Sakata et al. (2016)		X		monthly	10-40 m depth x 10km length	Seepage rage 1m^3/s/km
Inverse modeling	Tuan Pham Van and Sucharit Koontanakulvong (2018)		X		monthly	Riverbed thickness x 10km length	Riverbed conductance 1.2-4.5 m/day
Isotope samples	Fareze et al. (2016), González-Trinidad et al. (2017)			X	1 Year	65-114m	Indicated proportion of recharge sources
Monitor soil moisture + seepage meters + isotope samples	This study	X	X	X	Daily - monthly - quarterly	10-500cm depth in local scale for land recharge, 40 cm depth in 20 km length for riverbed.	

3.1 Deep percolation estimation

Since 1960s, there are varied commonly methods using to estimate natural ground water recharge (Kumar, 1997): i) Soil water balance method; ii) Zero flux plane method; iii) Inverse modeling technique;

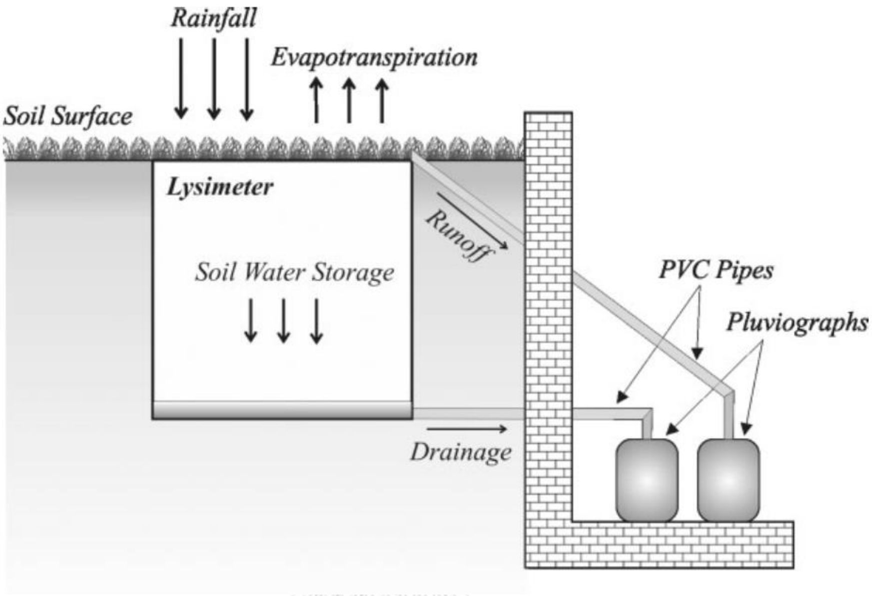


Figure 3. 1: Schematic representation of the controlled variables in lysimeter (Feltrin et al., 2011)

The soil water balance model was first applied to estimate drainage from precipitation for developing water crop yield since 1960s (Baier & Robertson, 1966; Baier & Section, 1972; Nix, 1975; Reddy, 1983). Lysimetry has long been used successfully as field measuring to estimate soil moisture change and deep drainage (Figure. III-1). However, most of the application in irrigated agriculture was applied in paddy field scale, so the surface runoff was assumed negligible (Hassan & Bhutta, 1996; Lal, 1991). This assumption lead to overestimate groundwater recharge. Later, the models have been modified to build direct recharge function from rainfall (Feltrin et al., 2011; Gee & Hillel, 1988; Lal, 1991; Lloyd, 1986). The direct runoff was estimated by SCS method. The soil moisture change was measured by gravimetric technique, electrical-resistance, heat-diffusion, absorption, tensiometric, penetration, radioactive. The disadvantage of the method is required a lot of data for calibration and validation in spatial and time (Kumar, 1997; Simmers, 1987).

Kendy et al. (2003) estimated precipitation and irrigation-generated areal recharge via simple soil-water-balance model from easily accessible climate, loam soil and crop data. the model assumption includes water flows vertically downward under a unit gradient; evapotranspiration was calculated by the function of leaf-area index; and evaporation and transpiration are distributed through the soil profile as exponential functions of soil and root depth, respectively. According to 12 success test sites, the drainage from the soil profile indicated linear with precipitation and irrigation inputs.

Thomas, Molénat, Caubel, Grimaldi, and Mérot (2008) examined components of the water balance related to root-water uptake in the soil below a hedgerow. The temporally and spatially heterogeneous boundary conditions was simulated via the modified SWMS-2D model. The validation indicated good performance with observed data from a previous field study. The study found that soil-water content is significantly depending on the root-water uptake.

Upreti and Ojha (2015) quantified deep percolation in sandy loam via the water-balance approach. The evapotranspiration was employed through Penman-Monteith method. A lysimeter setup surrounded by the field has been installed in the field lab to conduct the field water contents. Regular measurements of soil moisture were made at the depths 0-20 cm, 20-40 cm, 40- 60 cm, 60-80 cm and 80-100 cm using gravimetric method. The deep percolation was estimated from 0.4-0.7 mm/day.

Besides, the zero-flux plane (ZFP) is the common method to estimate water movement in unsaturated soil. The method relies on the location of a plane of zero hydraulic gradient in the soil profile. Recharge over a time interval is obtained by summation of the changes in water contents below this plane. The position of the zero-flux plane is usually determined by installation of tensiometers.

M. Sharma, Bari, and Byrne (1991) computed variations in recharge over a period of three years beneath a native vegetation utilizing the zero-flux plane method. The fields data were measured via a neutron probe at eight locations beneath a native vegetation in a semiarid region, Western Australia, under precipitation of 775 mm/year. The study found that water flux at a depth of 18 m (just above the water table) varied from 65 to 80 mm/ year.

Khalil, Seki, Miyazaki, Mizoguchi, and Sakai (2006) analyzed of the ZFP movements in sandy clay soil from laboratory experiments and numerical simulations. Periodical water supply experiment was done for 18 days. 10 mm of water was provided 5 times periodically (1st, 5 th, 8 th,12 th, 15th day) to the top of the column. The rate of the downward movement of ZFP for sandy clay soil was estimated 2.4 cm/day.

Brutsaert (2014) demonstrated further insight in the nature of this zero-flux plane. The results showed the depth of the zero-flux plane increases gradually as evaporation and infiltration proceed, this increase is likely to be quite limited. The obtained expression seems close to an exponential decay function of time in long duration.

Numerical modeling has often been used this function to predict the water flux through the unsaturated zone: such as UNSAT-H (Fayer & Jones, 1990), DAISY(Hansen, Jensen, Nielsen, & Svendsen, 1990), SWIM (Krysanova, 2000), and HYDRUS (Simunek et al., 2005) have been widely adopted to predict recharge estimates using the basis of Richards' Equation (Benson, 2007). These models were applied successful to evaluate coefficients of groundwater recharge by the precipitation (Yeh, Lee, Chen, & Chen, 2007), estimate average mean annual groundwater recharge (Cao, 2011), analysis the impact of different thickness and lithology of vadose zone to groundwater recharge (Lu, Jin, van Genuchten, & Wang, 2011).

Van den Bosch, Ritsema, Boesten, Dekker, and Hamminga (1999) examined the flow process in sandy soils with different horizon stratification and land use via ne-dimensional convection–dispersion model. Field average soil water content and bromide profiles were measured seven times in 474 days. The drainage through the bottom of the profile at 2 m below soil surface was calculated 20 cm after receiving 80 cm precipitation in 474 days.

Wang et al. (2014) estimate the yield and water productivity (WP) for melon in Gansu province, Northwest China via developed one-dimensional soil water flow. The model based on CHAIN 2D coupling with crop growth model of EPIC to simulate the dynamic root growth, root water uptake and crop yield under different furrow irrigation scenarios for melon in the study area. Soils in the experimental site are sandy loam at the depth of 0–30 cm and silt loam at depths larger than 30 cm. Simulation of total water use, leaf area index, melon yield and soil water dynamics fitted well with the field observations. The water yield increased through a quadratic function of relative irrigation.

Koontanakulvong and Suthidhummajit (2015) investigated the relationship of recharge rate with climate condition, to assess the impact on groundwater recharge in the Upper Central Plain. The relationship of recharge rate with climate data was developed in terms of precipitation, evaporation and temperature and soil type under monthly time series data via inverse groundwater modeling. The recharge functions were comprehensively correlated with precipitation minus evaporation and be able to apply to the impact of climate change on groundwater recharge and water table based on future climate data.

Ehtiat, Mousavi, Vaghefi, and Ghaheri (2016) estimated recharge rates by using autocalibration, empirical return coefficient and distributed hydrological modelling (SWAT) approaches. The models were finally compared and validated against observed monthly data on groundwater levels at observation wells for a 5-year historical period. The results of a groundwater model would rely on a trade-off between the accuracy of the estimated spatial-temporal variations of recharge and the significance of its impact on the water budgets of a groundwater system.

3.2 River and groundwater interaction parameter determination

Groundwater-river water interaction has received a lot of attention in recent decades. Thomas C Winter and Rosenberry (1995) and Thomas C Winter (1999) provided similar approach, focusing particularly on the hydrologic conditions related to various types of surface waters beds. Marios Sophocleous (2002) summarized the fundamental concepts and implications of groundwater – river water from a predominantly hydraulic- hydrogeological viewpoint. Rosenberry and LaBaugh (2008) as well as Kalbus, Reinstorf, and Schirmer (2006) give overviews of field techniques for estimating fluxes between groundwater and surface water at different scales. However, the regional scale groundwater modeling still remains challenging task when dealing with heterogeneities in the aquifer and surface water channels (e.g. Fleckenstein, Niswonger, and Fogg (2006)). This makes it difficult to transfer knowledge obtained at the point scale to the local and catchment scale (Barthel & Banzhaf, 2016). There are three of the most commonly used methods to measure flow of water between surface-water bodies and the ground-water domain: water-level measurements and flow-net analysis; hydraulic potentiomanometer; seepage meters.

The flow-net analysis method, often called the “Darcy approach,” is probably the most frequently used method for quantifying flow between ground water and surface water, especially on a whole-lake or watershed scale. In this method, a combination of measurements of water levels in wells near shore and measurements of river water stage are used to calculate gradients and water flow between the wells and the surface-water body

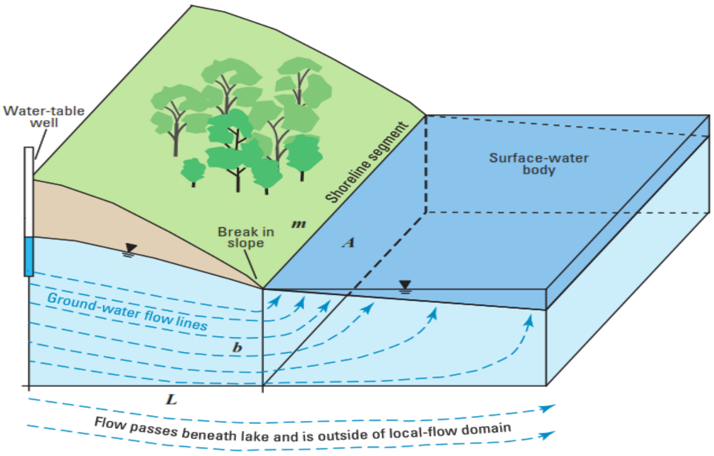


Figure 3. 2: Typical hydraulic conditions in the vicinity of the shoreline of a surface-water body (Rosenberry & LaBaugh, 2008)

This approach is wisely applied in groundwater modeling. While being apparently straightforward, the concept has been criticized, as the streambed leakage coefficient or hydraulic conductivity river bed, which is typically not measurable directly in the field, can also change drastically over time (Kollet & Maxwell, 2006). Therefore, it is usually determined by inverse modeling together with other parameters, e.g. the hydraulic conductivity of river bed (Carrera, Alcolea, Medina, Hidalgo, & Slooten, 2005; Kollet & Zlotnik, 2003; Tuan & Koontanakulvong, 2017). A calibrated modeling parameter which can hardly be verified or even constrained by field observations represents a considerable weakness of mechanistic modeling concepts. Therefore, the flux exchange need to be evaluated with others method in order to avoid violation of underlying assumptions (Rosenberry & LaBaugh, 2008).

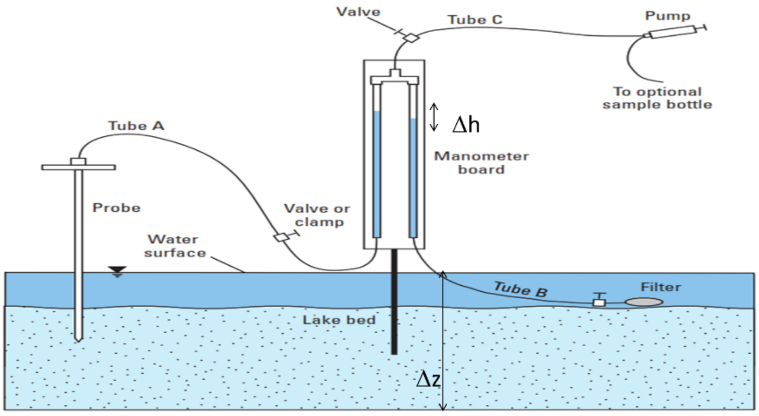


Figure 3. 3: Components of the hydraulic potentiomanometer system (T. Winter, LaBaugh, & Rosenberry, 1988)

The hydraulic potentiomanometer, sometimes referred to as a mini-piezometer, is a portable drive probe connected to a manometer (Figure III-3). The manometer provides a comparison between the stage of a surface-water body and the hydraulic head beneath the surface-water body at the depth to which the screen at the end of the probe is driven (T. Winter et al., 1988). The difference in head divided by the distance between the screen and the sediment-water interface is a measurement of the vertical hydraulic-head gradient. This hydraulic gradient applied to calculate hydraulic conductivity of the sediments at riverbed. Head differences can be amplified by use of alight oil in place of air at the top of the manometer (S. E. Kelly & Murdoch, 2003). This method is useful to determine the horizontal and vertical extent of unsaturated sediments (Rosenberry, 2000; Schubert, 2002).

Duff, Toner, Jackman, Avanzino, and Triska (2000) determined groundwater discharge into a sand and gravel bottom river via chloride dilution and seepage meter techniques. Chloride dilution experiment was processed at four locations along the study reach, 165, 294, 468 and 580 m from the injection site. Seepage flux measurements were made during two passes through the reach. The direct estimates of groundwater discharge by chloride dilution give better proportion sources of recharge than seepage meters. Meanwhile, the seepage meters are possible to indicate the flow direction between river and aquifers.

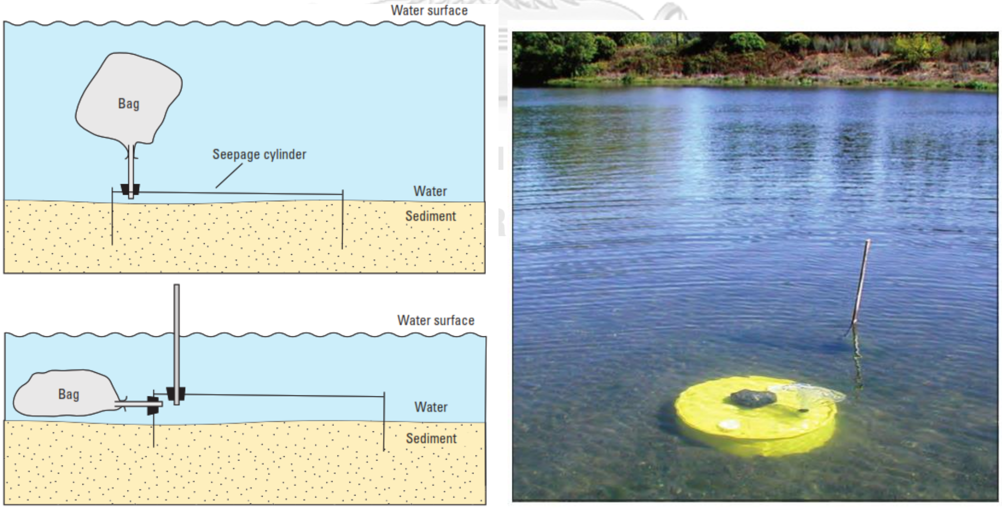


Figure 3. 4: A Half-barrel seepage meter (Lee & Cherry, 1979)

Shinn, Reich, and Hickey (2002) conducted three seepage meter designs to determine the lateral movement of groundwater and vertical seepage into Florida Bay and the reef tract. The mean rates obtained from seepage network of meters was 15.1 $l/m^2/day$. The collected seepage volume showed a strong relationship with wave height. The study found that the Bernoulli effect may relief in some areas where there are waves and/or currents.

Russoniello and Michael (2015) examined seepage meter measurements in the presence of steady groundwater flow and surface water waves. The tank experiments were conducted to determine effects of mechanical resistance on measurement efficiency and occurrence of directional asymmetry that could lead to erroneous net flux measurements. Seepage meter net flux measurements averaged 0.08 cm/h. The results pointed out seepage meters may provide accurate measurements of both discharge and recharge under steady flow conditions and illustrate the potential measurement errors associated with dynamic wave environments.

Rosenberry, Briggs, Delin, and Hare (2016) used fiber-optic distributed temperature sensing (FO-DTS), seepage meters, and vertical temperature profiling to locate, quantify, and monitor areas of focused groundwater discharge in a geomorphically simple sand-bed stream. Seepage rates in cold-bed areas ranged from 0.20 to 3.00 m d^{-1} with a median value of 0.83 m d^{-1}. Seepage rates in areas not determined by FO-DTS to be cold ranged from -0.55 to 0.93 m d^{-1} with a median value of 0.17 m d^{-1}. In general, seepage in cold zones was nearly 5 times faster than at typical bed temperatures.

Sakata, Baran, Suzuki, and Chikita (2016) model vertical hydraulic gradient to estimate river seepage in the Toyohira River alluvial fan, Japan by conditioning downward groundwater flow. The VHG for the boundary was assigned on the basis of a VHG map manually constructed from several piezometer nests. Model calibration was performed same hydraulic heads as the observations by adjusting the initial map and layer-scale anisotropy of permeability. The leakage was determined to be approximately 1 m^3/s between KP 15 and KP 18.5.

Tuan Pham Van and Koontanakulvong (2018) conducted groundwater and river interaction parameters along Saigon River by using inverse groundwater model. Conductance of riverbed was calibrated and verified piezometric head at 3 cross-sections. The model found that aquifer lost water to river in upper part Saigon River and gained water from river in the lower part during 2000 to 2007. According to groundwater balance, the primary sources of second aquifer to supplement the depleted aquifer storage under increasing pumping come from first aquifer. In line with gradually pumping rate, the river recharge increased approximately 56% during 2000 to 2007 at TV6 and about 50 % at TV7.

3.3 Analysis of groundwater recharge using chemical/ stable isotope

The tracers can be specifically detected in very low amounts and concentrations which do not disturb the hydrologic system under investigation (Moser & Rauert, 2005). Since the late fifties, the use of radioactive tracers led to great advances in a number of other countries as well, such as Austria, France, Great Britain, Israel, the USA and Japan. The natural tracers most commonly used in modern recharge studies are ^{3}H, ^{14}C, ^{36}Cl, ^{15}N, ^{18}O, ^{2}H, ^{13}C, and Cl due to half-lives from few years to hundred thousand years. Numerous of researches showed that the advantage of radioactive in groundwater recharge investigation such as identify leak zone in reservoir (Guizerix, 1983; Makovski, 1970), evaluate the melt water infiltrated to the soil and discharge to stream channels(Dincer, Payne, Florkowski, Martinec, & Tongiorgi, 1970); date groundwater with residence times(Vogel, Grootes, & Mook, 1970); localize and measure the seepage flow in dams (Drost, 1989). As simple detection in the borehole, short half-lives (five years age), and no sorption, the environmental nuclides ^{3}H and ^{2}H methods are useful in application for a direct measurement of the water movement in the unsaturated zone and thereby of the groundwater recharge rate (Moser & Rauert, 2005; Seiler, 1998; P. Sharma & Gupta, 1985). However, this technique shows some promise for problems of mixing of water of different origins. The survey work is necessary to evaluate the phenomena with the usefulness of radioactive tracer (Aggarwal, Froehlich, & Gat, 2005).

While, stable isotope methods were introduced into catchment hydrology research in the 1960s as complementary tools to quantify fluxes in the hydrologic cycle. Since water is composed of hydrogen and oxygen, the main isotopes studied in water are ^{16}O, ^{17}O, ^{18}O, ^{1}H and deuterium (^{2}H) (Clark & Fritz, 1997). The ratios of the isotopes of oxygen and hydrogen present in water have been used for decades to distinguish sources of water, including ground-water discharge to surface-water bodies (Asano, Uchida, & Ohte, 2002; Dincer, 1968; Ford, 2016; Liu et al., 2016; Maloszewski, Stichler, Zuber, & Rank, 2002; H. Wu et al., 2017). These isotopes are useful because they are part of the water and not solutes dissolved in the water. The method works well when the degree of isotopic fractionation of the water is different for different sources of water. Isotopic measurements are made relative to a reference standard and reported in “delta notation,” which has the equation (Craig, 1961a):

The isotopic composition of precipitation is variable due to temperature (Al-ameri, Schneider, Abo-Lohom, & Janetz, 2014; Clark & Fritz, 1997; Hoffmann, Cuntz, Jouzel, & Werner, 2005; Seeyan & Merkel, 2014). Isotope composition of winter precipitation tends to be more depleted than summer rain. Due to this difference, the relative contributions of these different types of precipitation to the amount of groundwater in a shallow aquifer can be determined (Sklash, Farvolden, & Fritz, 1976). The closer the groundwater's isotopic signature is to one of these, the more that type of precipitation contributes to recharge.

Yeh, Lin, Lee, Hsu, and Wu (2014) identified the possible sources of groundwater and the seasonal variations in groundwater recharge in the eastern Taiwan Huanlian River Basin using environmental stable isotopes. According to the mass balance analysis of the isotope composition of hydrogen and oxygen in the basin, the proportions of recharge from mountain river water and plain rainfall are 83% and 17% of the total groundwater recharge in the Huanlian River Basin, respectively.

Fareze, Rajaobelison, Ramaroson, and Vallet-Coulomb (2016) determined the groundwater origin and recharge estimation in the sedimentary aquifer of Mahafaly, southwest of Madagascar via environment isotopic. The groundwater chemical type corresponds to the geological formation and the altitude of the sampling site. The isotope compositions of groundwater indicated a partial recharge from the local precipitation. Generally, the annual total recharge of groundwater in the study zone is estimated to $2.7*10^8 m^3$/year corresponding to the 4500km² of the total site area.

González-Trinidad et al. (2017) identified different sources of water contributing to the groundwater recharge by obtaining the isotopic characterization of rainfall and groundwater of the Calera aquifer. The sample was collected considering the elevation of the sampling locations. According to 4 isotope clusters, the flow patterns and different hydrogeologic environments are strongly regression with their slope and potential hydraulic connection between river and aquifers.

Yeh and Lee (2018) investigated the sources of recharge in shallow and deep groundwater in the Penghu Islands, Taiwan Strait from isotopic composition in precipitation, and aquifers. According to 52 groundwater samples from the Penghu Islands, the isotopic composition obvious pointed that the groundwater is sourced mainly from local precipitation. Although some shallow groundwater has heavier isotopic composition, the results indicated no signs of seawater in deep groundwater.

3.4 Groundwater sustainable yield and pumping management

Groundwater sustainable yield can be summarized as an available yield under a rational development strategy that can maintain the normal exploitation for a long time without any adverse effects while bringing the maximum integrated benefits to the economy, society and environment (Fetter Jr, 1972; Freeze, 1971; Kalf & Woolley, 2005; MA Sophocleous et al., 1999; Marios Sophocleous & Perkins, 2000; T. Yang et al., 2008; Zhou, 2009).

McKinney and Lin (1994) incorporated groundwater modeling into a genetic algorithm to solve three groundwater management problems: maximum pumping from an aquifer; minimum cost water supply development; and minimum cost aquifer remedial. The constraints of the management mode include (1) upper bounds on contaminant concentration at regulatory compliance points in the aquifer at the end of remediation; (2) an upper bound on the treatment system effluent concentration; (3) an equation for the treatment system influent concentration as a function of the initial contaminant concentration from each extraction well; (4) air-stripping tower performance equation; (5) the requirement that all extracted water be treated and rejected to the aquifer; (6) bounds on hydraulic head at various locations in the aquifer; and (7) upper and lower bounds on the extraction and injection rates. The solving genetic algorithm (GA) problems on massively parallel computers are significant for problems where the simulation time required to complete each generation is high. For complex groundwater management problems (e.g., multiphase aquifer remediation) a parallel implementation of the GA and the simulation model will likely be required.

Sun and Zheng (1999) combined MODFLOW and dynamic optimization method to find desirable policies to achieve various groundwater management objectives. Although, the long-term pumping rate was solved by trial- error method, for further application, the conceptual model requires improved procedure to respect boundary condition.

Kataoka and Kuyama (2008) described the experience of groundwater management in three Asian mega-cities, namely Bandung (Indonesia), Bangkok (Thailand) and Osaka (Japan), where faced extensive groundwater pumping problems. Groundwater is abstracted mainly by the industrial sector and domestics in three cities. To reduce groundwater abstraction and mitigate drawdown of groundwater tables, groundwater management scheme and groundwater tax has been implemented. Due to strengthened groundwater management policy, the groundwater level has recovered in recent years in the Bangkok city and Osaka city. The successes groundwater pumping management in Thailand depends on availability of water substitute, socio-economical driven situation, ratio of groundwater charge and surface water supply charge, water supply coverage, and policy/campaign push from the Government(DGR

(Department of Groundwater Resources), 2008). However, Bandung City was struggling for the effective implementation of groundwater regulation because the public water supply does not have enough capacity to supply water to the industries. Therefore, it was revealed that improving the capacity of the public water supply systems is the key to reduce groundwater use of industries. Besides, water recycling was promoted to reduce water use in the industrial sector. However, it may not be the case in Bandung because about 50 percent of the industries in Bandung are textile companies, in which water-recycling potential is low compared with other industries such as steel and chemical companies. The strategy for water recycling needs to be elaborated considering the structure of industries.

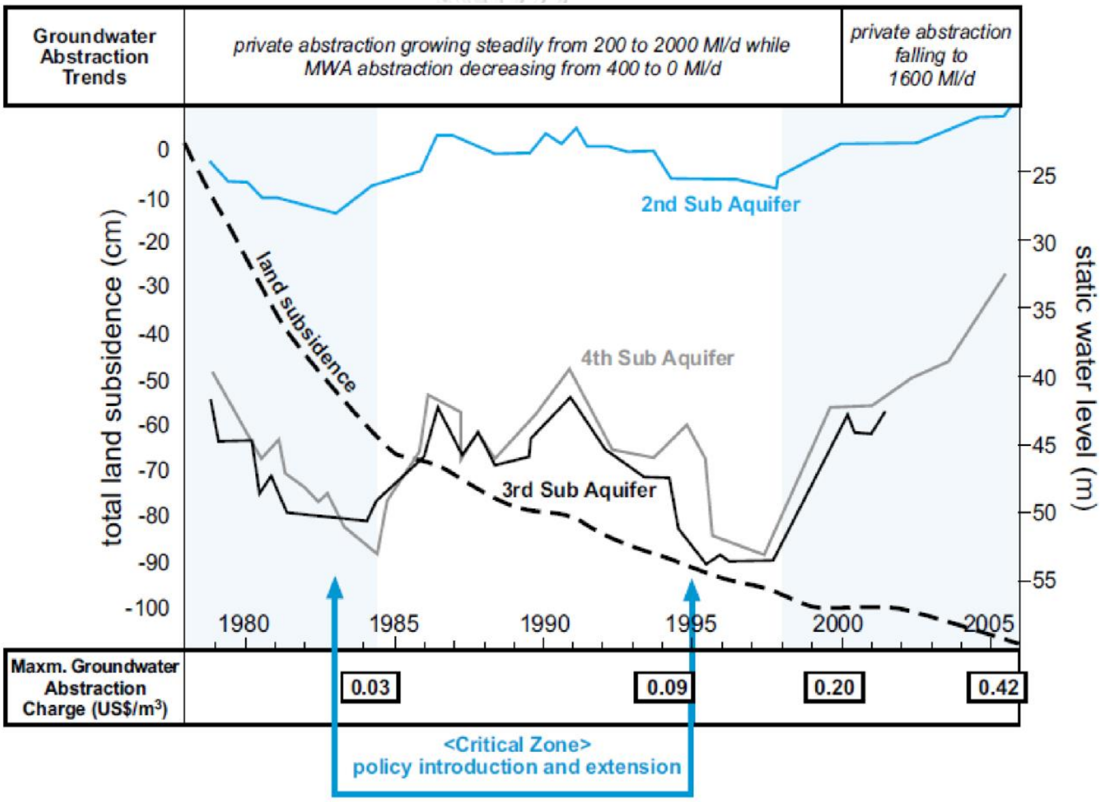


Figure 3. 5: Mitigate drawdown by groundwater management policy in Bangkok, Thailand (DGR (Department of Groundwater Resources), 2008)

Shi et al. (2012) applied integrated evaluation model to identify the sustainable groundwater yield in a Chinese semi-humid basin. The sustainable groundwater yield was determined by balancing series of purposes including the maximal efficiency of water use, the integral benefit of development and utilization, the optimized environmental water demand and the minimal anthropogenic influence on groundwater system. Results indicated the optimized groundwater yield could be sustained by intensive reservoir supply and maintain suitable ecological water demand simultaneously.

Yihdego and Paffard (2016) assessed sustainability groundwater for potential development water demand on sub-catchments of Lake Nyasa/Malawi basin, Tanzani via numerical groundwater models MODFLOW. A water-budget model output was utilized in estimating recharge which allows for an evaluation of the future groundwater sustainability, with several sub-basin extraction limits/annual safe yields in the Lake Nyasa basin. The projected groundwater demand would increase from 11.3 and 103% by 2035. The results suggested that by 2035 water demand of some sub catchments would be nearly at or exceeding the annual safe yield leading to no room for socio-economic development. To meet the projected future water demand with sustainable groundwater abstraction, the groundwater recharge needs to increase from 10% of the total annual recharge to 20% in these catchments.

Arlai, Koch, and Lukjan (2018) estimated the sustainable groundwater yield for the near future in the Wiang Pa Pao aquifer system, the Kok River Basin in northern Thailand. The groundwater yield was estimated by “trial and error” at various pumping rates until a sustainable groundwater yield under the water level constraint. The study found that the total sustainable groundwater yield for the next 20 years was 169,794 m^3/day for the Wiang Pa Pao Basin.

CHAPTER IV

TECHNIQUES, THEORIES AND CRITERIA USED

This chapter describes field measurement surface – groundwater interaction techniques, theories in used to develop surface – groundwater interaction for hydrogeology modeling and constrain criteria to recommend on sustainable groundwater yield and optimal pumping management in Saigon River Basin. In land recharge part, the percolation is estimated using soil moisture approach. This simulation is verified by observed soil moisture in the field. During this part, the percolation flows are analyzed to determine the function between deep percolation, effective rainfall, and sand percentage. Then, the results are applied over Saigon River Basin model to examine the feasibility of land recharge function. While, the seepage measurement was proceeded along Saigon river to carry out river – groundwater interaction parameters. The land recharge function, conductance was calibrated and validated in development groundwater modeling via piezometric head. Later, the fluxes exchange between surface water and groundwater confirmed via composition of δH^2 in river, groundwater, rainfall. In the last stage, the sustainable groundwater yield and optimal pumping management was analyzed considering drawdown criteria and applicant river – groundwater interaction process on aquifer systems in Saigon River Basin.

4.1 Techniques used in soil moisture sensor

Soil moisture sensor adapted in this study is low-cost soil moisture profile probe from Kojima et al. (2016). The soil moisture sensor developed includes 2 parts: sensing parts and reading board. The copper sensing part consisted of two wide bars, with a width and length of 25 and 55 mm, respectively. There was a 1 mm gap between the two bars. These two bars work as a resistor. The wiring part extended to the end of the copper plate and was connected to a soil moisture module (Arduino board) (see Figure 4. 1). Then, the soil moisture sensing parts and wiring are attached to the aluminium bar. The circuit includes five soil moisture sensing parts to measure the electrical resistance of soil at 1m, 2m, 3m, 4m, and 5m. The reader board consists of soil moisture module and Lambda board. The soil moisture module measures the soil resistance, while the Lambda board records the data hourly. The power is supplied from USB 5v 1A. The data was recorded in cloud and downloaded weekly. The resistance of each soil type is calibrated with moisture of soil sample by gravimetric method in the lab (sample as Figure 4. 2). The sensitivity resistance of sensor ranges 200 -1300 Ω, which corresponds to soil moisture 5-40 (m^3/m^3). Then, the record resistance in three field sites are converted to soil moisture. The soil moisture approach summarizes in appendix A.

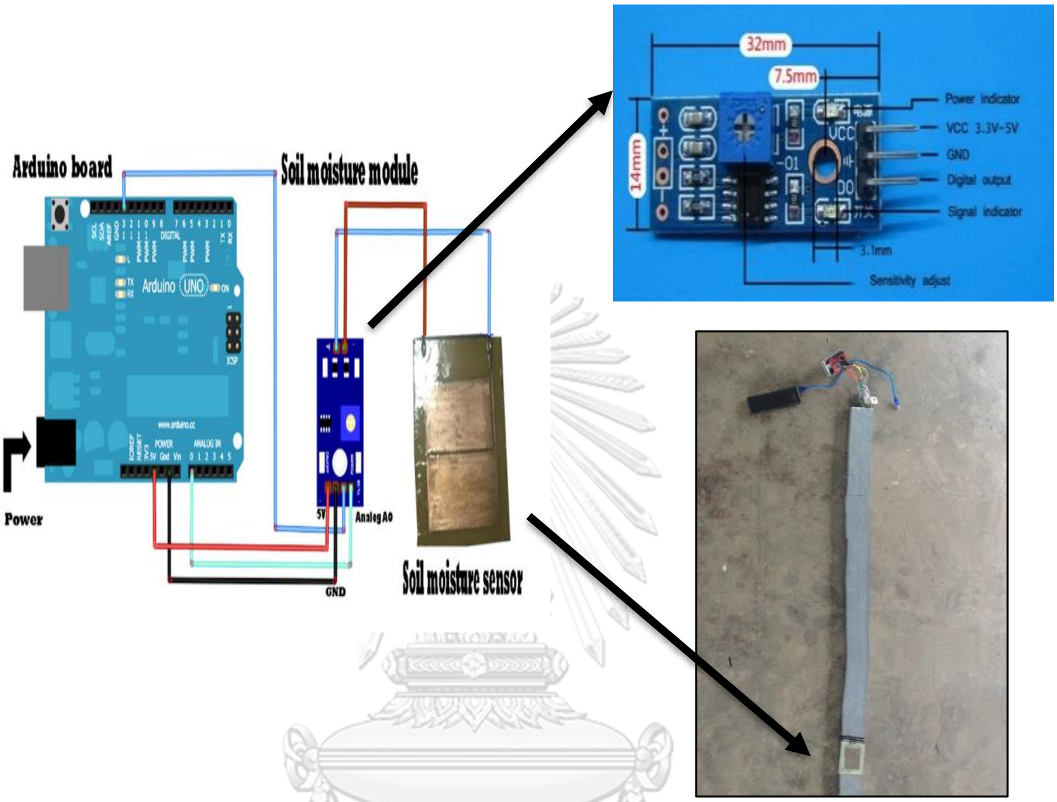


Figure 4. 1: The structure of digital measurement soil moisture

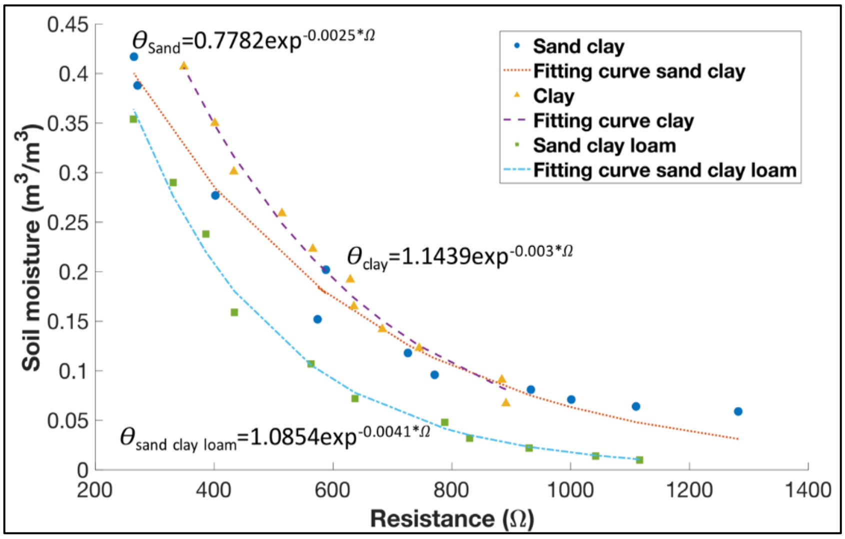


Figure 4. 2: Calibration curves of soil moisture and resistance sensor

4.2 Deep percolation process

The appropriate equation for one dimensional vertical flow in the unsaturated zone is (Richards, 1931; Rushton, 1988)

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial z}\left(K(\psi)\right) \qquad \text{(Equation 4. 1)}$$

where θ is the volumetric water content (% or Vol/Vol),

K is the hydraulic conductivity (LT^{-1}),

Ψ is the matric suction potential (L)

t is the time (T) and

z is the vertical ordinate (L).

Both the volumetric water content (θ) and the hydraulic conductivity (k) are functions of the unknown potential Ψ. The Van Genuchten (1980) function water-retention characteristics of many homogeneous soils describes as:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{[1-|\alpha h|^n]^m} & h<0\\ \theta_s & h\geq 0\end{cases} \qquad \text{(Equation 4. 2)}$$

$$K(h)=K_s S_e^{1/2}\left[1-(1-S_e^{1/m})^m\right]^2 \qquad \text{(Equation 4. 3)}$$

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad \text{(Equation 4. 4)}$$

$$m=1-1/n\ , \quad n>1 \qquad \text{(Equation 4. 5)}$$

S_e is the effective water content

θr denotes the residual water content, in this study, the computed water content was compared with monitored water content in the field. The collected data presents in appendix A).

θs denotes the saturated water content

K_s is the saturated hydraulic conductivity

a is the inverse of the air-entry value (or bubbling pressure)

n is a pore-size distribution index

The x-components of the percolation rate are computed for each node N according to (Simunek, Van Genuchten, and Sejna, 2005)

$$q_N^{j+1} = -K_{N-\frac{1}{2}}^{j+1}\left(\frac{h_N^{j+1}-h_{N-1}^{j+1}}{\Delta x_{N-1}}+1\right)-\frac{\Delta x_{N-1}}{2}\left(\frac{\theta_N^{j+1}-\theta_N^{j}}{\Delta t}+S_N^{j}\right)$$

(Equation 4. 6)

θ is the volumetric water content, (L^3L^{-3})

K is the hydraulic conductivity (LT^{-1}),

h is the pressures head (L)

S is a sink term [T^{-1}]

Δt is time calculation (T)

Δx is grid size

j is time step

N indicate the position node in the finite difference mesh.

As results of deep percolation process, the land recharge function of each soil type was built on relationship between effective rainfall, deep percolation.

$$R_e=a*e^{ER*b} \quad \text{(Equation 4.7)}$$

Re is land recharge or deep percolation rate (LT^{-1})

ER is effective rainfall (LT^{-1}), which calculated by rainfall minus evaporation.

a, b is coefficient which was analyzed in deep percolation process

e is natural logarithm which approximately equal to 2.718

4.3 Direct measurement of the interaction flux (via seepage meters)

The hydraulic conductivity of sediment riverbed is estimated using the equation 4.8 and equation 4.9 (B. P. Kelly & Blevins, 1995; S. E. Kelly & Murdoch, 2003; Lee & Cherry, 1979):

$$\mathrm{k_v} = \frac{\mathrm{Q\Delta z}}{\mathrm{A_b\Delta h}} \quad \text{(Equation 4. 8)}$$

$$C = k_v * w \quad \text{(Equation 4. 9)}$$

Where Q is flow rate, which can be measured by seepage meters (L^3T^{-1})

Δz is thickness of sediments (L), which is measured from the field,

Δh is the difference piezometers (L), which considered as different head between river and observed well distance 100 m from the river,

w is the width river cross section (L), which was selected from river cross-sectional data,

A_b is the cross-section area of seepage meters (L^2)

K_v is the vertical hydraulic conductivity of sediment (LT^{-1})

C is the conductance of riverbed (L^2T^{-1})

The details of experiment are described in appendix B.

4.4 Mass balance of isotopic compositions of groundwater

Analysis the proportion of groundwater recharge base on composition of stable isotope. The analyst for simple two-component mixing model is apply as (Rosenberry & LaBaugh, 2008):

$$\mathrm{Q_s\delta_s = Q_{GW}\delta_{GW} + Q_P\delta_P}, \text{ if groundwater leakage to stream} \quad \text{(Equation 4. 10)}$$

$$\mathrm{Q_{Gw}\delta_{Gw} = Q_S\delta_s + Q_P\delta_P}, \text{ if stream recharge to groundwater} \quad \text{(Equation 4. 11)}$$

where Q is discharge,

δ is the stable-isotopic composition in parts per thousand enrichment or depletion (“per mil”) relative to a standard,

Q_S is stream water (%),

Q_{GW} is ground water (%),

Q_P is precipitation (%).

4.5 Interpolation method for groundwater parameter distribution

Kriging method

Since errors in this kriging method are independency from variable and dependent to spatial location and it cause to predict the best location sampling is possible. The kriging method was applied to distribute hydraulics conductivity for 4 aquifers in Saigon River Basin. Variogram relationship based on the measured points is as follows:

$$\boldsymbol{\gamma}(\mathbf{h}) = \frac{\mathbf{1}}{\mathbf{2n(h)}}\sum_{\mathbf{i=1}}^{\mathbf{n(h)}}[\mathbf{z(x+h) - z(x)}]^{\mathbf{2}} \quad \text{(Equation 4. 12)}$$

where $\gamma(h)$: is the variogram for a distance (lag) h between observations z(x) and z(x+h).

n (h): is the number of pairs of observations which are at distance h. z(x): the observed variable.

z (x+h): the observed variable is the h distance from z (x) and variogram $\gamma(h)$.

Natural Neighbor

Based on the natural neighbor coordinates developed by Sibson (1980) from weighted average interpolation technique, the study applied to interpolate spatial of aquifers system in Saigon River Basin:

$$\mathbf{G(x,y) = \sum_{i=1}^{n} w_i f(x_i, y_i)} \qquad \text{(Equation 4. 13)}$$

Where G(x,y) is the NN estimation at (x,y);

n is the number of nearest neighbors used for interpolation;

$f(x_i,y_i)$ is the observed value at (x_i,y_i);

and w_i is the weight associated with $f(x_i,y_i)$.

4.6 Groundwater flow model

The groundwater systems in this study was model via Groundwater modeling system (GMS) MODFLOW. The regional groundwater flow modeling was simulated base on the governing equation in three-dimensional movement of ground water

$$\frac{\delta}{\delta x}\left[K_{xx}\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta y}\left[K_{yy}\frac{\delta h}{\delta y}\right]+\frac{\delta}{\delta z}\left[K_{zz}\frac{\delta h}{\delta z}\right]+W=S_s\frac{\delta h}{\delta t} \qquad \text{(Equation 4. 14)}$$

Where K_{xx}, K_{yy} and K_{zz} are the values of hydraulic conductivity along the x, y, and z coordinate axes and h is the potentiometric head (hydraulic head)

W is a volumetric flux per unit volume representing sources and/or sinks of water, where negative values are water extractions, and positive values are injections/recharge. It is a function of space and time (i.e. W = W(x, y, z, t)).

S_s is the specific storage of the porous material and may be function of space.

t is time.

A spatial discretization of an aquifer system with a mesh of blocks called cells, the locations of which are described in term of rows, columns and layers. An i, j, k indexing system is used. For a system consisting of “nrow” rows, “ncol” column, and “nlay” layers, i is the row index, i = 1,2,....nrow; j is the column index, j = 1,2,....ncol; and k is the layer index, k = 1,2,.. n layer (Figure. IV-4).

The groundwater flow equation in finite difference form follows from the application of the continuity equation: the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. Under the assumption that the density of groundwater is constant, the continuity equation expressing the balance of flow for a cell is

$$\sum Q_i = S_S \frac{\Delta H}{\Delta t} \Delta V \qquad \text{(Equation 4. 15)}$$

where Q^i is a flow rate into the cell (L^3T^{-1});

S_S has been introduced as notation for specific storage in the finite difference formulation; its definition is equivalent to that of S_s in Equation IV-15, i.e., it is the volume of water which can be injected per unit volume of aquifer material per unit change in head (L^{-1});

ΔV is the volume of the cell (L^3);

and Δh is the change in head over a time interval of length Δt.

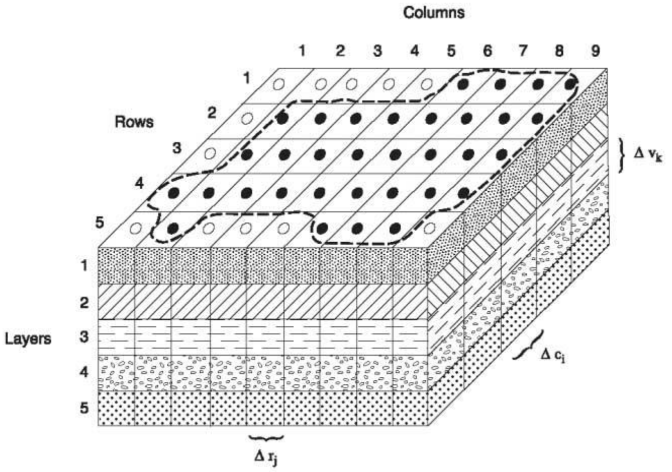


Figure 4. 3: A discretized hypothetical aquifer system (McDonald & Harbaugh, 1988)

------- aquifer boundary,● active cell, o inactive cell, Δr_j dimension of cell along the row direction; subscript)J (indicates the number of the column, Δc_i dimension of cell along the column direction; subscript)I (indicates the number of row, and Δv_k dimension of the cell along the vertical direction; subscript)K (indicates the number of the layer

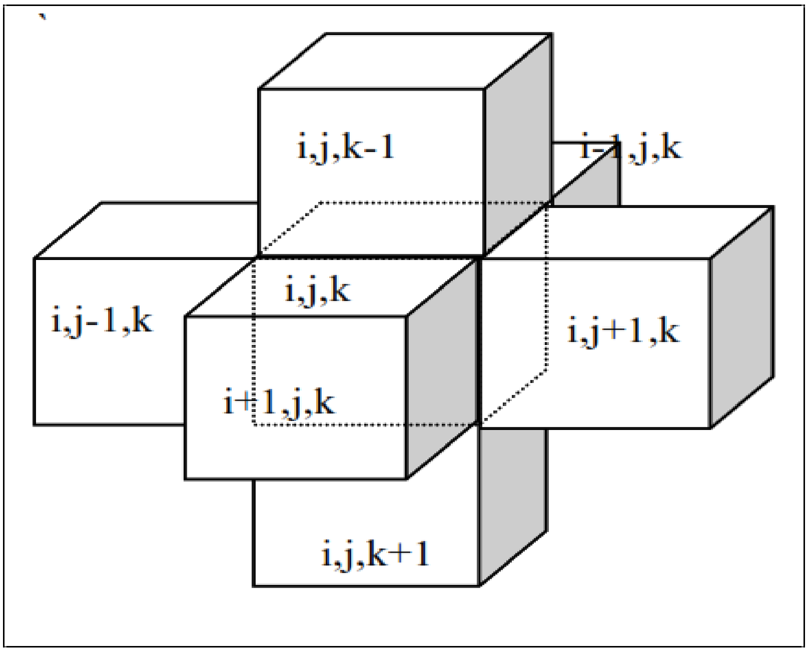


Figure 4. 4: Cell i, j, k and indicates for the six adjacent cells (McDonald & Harbaugh, 1988)

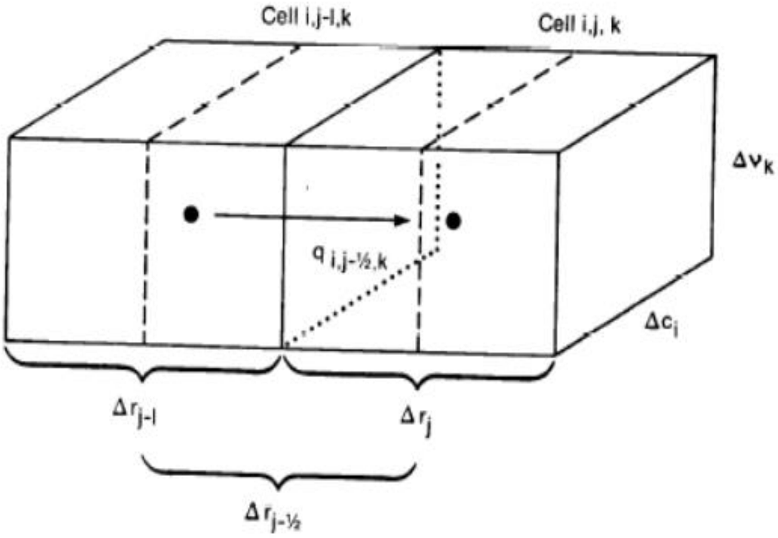


Figure 4. 5: Flow into cell i, j, k from cell i, j-1, k (McDonald & Harbaugh, 1988)

Figure. IV-4 depicts a cell i, j, k and six adjacent aquifer cells, i-1, j, k; i+1, j, k; I ,j-1, k; i, j+1, k; i, j, k-1; and i, j, k+1. To simplify the following development, flows are considered positive if they are entering cell i, j, k; and the negative sign usually incorporated in Darcy's law has been dropped from direction from cell i, j-1, k (Figure IV-5), is given by Darcy's law as

$$q_{i,j-\frac{1}{2},k} = KR_{i,j-\frac{1}{2},k} \Delta c_j \Delta v_k \frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_{j-1/2}} \qquad \text{(Equation 4. 16)}$$

$h_{i,\,j,\,k}$ is the head at node i, j, k;

$h_{i,\,j-1,\,k}$ is the head at node i, j-1, k;

q is the volumetric fluid discharge through the face between cells i, j, k and i, j-1, k (L^3T^{-1});

$KR_{i,\,j-1/2,\,k}$ is the hydraulic conductivity along the row between nodes i, j, k and i, j-1, k (LT^{-1});

$\Delta c_j \Delta v_k$ is the area of the cell faces normal to the row direction;

$\Delta r_{j-1/2}$ is the distance between nodes i, j, k and i, j-1, k (L).

The model common grid size for a basin-scale model (for a basin of thousands of square kilometers) range from a kilometers to several kilometers (Maliva, 2016). The grid size were considered in three determining factors: (1) computational efficiency, (2) proper representation of available data, and (3) effective simulation of regional-scale groundwater flow (Zhou & Li, 2011). Plus, the computed groundwater level of one-kilometer grid size remained in responding to observation's. Hence, this study builds groundwater system in Saigon River Basin with grid size one-kilometer length.

The Saigon River Basin include three boundary conditions: no flow condition, specific condition, and general head condition. In the interface of mountain areas and at the places perpendicular to the groundwater flow direction, the boundary is defined as a "no flow" boundary as they are impermeable boundaries. Along the groundwater flow direction, the boundary is defined as a "specific head" boundary. The specific head is based on observed groundwater nearby. General head conditions represent for places close to coastal line where the heads influenced by a sea water level. For the vertical boundary conditions, the outcrop area of aquifers was defined for land recharge boundary condition. The exchange among aquifers was considered as flow between blocks by Darcy's law (Equation 4.-16). The bottom boundary condition at the base of the deep aquifer was treated as no-flow boundaries.

Calibrate and validate conductance along Saigon river for groundwater modeling by 'trial and error' through piezometric. The fixed boundary condition base on stage in the river, hydraulic head in the part of the groundwater system underlying the river, riverbed bottom elevation, and hydraulic conductance of the riverbed. The equation is presented to calculate the exchange flow rate as follow:

$Q_r = C(S\text{-}H)$ when $H \geq RBOT$ (Equation 4. 17)

$Q_r = C(S\text{-}RBOT)$ when $H < RBOT$ (Equation 4. 18)

Where: Q_r is the river recharge [L^3/T], when river gains water from aquifer, the exchange flow is defined as river recharge out (RRO). In contrast, when river lost water to aquifer, the exchange flow is defined as river recharge in (RRI). The ratio exchange fluxes were evaluated by mass balance of isotopic compositions.

C is the hydraulic conductance of the riverbed, which was measure thought field works.

S is the stage in the river reach (L), which was recorded monthly at field stations.

H is the computed hydraulic head in the GW system underlying the river reach (L);

RBOT is the elevation of the riverbed bottom (m).

4.7 Groundwater flow budget

To analyze fluxes exchange from surface – groundwater interaction process in Saigon River Basin, the study applied water budget tool in GMS model. The water balance equation can be defined as:

$$(Q_L + Q_{RR} + Q_{BR}) - (Q_{RD} + Q_{DB} + Q_P) = \Delta S$$

where QL is the land recharge (L^3/T), which adapted land recharge function built via soil moisture sensor,

Q_{RR} is the river recharge (L^3/T), which calculated via calibrated conduction of riverbed along Saigon river,

Q_{BR} is the recharge from the lateral boundaries (L^3/T), which was fixed as specific piezometric head.

Q_{RD} is discharge from groundwater to a river (L^3/T),

Q_{DB} is the discharge from the lateral boundaries (L^3/T),

Q_p is the artificial pumping (large quantity wells and pumping water for irrigation) (L^3/T),

and ΔS is the storage change of the aquifers system (L^3/T).

4.8 Criteria used to estimate sustainable groundwater yield in Saigon River Basin

To recommend suitable groundwater pumping yield for each aquifer, the sustainable groundwater yield coupling surface – groundwater interaction was accessed with considering drawdown, saline interface, land use criteria. The criteria groundwater pumping yield in this study was considered as follows:

Drawdown criteria: According to Ho Chi Minh City People's Comittee (2007) on reducing underground water exploitation, because the depth aquifer 1 and aquifer 2 in the Saigon River Basin vary from -50 to -100 m. MSL, the pumping is prohibited in the area which drawdown is lower than -20 m. MSL. The aquifer 3 and aquifer 4 distribute from -100 m. MSL, consequently the pumping is allowed with drawdown over 40 m. MSL. However, under increasing pumping rate, the drawdown in some area of aquifer 2 is -35 m. MSL without significant affect to aquifers. Hence, this study considered drawdown criteria in aquifer 2 is not lower than – 35 m. MSL. The drawdown criteria in aquifer 1, 3, and 4 are followed the groundwater pumping laws of Vietnam.

Saline criteria: The salinity has been existed in some area in downstream. Since the length and area of seawater intrusion in the aquifer are governed by the hydraulic gradient (Guo, Huang, Zhou, & Wang, 2019). The gradient of salinity will be maintained not over current situation to avoid increasing salt intrusion. Therefore, the groundwater level in downstream will be limited as current situation.

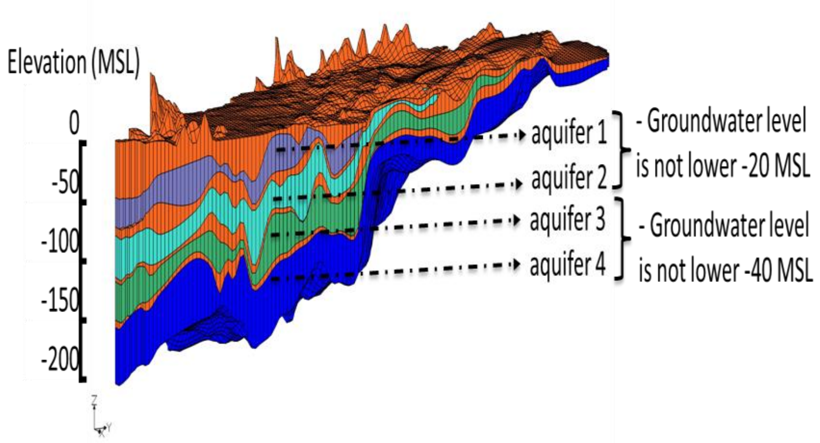


Figure 4. 6: Drawdown criteria (Ho Chi Minh City People's Comittee, 2007)

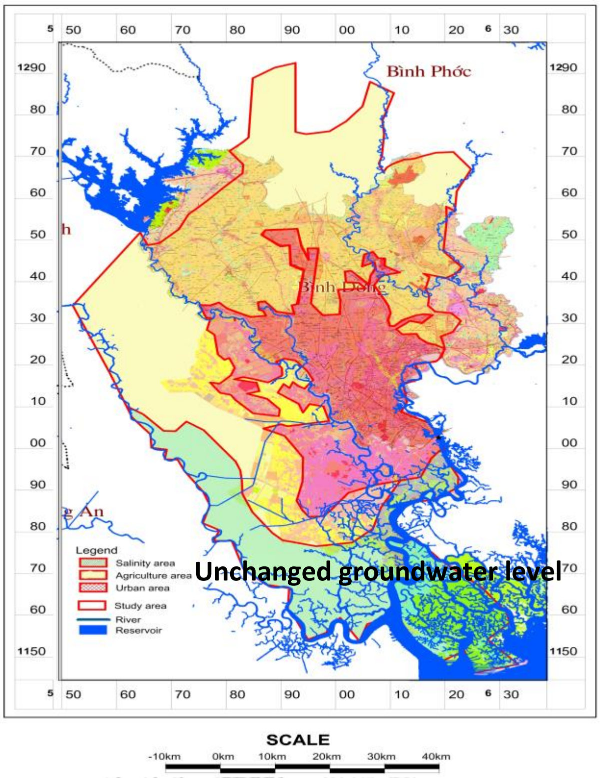


Figure 4. 7: Potential salinity boundary

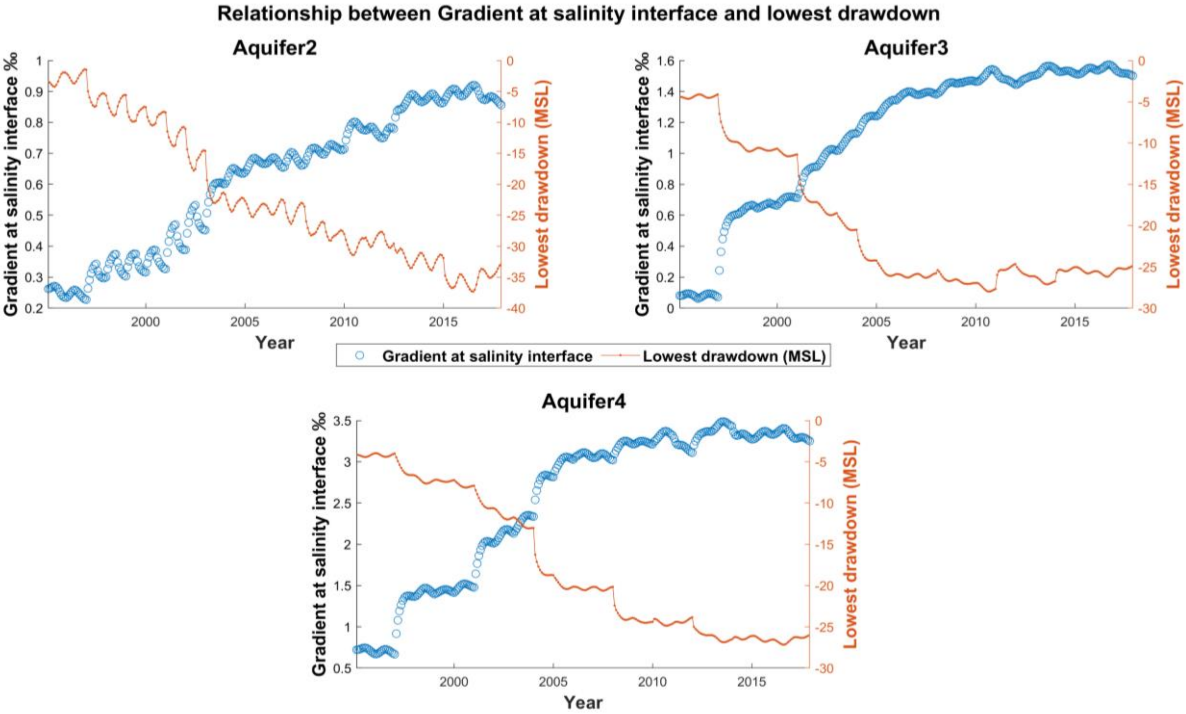


Figure 4. 8: Gradient at salinity interface line and drawdown in the areas with cones of depression

Groundwater pumping zone: Since groundwater in the Saigon River Basin mainly supply for domestic and industry, the study focused on groundwater pumping management in urban areas from the master plan of Hochiminh City and Binh Duong Province. In addition, because the thickness of aquifers is over 20 meters in the area near the river, the additional wells were allocated along the Saigon River.

Groundwater pumping intensity: Optimal pumping in this study considered maximum pumping per square kilometers in four aquifers without bringing negative impacts to aquifers. In order to avoid critical drawdown in the cone of the pumping are, the study analyzed groundwater pumping intensity in Saigon River Basin from existing pumping scheme. The optimal groundwater pumping intensity selected the abstraction remained groundwater level higher than drawdown criteria.

Sustainable groundwater yield: sustainable groundwater yield was defined as the maximum groundwater pumping in the region under control drawdown criteria. The drawdown criteria consider groundwater pumping laws of Vietnam, the hydraulic gradient of saline shoreline. Regarding drawdown criteria and hydraulic gradient of saline shoreline criteria, the drawdown constraints are – 35m. MSL for aquifer 2, and -26 m. MSL for aquifer 3 and aquifer 4. The sustainable pumping yield was estimated by increasing pumpage until the lowest drawdown of aquifers meets the drawdown constraint. The simulation inputs utilized the past 20 years of climate data.

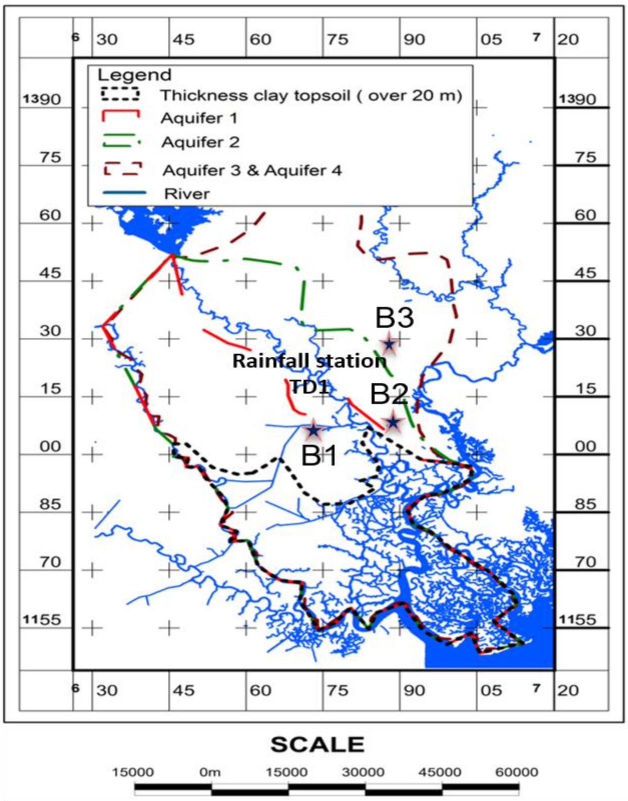
CHAPTER V

FIELD MEASUREMENTS OF INTERACTION PARAMETER

This chapter describe field measurement of interaction parameters in Saigon River Basin. The deep percolation analysist included four main parts: 1) soil moisture of three soil type was monitored from Oct 2017 to Dec 2018 via soil moisture sensor. The characteristic of soil moisture in three soil types are described under impact effective rainfall; 2) the vertical flow was simulated by soil water flow model (HYDRUS 1D). The retention parameters were calibrated and verified by monitored soil moisture; 3) the relationship percolation fluxes with effective rainfall and soil type were analyzed from 1-meter to 5-meter depth; 4) The seepage measurements along Saigon River Basin was proceeded to investigate conductance of riverbed.

5.1. Monitored soil moisture and effective rainfall

A monitor soil moisture experiment via resistance sensor was installed to quantify response of deep percolation to different soil types from Oct 2017- Oct 2018. The resistance of installed sensor was calibrated with soil moisture of each soil type, which was measured by gravimetric method. The calibration indicated that the sensor can measure soil moisture in range 5-40% responding to resistance 200-1300Ω. The replicate experiments of soil moisture have not been done by other equipment because additional soil moisture experiments were too expensive. Then, the auto recorded soil moisture sensors were installed from 1-meter depth to 5-meter depth at 3 field sites, cause the saturated zone existed at the 6-10-meter depth below the topsoil. The site selections focused on three presentative soil types in Saigon River Basin: sand clay loam, sand clay, clay (Figure 5. 1). The experiment site located in non-irrigation area. Hence, the irrigation and transpiration were neglected in the experiment. The composition of three soil type from sieve analyst are showed in Figure 5. 2. The sandy clay loam consists of 64-70% sand, 6.5-14.6% silt, and 23-28% clay. The sandy clay comprises 50-61% sand, 5-10% silt, and 34-39% clay. The clay soil is composed of 17-23% sand, 2-5% silt, and 73-87% clay. The precipitation and evaporation data were collected from the station of Southern Regional Hydrometeorology Center Department of Resources and Environmental, which distances approximate 10 kilometers from the experiment site.



FIELD TEST
B1- Sandy clay loam, B2- Sandy clay, B3- Clay

Figure 5. 1: Measured soil moisture area

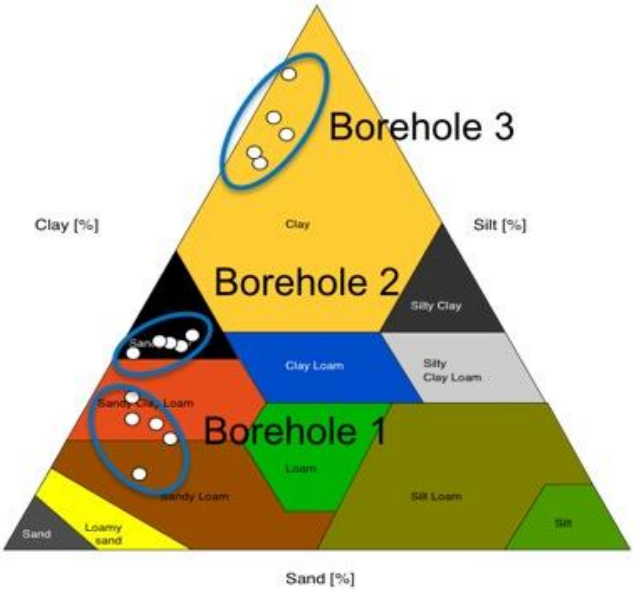
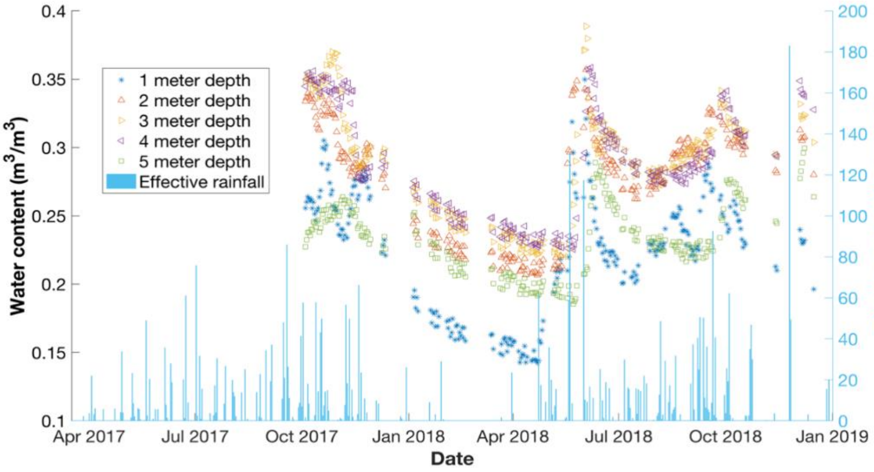
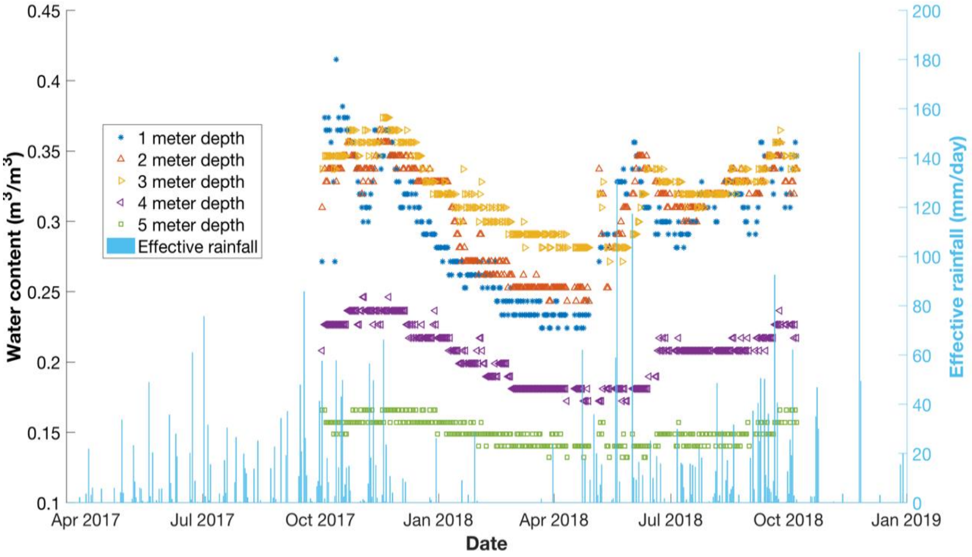


Figure 5. 2: Classify of soil types in study area

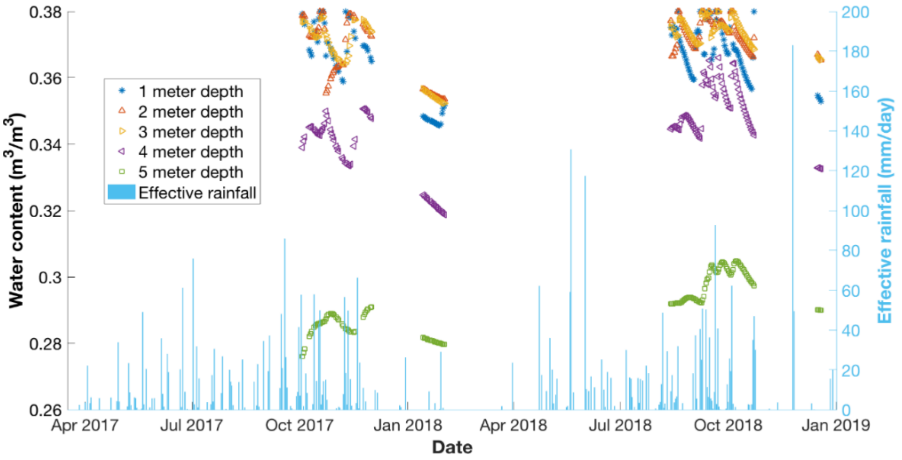
Figure 5. 3 illustrates the monitored soil moistures of three soil types. The soil moisture of sandy clay loam, sandy clay and clay are from 0.12 to 0.38 m^3/m^3, 0.12 to 0.35 m^3/m^3, and 0.28 to 0.38 m^3/m^3, respectively. The upper layer consists of soil moisture higher than the deeper. The measured soil moisture obviously corresponded to effective rainfall. The soil moisture increases in rainy season 2017 and decreases in dry season 2018. At 5-meter depth, the water content of clay is highest, while sand clay loam presents the lowest soil moisture. The measurement data show that installed soil moisture sensors gave reliable values under natural field conditions. Then, the field soil moisture data via installed sensors utilized to calibrate the deep percolation process under effective rainfall of three soil types.



a) Monitored soil moisture of sand clay loam and effective rainfall



b) Monitored soil moisture of sandy clay and effective rainfall



c) Monitored soil moisture of clay and effective rainfall

Figure 5. 3: Monitored soil moisture of three soil types (sandy clay loam, sandy clay, clay)

Figure 5.4 shows soil moisture movements of 3 soil types in wetting and drying phases from the field sensor measurement. In wetting season, the movement of soil moisture in clay is the highest, while sand clay loam shows the lowest movement in soil moisture. In drying season, the movement of soil moisture in sand clay loam is the highest, while clay release the lowest movement in soil moisture. Therefore, the sand clay loam and sand clay gave water easily pass through soil texture, meanwhile water are captured in clay texture and flow slowly to deeper depth. Likewise, soil moisture movements decrease from upper depth to lower depth. Inconsequent, deep percolation in three soil types diminish from topsoil to bottom soil.

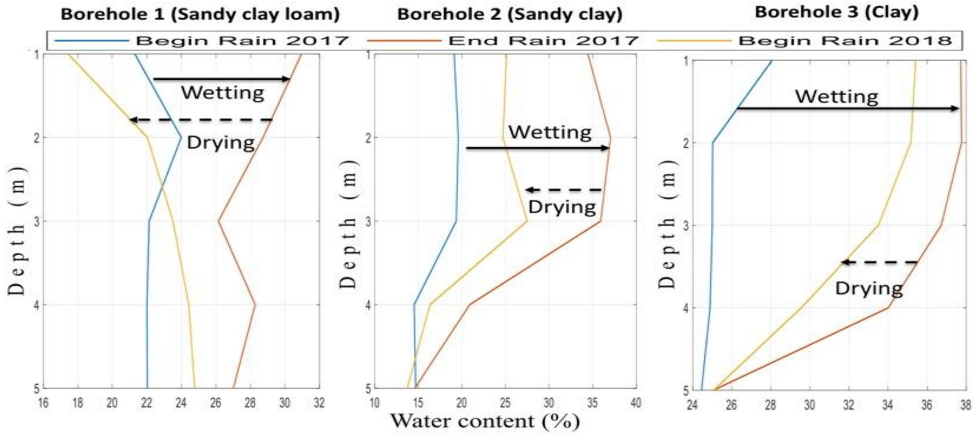


Figure 5. 4: Soil moisture movements of 3 soil types at rainy season 2017 and dry season 2018

5.2 Deep percolation analysis

To understand deep percolation process, this study simulated deep percolation process via one dimensional soil water flow model (HYDRUS 1D). The deep percolation flow was built from 1 -5 meters. The boundary condition of topsoil utilized rainfall and evaporation in the region. The bottom soil's condition considered as free flow. During the simulation of vertical soil water flow, the retention parameters of each soil type were estimated via invert method. The calibrated parameters relied on performance statistics of observed soil moisture. In the calibration step, the calculated soil moistures of three soil types match well with observed data (as samples in Figure 5.5 – Figure 5.7). The maximum error (%) is 2.98 to 1.45. The minimum error (%) is 0. The mean error (%) is 0.3 to 1.5. The RMSE is 0.4 to 1.8. The R-square is 0.64 to 0.912. In the verification step, the calculated soil moistures of three soil types are closed with observed data. The maximum error (%) is 4.68 to 1.35. The minimum error (%) is 0. The mean error (%) is 0.4 to 1.1. The RMSE is 0.5 to 1.2. The R-square is 0.66 to 0.94. The R-square in clay showed low performance because the monitored sensor of clay was accidentally inactive during the dry season 2018. However, the statistic performance of soil moisture in clay responded with 66% of monitored data and be able to build land recharge function. The summary results of calibration and verification of soil moisture are shown in Table 5. 1.

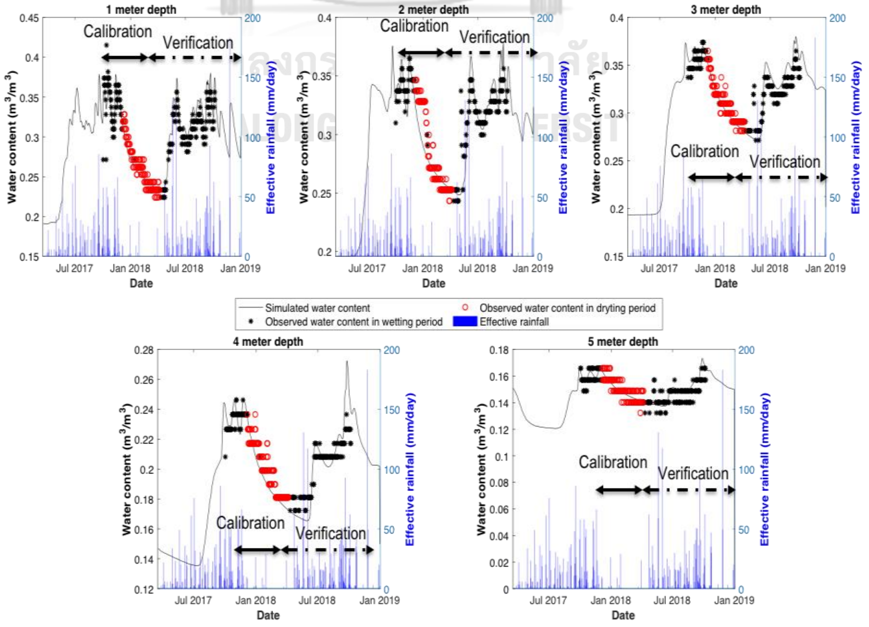


Figure 5. 5: Calibration and verification soil moisture model of sandy clay loam

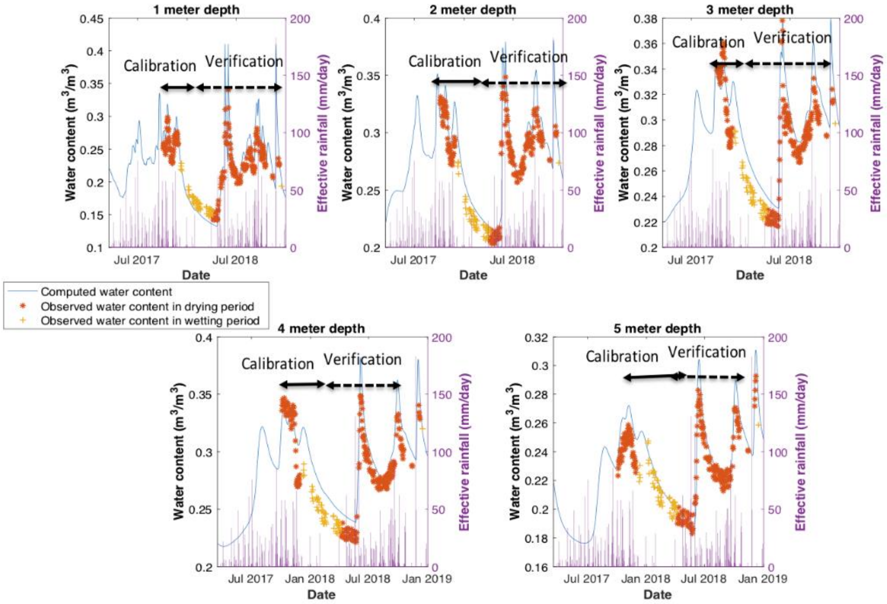


Figure 5. 6: Calibration and verification via soil moisture of sandy clay

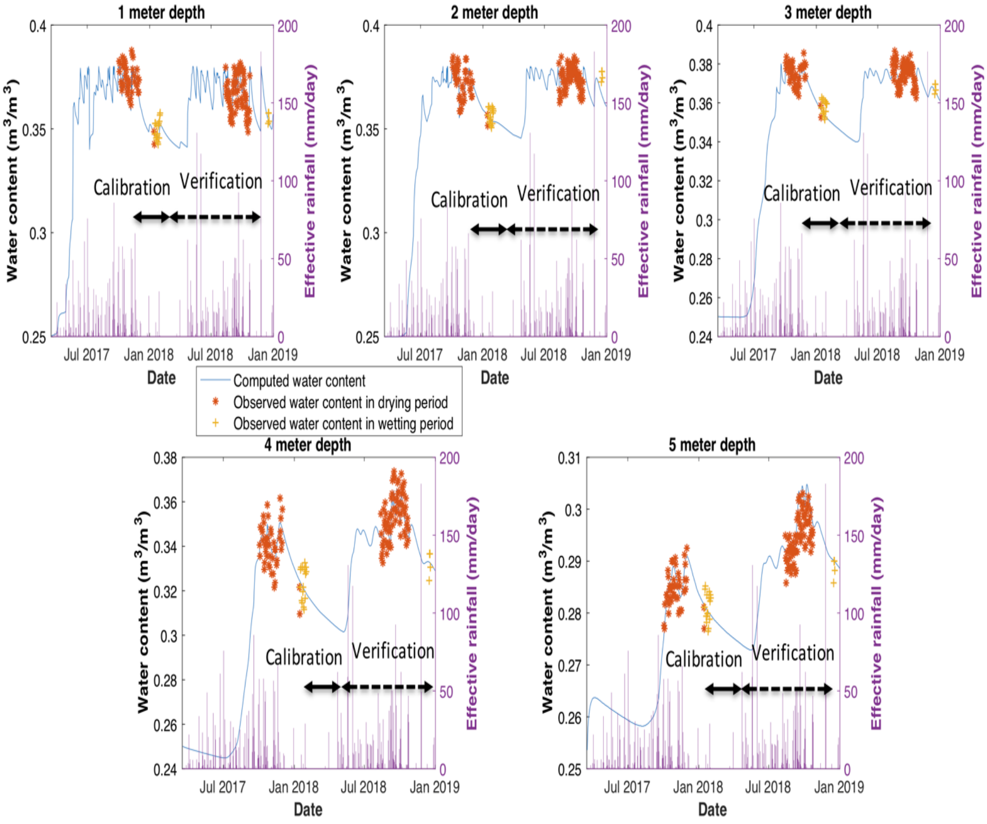


Figure 5. 7: Calibration and verification via soil moisture of clay

Table 5. 1: Statistic parameters of soil moisture’s calibration and verification

Soil type	Period	Calibration			Verification		
		Mean Error	RMSE	R^2	Mean Error	RMSE	R^2
Sand clay loam	Dry	1.4	1.5	0.806	1	1.1	0.852
	Wet	1.5	1.8	0.912	1	1.2	0.940
Sand clay	Dry	1.0	1.2	0.706	0.5	0.6	0.660
	Wet	0.8	1.2	0.874	1.1	1.3	0.806
Clay	Dry	0.3	0.4	0.642	0.5	0.6	0.608
	Wet	0.4	0.5	0.658	0.4	0.5	0.612

Table 5. 2: Soil retention parameters after calibration and verification

	Depth (m)	0-1	1-2	2-3	3-4	4-5	defaulted in Hydrus 1-D
Sand clay loam	θ_r	0.065	0.061	0.061	0.06	0.06	0.065
	θ_s	0.41	0.38	0.38	0.39	0.38	0.39
	α (1/mm)	0.0075	0.0029	0.00277	0.0029	0.0025	0.0059
	n(-)	1.89	1.6	1.64	1.48	1.7	1.48
	K(mm/day)	361	124.4	120.3	114	120	314
Sand clay	θ_r	0.1	0.1	0.1	0.1	0.1	0.1
	θ_s	0.38	0.38	0.38	0.38	0.38	0.38
	α (1/mm)	0.0035	0.0032	0.0031	0.0027	0.00015	0.0027
	n(-)	1.65	1.62	1.65	2.2	2.1	1.23
	K(mm/day)	55.8	51	45	60	65	51
Clay	θ_r	0.068	0.068	0.068	0.068	0.068	0.065
	θ_s	0.39	0.39	0.39	0.385	0.385	0.41
	α (1/mm)	0.0015	0.0012	0.0008	0.0006	0.0004	0.0008
	n(-)	1.29	1.25	1.25	1.26	1.75	1.09
	K(mm/day)	15.6	17.6	18.1	24	27	28

Table V- 2 shows the soil retention parameter values after calibration and verification. The soil retention parameters are proportional with the percentage of sand. The α, n, K parameters decrease in deeper depths. The sand clay loam has highest hydraulic conductivity. The lowest hydraulic conductivity is clay. In addition, the parameters of sand clay and clay showed good agreement with defaulted values from Hydrus1-D (Schaap, Leij, & Van Genuchten, 2001). However, the hydraulic conductivity of sand clay loam is lower than the defaulted value due to the higher silt ratio in the soil sample.

5.3 Land recharge function

As results of deep percolation flow model, the study analyzed deep percolation fluxes and built land recharge function from effective rainfall. To understand characteristics percolation in each soil type, the hysteretic soil-water retention curves (SWRC) of three soil types at the depths of 1m and 5 m from soil surface were demonstrated in Figure 5. 8. The results illustrated good fitting shape of the unsaturated hydraulic conductivity function near saturation. Moreover, the simulations show that hysteresis of percolation rate between drying phase and wetting phase relies on void space and pore size distribution, which are in good agreement with experimental results from H. Yang, Rahardjo, Leong, and Fredlund (2004). In example, with the lowest pore-size index, water is difficult to pass through clay, which causes large hysteresis for clay soil (see Table 5. 2). In addition, the percolation fluxes decrease in each soil depth due to the evapotranspiration influence at soil surface.

The average monthly percolation rates of three soil type patterns correspond to effective rainfall. The deep percolations proceed mainly in wet period, while in dry period percolation immature flow to bottom soil (as an example in Figure 5. 9, Figure 5. 10, Figure 5. 11). It can be explained that the evaporation is higher than rainfall during dry period. Under dry condition, the soil gives up its water content to the atmosphere, if it is wet, and gets dryer. The percolation rate at 5-meter depth is in range 0-4 mm/day. According to computed daily percolation flux from Hydrus, the average percolation rates of 3 soil types in dry and wet periods of 2017-2018 was calculated and showed in table V-3. Due to the permeability property of soil, the derived percolation rate in fluxes in deeper depth are lower than in upper depth of each soil type in the study area. The amount percolation is the highest for sand clay loam and the lowest for clay. The experiment data are in accordance with the percolation rate of sand clay loam (2.3 mm/day) in Phitsanulok, Thailand

(Kangboonma & Koontanakulvong, 2019; Pwint Phyu Aye, Koontanakulvong, & Tran Thanh Long, 2019).

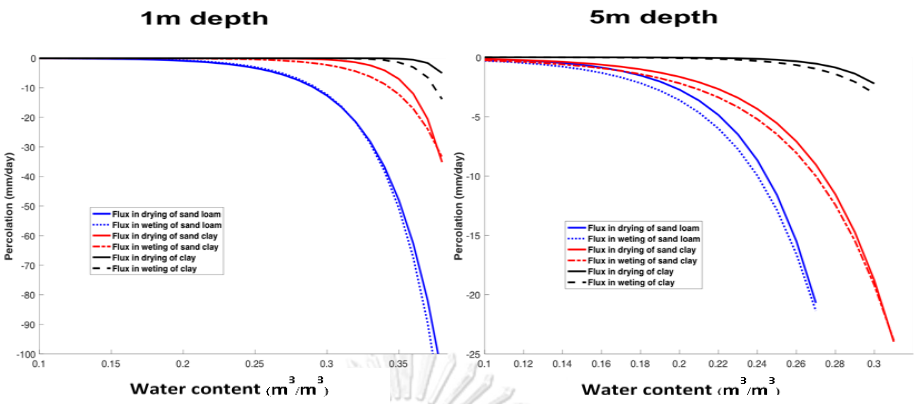


Figure 5. 8 The hysteretic soil-water retention curves (SWRC) of three soil types at 1m and 5m depth

Table 5. 3: Average percolation rates of 3 soil types in dry and wet periods of 2017-2018

Soil type	Period	Wet 2017	Dry 2017	Wet 2018	Dry 2018	Annual 2017 - 2018
	Days	238	146	251	30	384
	Effective rainfall (mm)	1651.72	143.08	1872.46	56.4	1794.8
	Rainfall intensity (mm/day)	6.94	0.98	7.46	1.88	4.67
Sand clay loam	Percolation [illegible] (mm/[illegible] Water content (m^3/m^3)	[illegible]	[illegible]	5.71	0.25	3.51
	Percolation rate 2m (mm/day)	4.46	0.31	4.55	0.22	2.88
	Percolation rate 3m (mm/day)	4.05	0.24	4.08	0.22	2.6
	Percolation rate 4m (mm/day)	2.97	0.15	3.3	0.18	1.9
	Percolation rate 5m (mm/day)	2.51	0.11	2.73	0.19	1.6
	Percolation ratio (-)	0.36	0.11	0.37	0.1	0.34

Soil type	Period	Wet 2017	Dry 2017	Wet 2018	Dry 2018	Annual 2017 - 2018
	Days	238	146	251	30	384
	Effective rainfall (mm)	1651.72	143.08	1872.46	56.4	1794.8
	Rainfall intensity (mm/day)	6.94	0.98	7.46	1.88	4.67
Sand clay	Percolation rate 1m (mm/day)	5.27	0.25	5.17	0.29	3.36
	Percolation rate 2m (mm/day)	4.33	0.2	4.87	0.25	2.76
	Percolation rate 3m (mm/day)	4.26	0.17	4.5	0.2	2.7
	Percolation rate 4m (mm/day)	3.01	0.13	3.12	0.17	1.92
	Percolation rate 5m (mm/day)	1.95	0.1	2.26	0.15	1.25
	Percolation ratio (-)	0.28	0.1	0.3	0.08	0.27
Clay	Percolation rate 1m (mm/day)	3.34	0.4	3.49	0.23	2.22
	Percolation rate 2m (mm/day)	2.74	0.11	3.4	0.21	1.74
	Percolation rate 3m (mm/day)	2.13	0.08	3.22	0.19	1.35
	Percolation rate 4m (mm/day)	1.45	0.08	2.48	0.15	0.7
	Percolation rate 5m (mm/day)	1.08	0.08	1.71	0.13	0.15
	Percolation ratio (-)	0.16	0.08	0.23	0.07	0.04

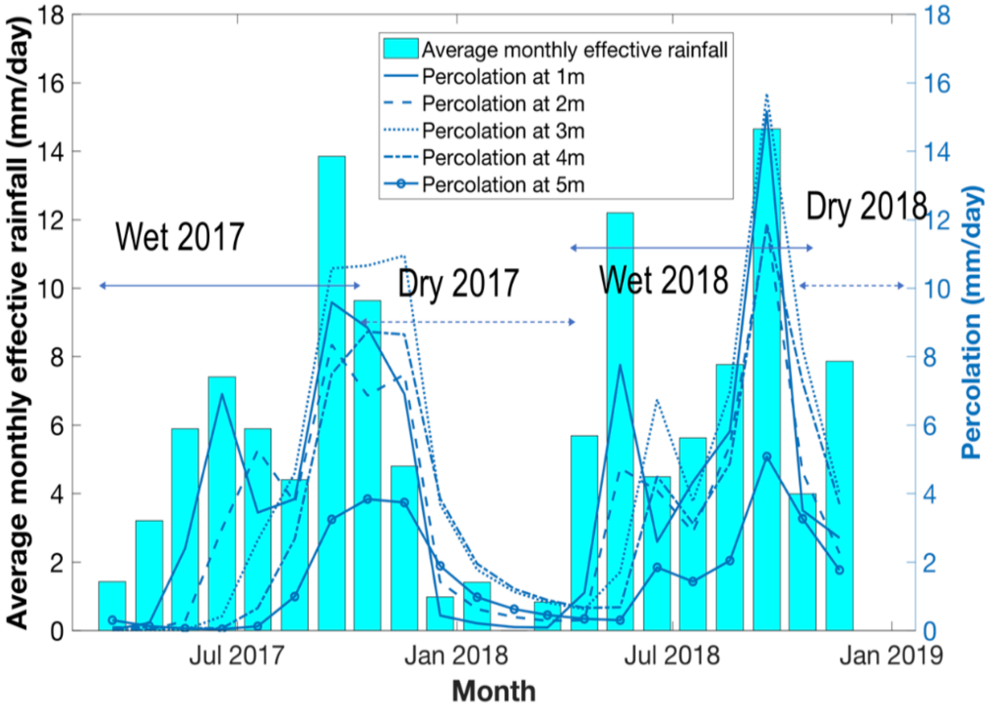


Figure 5. 9: Average monthly percolation rate of sandy clay loam and effective rainfall

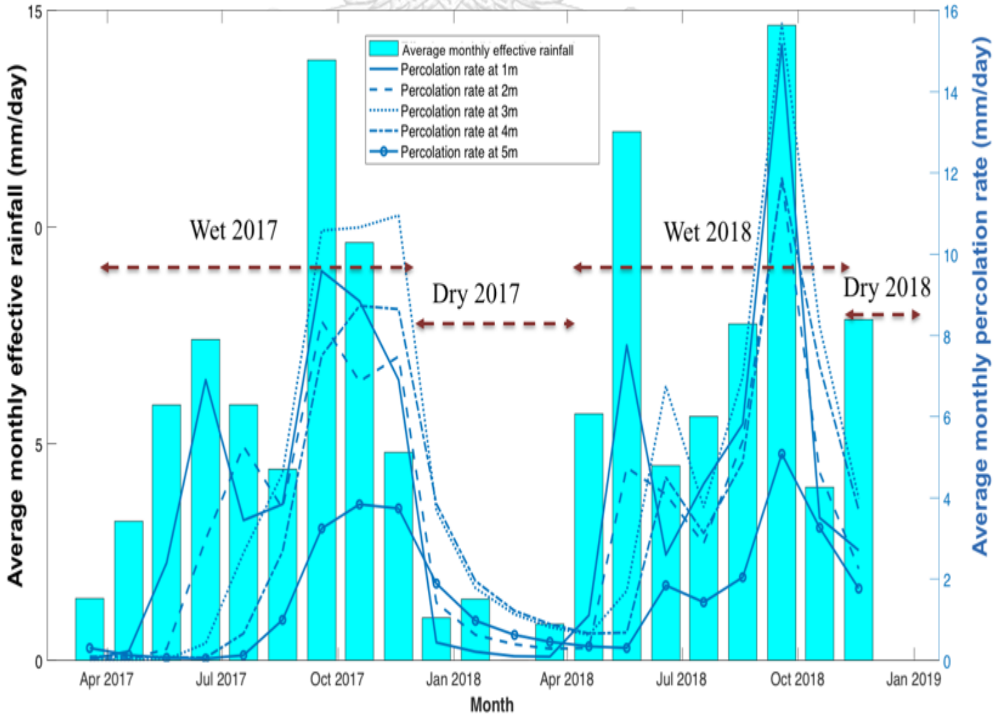


Figure 5. 10: Average monthly percolation rate of sandy clay and effective rainfall

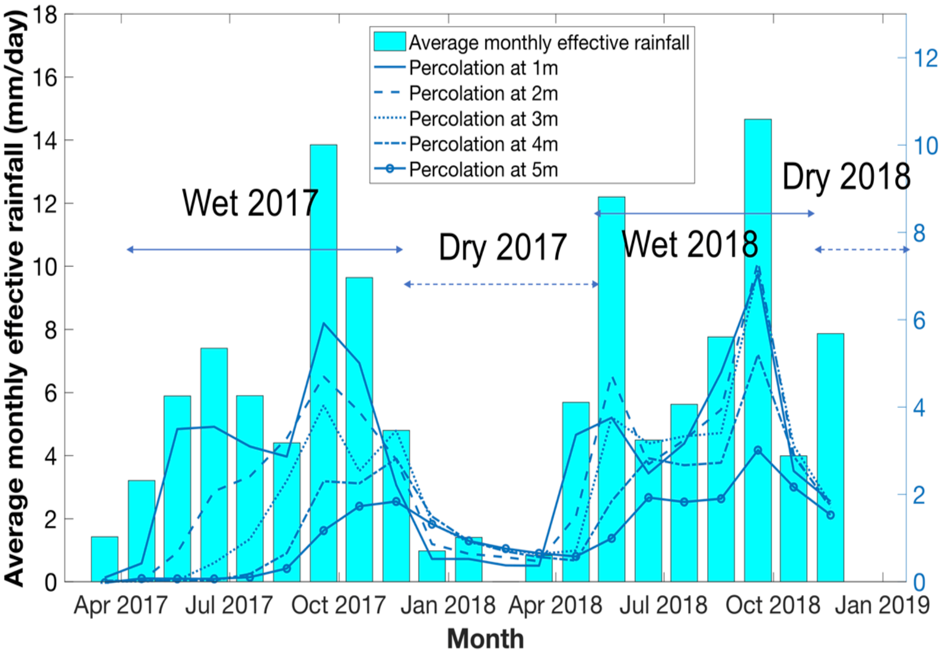


Figure 5. 11: Average monthly percolation rate of clay and effective rainfall

The percolation fluxes were compared with effective rainfall to find the percolation rate function of the study area. Since percolation process occur mainly in wet period, the percolation rate function was built with average monthly effective rainfall in wet season. Meanwhile, under high effective of evaporation the percolation is negligible in dry period. Figure 5. 12 demonstrates the percolation functions of soil types and in the wet periods. The highest percolation rate is sand clay loam and the lowest is clay. The deep percolation rates are affected from rainfall intensity. Under rainfall intensity 4-14mm/day, the average monthly percolation rate of sand clay loam, sand clay, and clay are in range 2-4.5 mm/day, 1.5-3.5 mm/day, and 0.5-2 mm/day, respectively. Besides, this experiment also reveals that grain size of soil and percentage of sand has strong relationship with percolation flux in wet period (as shown in Figure 5. 12 and Figure 5. 13), i.e., the higher sand percentage gives higher percolation rate.

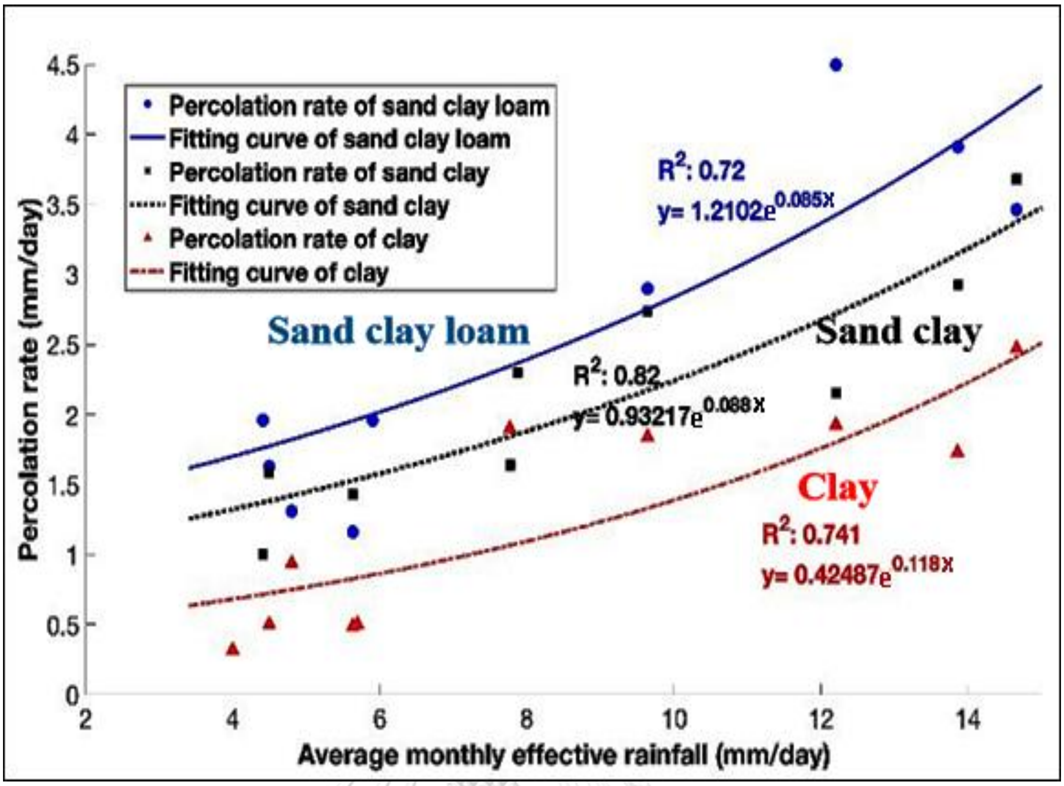


Figure 5. 12: Percolation functions of soil types and in the wet periods

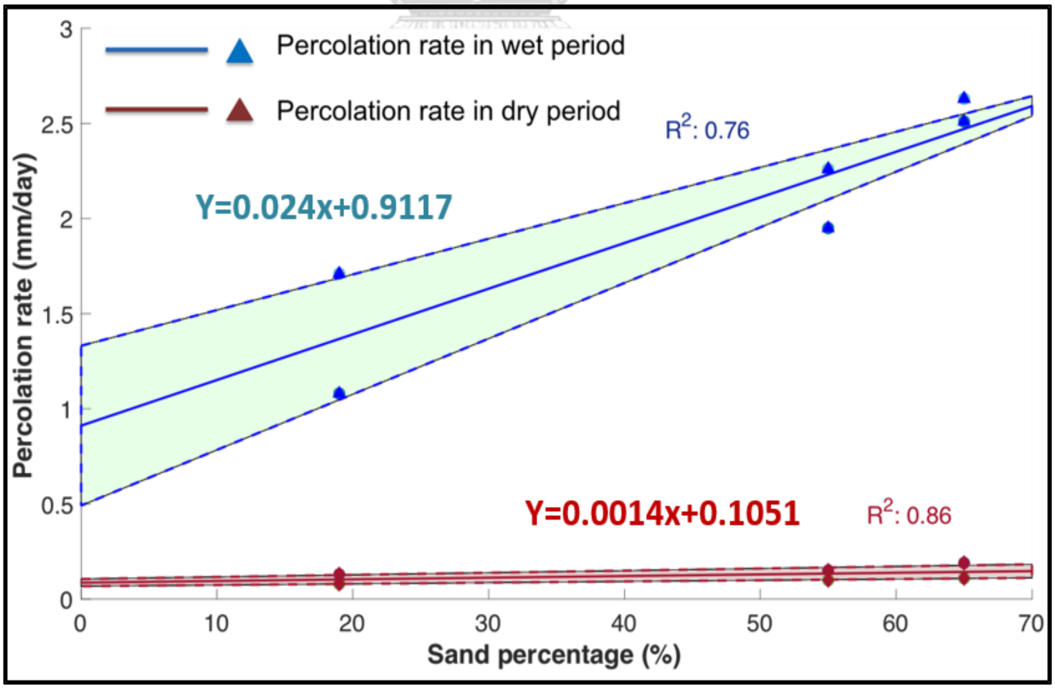


Figure 5. 13: Percolation functions of soil types and in the wet and dry periods

5.4. River - groundwater interaction parameters via seepage measurement

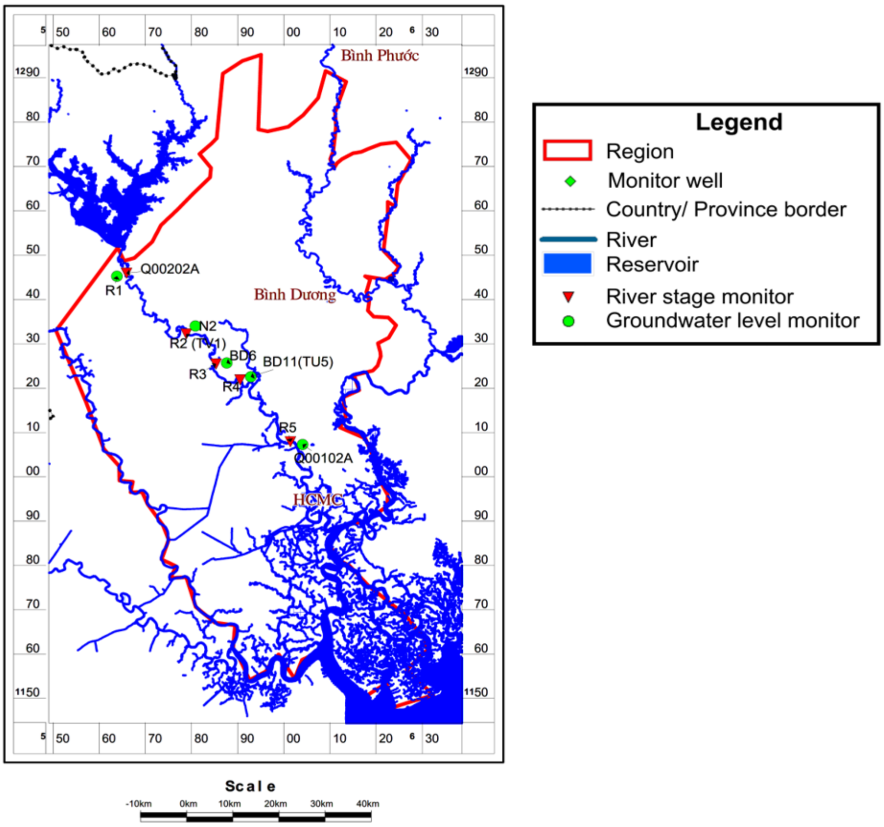


Figure 5. 14: Five sections to estimate river – groundwater seepage

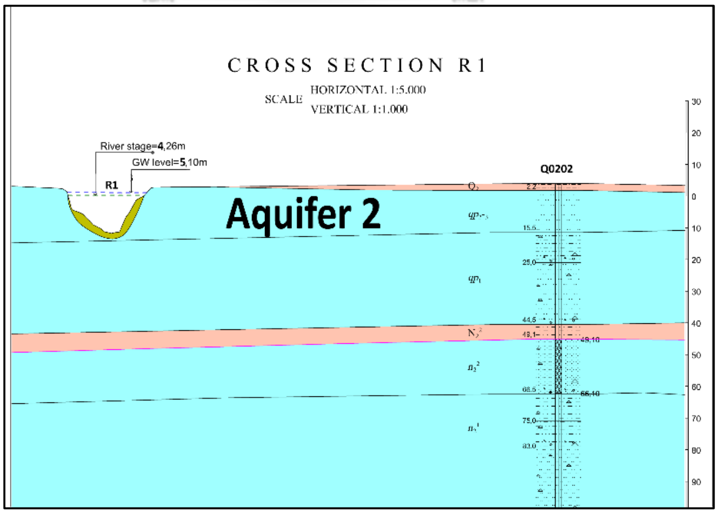


Figure 5. 15: Cross-section R1

In order to understand the characteristics of conductance coefficient of riverbed, the field seepage experiments are measured 5 stations along the river during August and

October 2018 (see location in Figure 5. 14). The details of seepage experiment and cross-section at five stations describe in appendix B. The seepage fluxes were collected by injected half-cut tank into riverbed. The different volumes in experiment duration considered as exchange fluxes of river – groundwater. The summary results of conductance from field seepage measurements are shown in Figure 5. 16. The values near the dam are from 4 m^2/d/m to 5.2 m^2/d/m. The values 35km from upstream are in range 3.2 – 4.7 m^2/d/m. At 60 km, the conductance values are from 2.1 m^2/d/m to 2.9 m^2/d/m. At 80 km, the measured values are in the range of 1.2-1.7 m^2/d/m. At 120 km, the conductance is 0.25 m^2/d/m. The results experiment are in good agreement with conductance previous study at 35-km, 60-km, 80-km (Tuan Pham Van & Koontanakulvong, 2018). Moreover, the soil test analysis reveals the proportion of sand-sized sediment tends to decrease along the river (see Figure 17). The change in sediment properties along the river implies that Saigon River's lithological sediments are the direct consequence of the decreasing conductance from upstream to downstream. According to the field measurement, the groundwater level was measured higher than river stage in upstream, contrariwise the river stage was above groundwater level in downstream (see Figure 16). Therefore, during field works, the experiment was collected leakage from riverbed in upstream and loss water to riverbed in downstream.

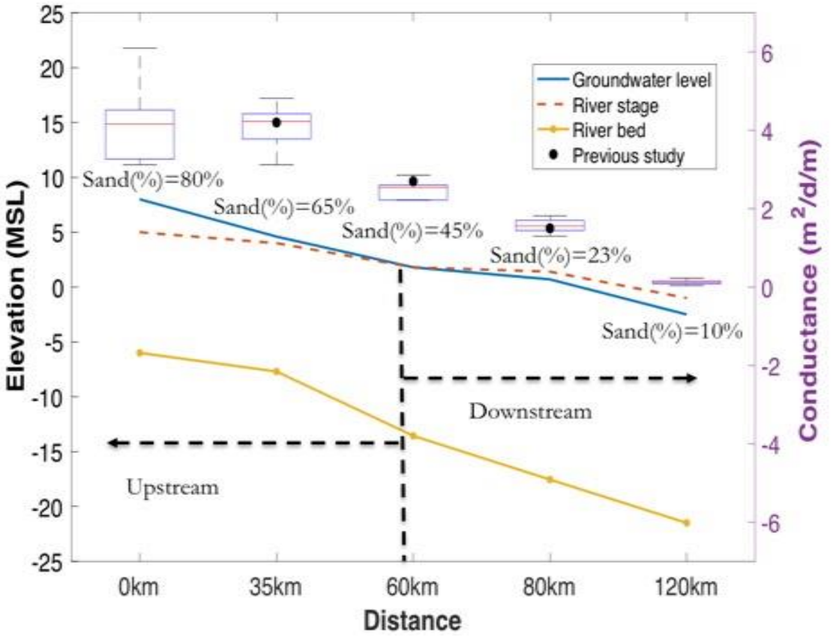


Figure 5. 16: Groundwater – river interaction parameters and river bed soil type along Saigon river (● previous study - Tuan Pham Van and Koontanakulvong (2018))

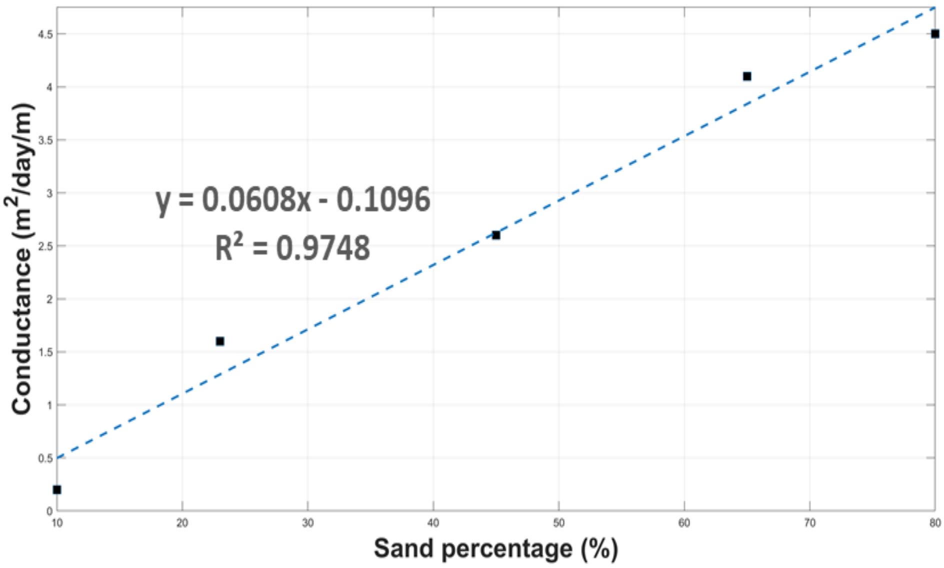


Figure 5. 17: Relationship between conductance of riverbed and sand percentage

5.4. Findings

The average monthly percolation rates of three soil type pattern correspond to effective rainfall, rainfall intensity and soil type. The soil moisture was high in wet season and low in dry season. Thus, the deep percolation proceeds mainly in wet period, while dry period gave very low percolation. The percolation rate decrease from topsoil to bottom soil depth. The soil moisture is stable in deeper soil depth. Therefore, deep percolation rate at 5-meter depth could be considered as rainfall recharge.

In this study, the rainfall recharge functions were built from average percolation rates of three soil type in dry and wet periods of Apr 2017-Dec 2018. Due to the permeability property of soil, the derived percolation rate in deeper depth are lower than in upper depth of each soil type in the study area. The percolation rate is the highest for sand clay loam and the lowest for clay. The average monthly percolation rate of sand clay loam, sand clay, and clay varies 2-4.5 mm/day, 1.5-3.5 mm/day, and 0.5-2 mm/day, respectively to rainfall intensity 4-14mm/day. Besides, grain size of soil and percentage of sand has strong relationship with percolation flux, i.e., the higher sand percentage gives higher percolation rate.

The groundwater-river interaction parameters were evaluated via field measurements and stable isotope compositions. The conductance values at 0km, 30km, 60km, 80km, and 120km are 4.5m^2/day/m, 4.2m^2/day/m, 2.5m^2/day/m, 1.7m^2/day/m, and

0.25m^2/day/m, respectively. The conductance value gradually decreases from upstream to downstream. The conductance in the riverbed also relies on the sand percentage of sediment.

Since, empirical formula rainfall recharge in previous studies only replied on groundwater level fluctuations without considering soil properties and water movement in unsaturated zone, such as Chân and Kỳ (2010a), Ha Quag Khai and Koontanakulvong (2015), this experiment presented an approach to estimate better deep percolation from effective rainfall via field soil moisture sensor system. The experiment gave an insight on deeper percolation characteristics as well as potential land recharge from rainfall utilizing soil moisture approach for future groundwater balance evaluation. Besides, the conductance of riverbed was measured and analyzed along Saigon river. The land recharge function and river – groundwater interaction function applied into groundwater modeling to access exchange flux between surface – groundwater in study area in the next chapter.

CHAPTER VI

THE SURFACE WATER AND GROUNDWATER INTERACTION FLUXES EXCHANGE

This chapter intend to find surface-groundwater interaction fluxes to aquifers system in Saigon River Basin. The simulation of river groundwater interaction process included four main parts: 1) development groundwater modeling; 2) Calibration and verification parameters from field measurement; 3) Qualification stable isotope composition of groundwater, river, and rainfall collected at 5 sections quarterly in the year 2018; 4) the groundwater budget was analyzed to improve understanding exchange fluxes from river, rainfall and groundwater in Saigon river aquifer systems.

6.1. Development of groundwater model

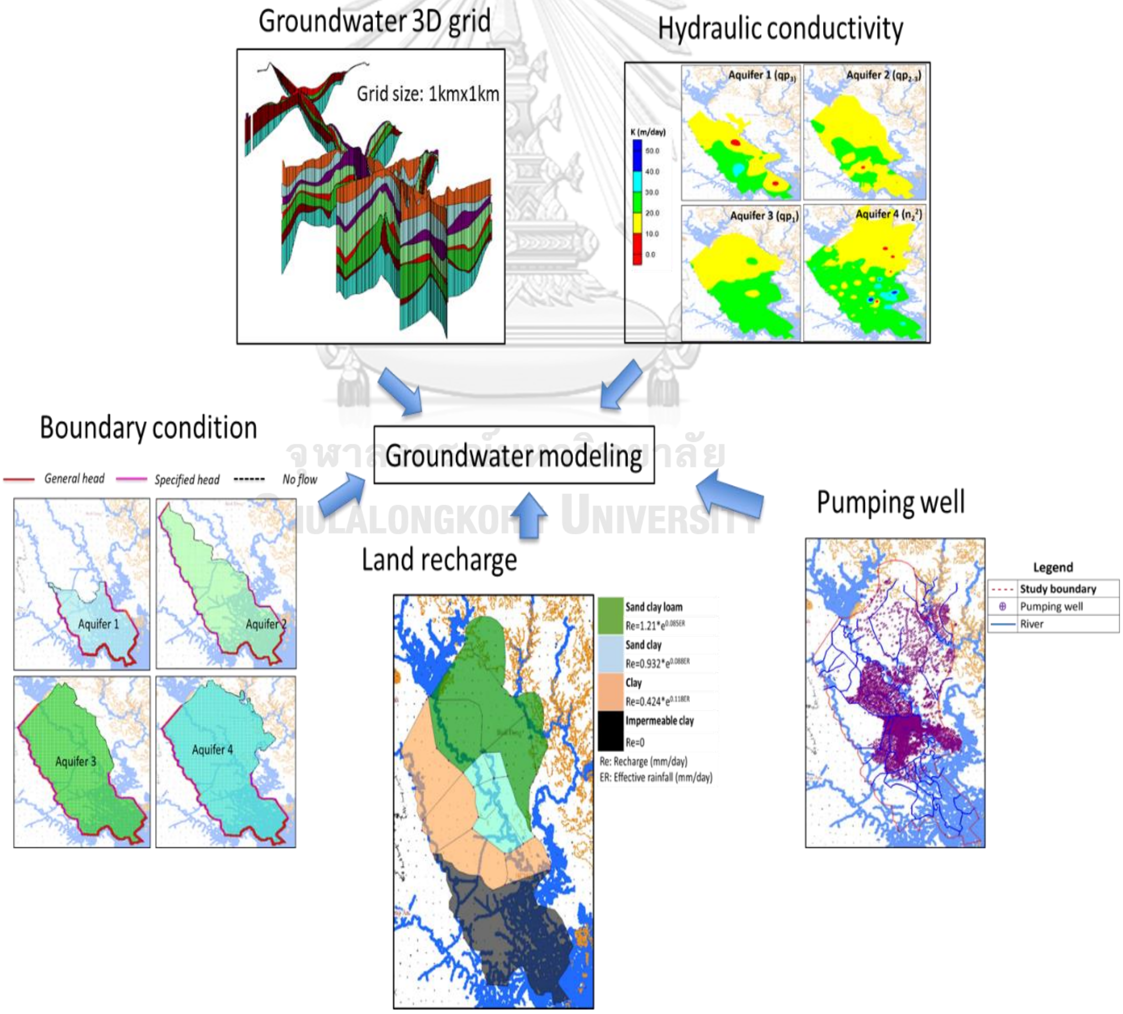


Figure 6. 1: Conceptual development groundwater modeling

In this study, the development groundwater model was built up to demonstrate hydrogeological domain and physical process of aquifers systems. The conceptual of groundwater modeling includes 3D hydrogeology spatial, distribution hydraulic conductivity, boundary conditions, land recharge function, pumping well (see Figure 6. 1). Since the groundwater systems in Saigon River Basin are confined aquifers, the groundwater system separated into 8 layers including 4 confined aquifers and 4 aquitards. According to the radius of investigated hydraulic conductivity Maliva (2016), the grid size of regional modeling varies from a kilometer to thousands of kilometers. Hence, the study distributes hydraulic parameters into grid size one-kilometer length. The elevation of each layer was interpolated by inverse distance weighed from 403 boreholes data (see details in Appendix C). The elevations of aquifers gradually decrease from northwest to southeast, meanwhile the thickness of aquifers increases from upper part Saigon river to lower part Saigon river.

The hydraulic conductivity of 4 aquifers was distributed from 200 well log data through Kriging method (see Appendix C). Table 6.1 shows the summary hydrogeology properties of 4 aquifers in groundwater model (DNRE-Binh Duong, 2017; Vuong, 2010). The hydraulic conductivity trend to increase from upper aquifer to lower aquifer. The aquifer hydraulic conductivity in the upper part Saigon River Basin varies from 10 - 20 m/day, while 20 - 30 m/day of hydraulic conductivity exists commonly at the downstream (see Figure 6.2). The specific storage coefficients of aquifers are 0.0001 - 0.00001 m^{-1}.

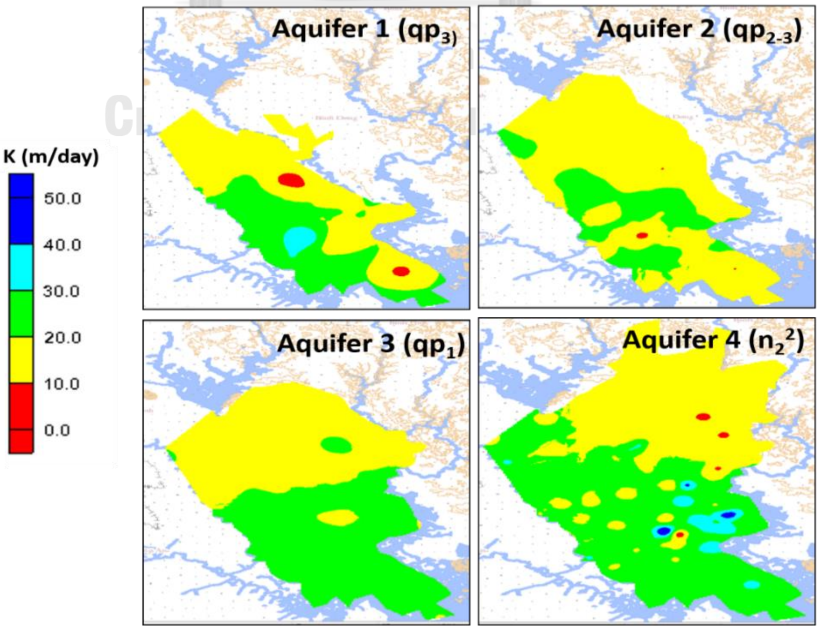


Figure 6. 2: Distribution of hydraulic conductivity of 4 aquifers via Kriging method

Table 6. 1: Summary of hydrogeological properties used in 4 aquifers (Vuong, 2010)

Parameters	Aquifer 1 (qp_3)	Aquifer 2 ($qp_{2\text{-}3}$)	Aquifer 3 (qp_1)	Aquifer 4 (n_2^2)
Distribution area (km^2)	3,158	4141	4983	6,640
Saline GW area(km^2)	1199	1190	1157	912
Fresh GW area (km^2)	1,959	2,951	3,826	5,728
Average thickness	22.6	27.2	27.1	37.6
Hydraulic conductivity (m/day)	5□40	5□30	10□30	5□45
Specific yield (μ)	0.255	0.261	0.258	0.258
Specific storage (μ *)	0.002	0.002	0.0001	0.0001

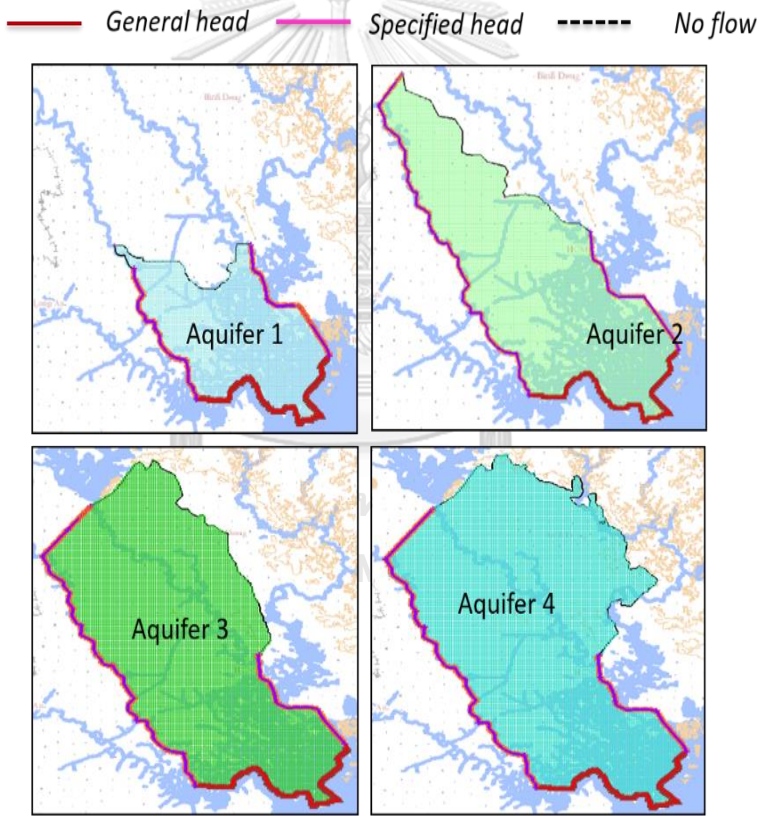


Figure 6. 3: Boundary condition of study area based on the observed wells

Figure 6. 3 presented the boundary conditions for Saigon River aquifers system. In the interface of mountain areas and at the places perpendicular to the groundwater flow direction, the boundary is defined as a “no-flow” boundary as they are impermeable boundaries (Qiu et al., 2015). Along the constraint line of the study area, the boundary of aquifers is defined as a “specific head” boundary. The specified head was set from

average monthly observed piezometric heads surrounding Saigon River Basin. General head conditions represent places close to the coastal line where the heads influenced by seawater level. The monthly observed seawater level was input for the general head.

The distribution of land recharge input to the conceptual groundwater model in the Saigon River Basin is demonstrated in Figure 6.4. Because the topmost clay layer near the sea has a thickness varying from 20 to 30 meters, the recharge in this zone is basically zero. In the study, the outcrop of aquifers was considered as same soil type through the hydrogeology map. Hence, the topsoil of groundwater systems in the Saigon River Basin can be defined in 4 zones: sandy clay loam, sandy clay, clay, and no recharge zone (thickness of clay is over 20 meters). The land recharge rate of sandy clay loam, sandy clay, clay were initially utilized the deep percolation function with effective rainfall in Chapter V (Long & Koontanakulvong, 2019). Then, the land recharge was calibrated to generate computed piezometric in the zone far from river to match with observations.

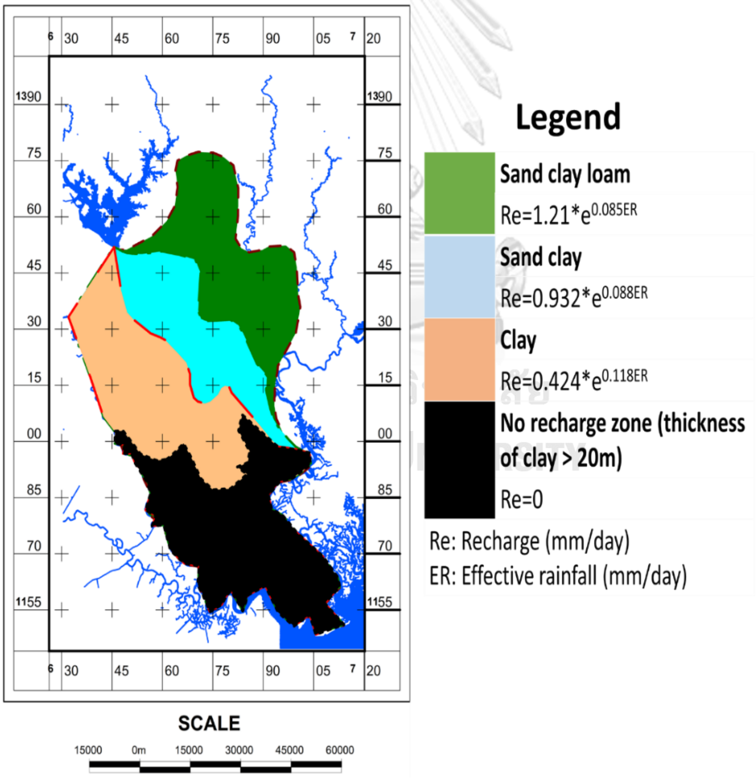


Figure 6. 4: Land recharge map for groundwater modeling (Long & Koontanakulvong, 2019)

Water levels along rivers were utilized average monthly monitored river stages. The pumping rate and hydrogeology parameters were extracted from survey hydrogeology map data of Vuong and Chan (DNRE-Binh Duong, 2017; Vuong & Long, 2016). The groundwater pumping input of aquifer 1, 2, 3, 4 during 1995 to 2017 are 19,255 - 55,711 m^3/day, 146,655 - 274,224 m^3/day, 42,092 - 165,005 m^3/day, 59,064 - 424,446 m^3/day, respectively. The groundwater pumping installed mainly in downstream, which located big cities as Hochiminh and Binh Duong Province.

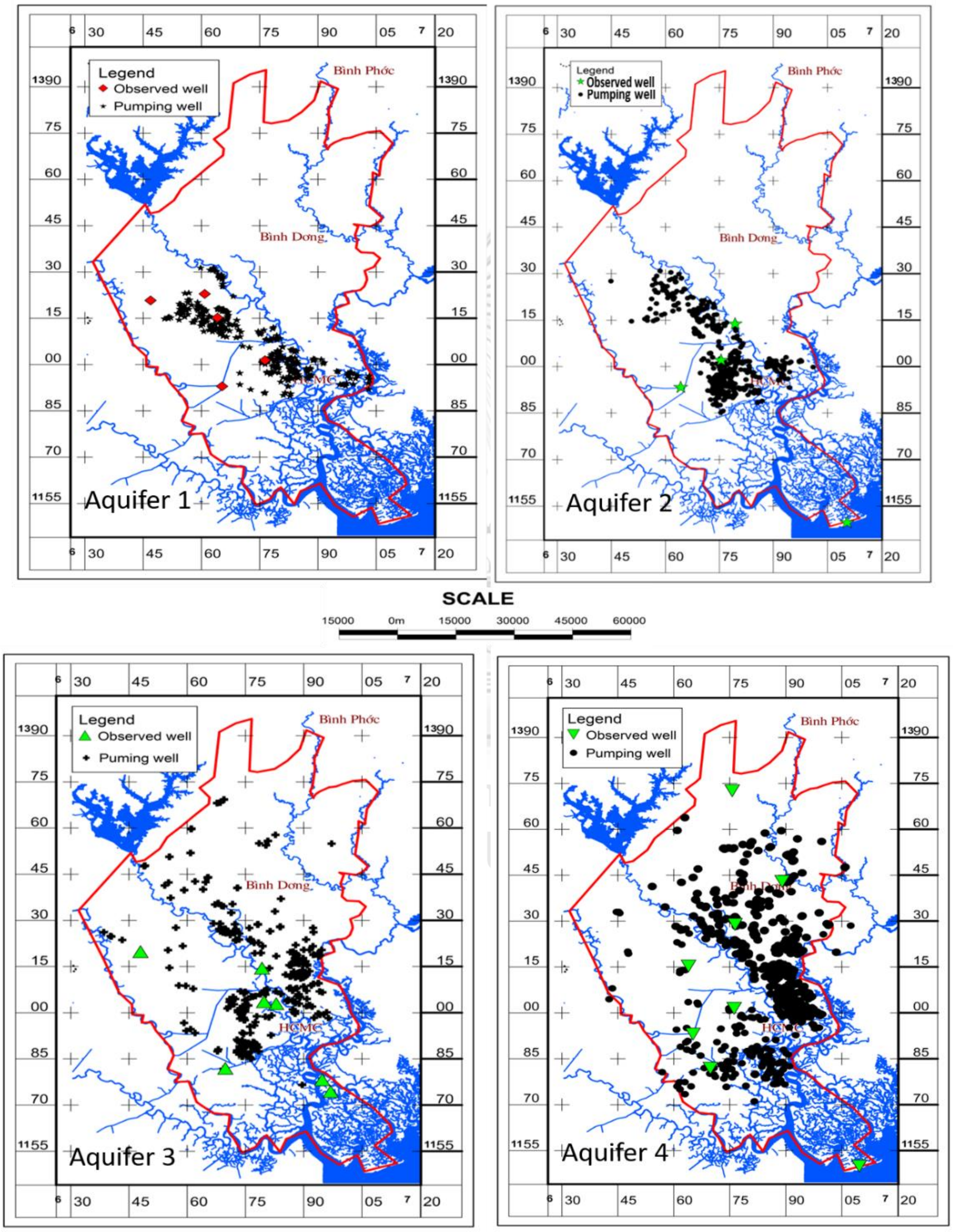


Figure 6. 5: Pumping well and rivers network

6.2. Calibration - validation groundwater model

The development of groundwater modelling in Saigon River Basin was calibrated and validated in 2 factors: land recharge function and river – groundwater interaction parameters. The land recharge function was validated with the observed well data distance to river while the river – groundwater interaction parameters was validated with five field measurements along Saigon River. The detail of calibration and validation describe as follows.

6.2.1 Calibration - validation of land recharge function

In this part, the land recharge was input to groundwater modeling by utilizing land recharge function and effective rainfall. According to mentioned boundary conditions above, the groundwater model was firstly run under steady state conditions in Jan 1995 then under transient conditions from 1995 to 2017. The calculated heads of four aquifers were compared with the measured ones at same period of time. Figure 6.6 demonstrates the results of steady- state calibration. The results matched well with observation data. The errors between simulation and observation are from -3m to 4m. The mean errors of aquifers are from 0m to 1m (see Figure 6.6). Thus, the initial hydrogeology parameters and piezometric heads utilized to simulate the groundwater systems of Saigon River Basin in the transient state process.

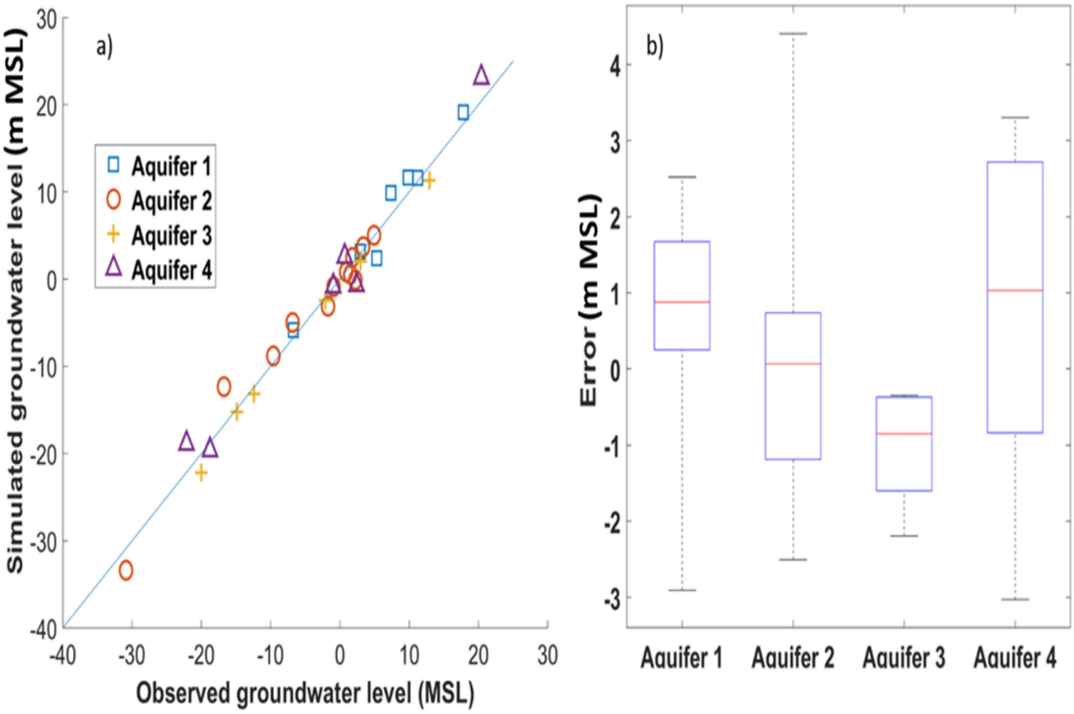


Figure 6. 6: Steady -state calibration in Jan 1995

Table 6. 2: Summary error of observed well data distance to river during calibration and verification from 1995 - 2017 (unit: meters)

Name	X	Y	Error calibration (1995 -2007)					Error verification (2008-2017)				
			Max	Min	Mean	SD	R^2	Max	Min	Mean	SD	R^2
Aquifer 1												
Q011020	594381.4	1201079	2.38	0	0.24	1.02	0.75	3.66	0.14	1.93	0.77	0.88
Q804020	582194	1214895	2	0.01	0.52	0.65	0.73	2.03	0	0.33	0.7	0.69
Q808020	583299.7	1192666	1.96	0.11	0.92	0.41	0.9	1.1	0.01	0.48	0.32	0.93
Q01302a	576847	1218095	2.42	0.11	1.25	0.51	0.67	2.06	0.03	1	0.42	0.79
Q023020	566208	1219460	1.18	0.01	0.1	0.38	0.74	1.35	0	0.44	0.46	0.68
Q0102A	562690	1249110	2.08	0	0.75	0.75	0.79	1.73	0.03	0.42	0.74	0.74
Q09902B	583690.9	1219403	2.79	0.02	0.5	0.98	0.73	3.19	0	0.37	0.99	0.75
Aquifer 2												
Q00202A	598276.5	1213671	2.99	0	0.2	0.85	0.72	1.2	0.01	0.18	0.4	0.69
Q808030M	583311	1192676	4.51	0	0.4	0.77	0.87	4.89	0	1.43	1.06	0.65
Q822030	627719	1150628	0.75	0.02	0.24	0.19	0.55	0.46	0	0.07	0.13	0.94
Q003320	588726.4	1200456	2.99	0.01	0.05	1.46	0.71	3.22	0.03	0.12	1.26	0.81
Q011340	594368	1201070	3.55	0.01	0.39	1.31	0.95	3.09	0	0.24	0.96	0.77
Q019340	596186	1197824	6.39	0.06	1.92	1.38	0.97	6.16	0.02	2.36	1.04	0.9
Aquifer 3												
Q00204a	597504.2	1214015	1.2	0	0.39	0.45	0.65	1.17	0	0.21	0.25	0.91
Q004030	601127.7	1202486	1.65	0.01	0.19	0.71	0.96	1.93	0.01	0.46	0.69	0.75
Q821040	612908.4	1177760	0.73	0.01	0.41	0.18	0.95	0.64	0.28	0.43	0.07	0.86
Q02304T	566208	1219460	1.47	0	0.06	0.4	0.57	1.02	0	0.2	0.36	0.83
Q017030	597939.2	1203073	1.39	0.07	0.39	0.35	0.93	0.74	0.08	0.3	0.34	0.8
Aquifer 4												
Q80404t	582023.9	1215815	1.95	0.01	0.33	0.74	0.6	2.14	0.02	0.49	0.82	0.61
Q808040	583306	1192674	2.52	0.01	0.99	1.03	0.94	2.84	0	0.38	0.88	0.89
Q22504Z	607367	1242482	1.97	0.03	0.11	0.86	0.85	1.98	0.01	0.02	0.83	0.91
Q822040	626040	1150240	0.35	0	0.12	0.11	0.71	0.56	0.01	0.27	0.13	0.95

To estimate groundwater budget under growing pumping rate, the calibration in the transient state has been carried out during 1995–2007, while the verification was processed from 2008-2017 (example in Figure 6.7). During the transient-state calibration, the land recharge distribution of each soil type was minorly tuned to assist simulation well fitted with observation data in dry and rain season. Table 6.2 shows the summary error of 4 aquifers during calibration and verification from 1995 – 2017. The R^2 are from 0.62- 0.9. The max error is 4.5m. The underestimate pumping rate in seasonal may cause errors 4m in some time step. The residual standard deviation varies between 0.19 – 1.4m. The total head change observed in Saigon River Basin is 20 m. MSL. Hence, the residual standard deviation of the piezometric heads is less than 10 percent of the total change observed head across the model domain. Therefore, the calibration and verification performed generally computation satisfied with observation. Henceforth, the fluxes from land recharge function in Saigon River aquifers systems was confirmed through the piezometric head.

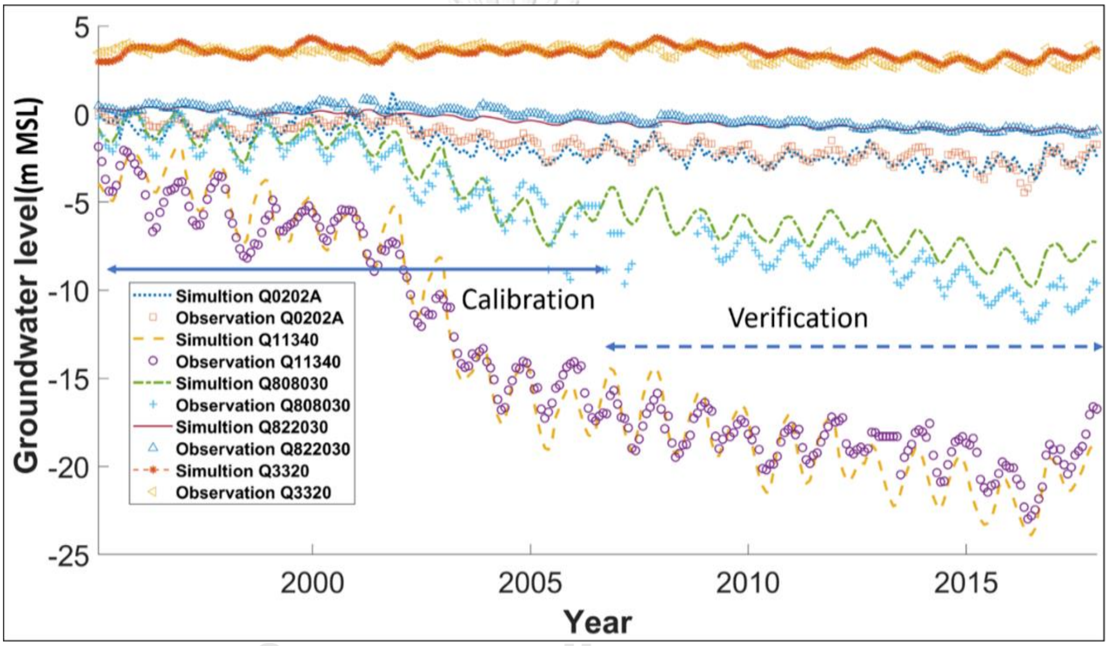


Figure 6. 7: Transient calibration results of aquifer 2

Since the exchange flux between aquifers was generated as flow between vertical blocks by Darcy’s law, the study also attempted to calibrate leakage between aquifers via the piezometric head. Figure 6. 8 presents the result of calibration leakage between aquifer 2 and aquifer 3. Under the distribution vertical hydraulic conductivity, the computed piezometric head shows the good fitting with the observation’s. Henceforward, the magnitude of leakage between aquifers in the Saigon River Basin model can be adopted for groundwater simulations in the study.

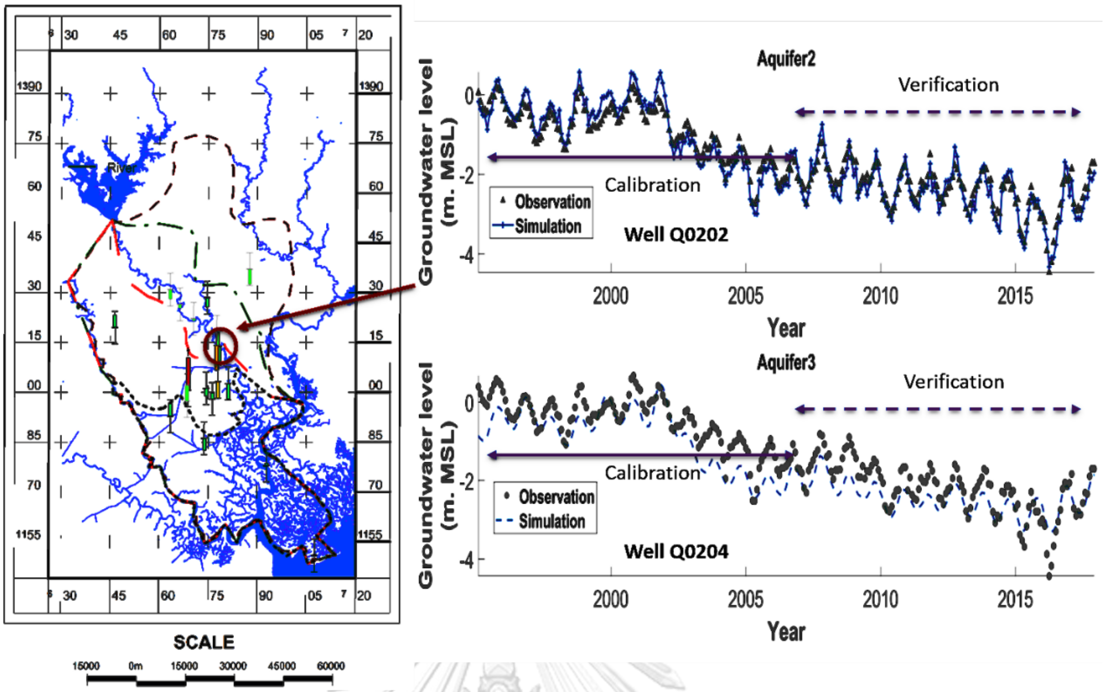


Figure 6. 8: Result of calibration leakage between aquifer 2 and aquifer 3

6.2.2 Calibration - validation of groundwater – river interaction parameters

According to calibrated land recharge function in groundwater modelling, the conductance coefficient was improved via inverse modelling at five sections which named R1-Q102, R2-N2, R3-BD06, R4-BD11, R5-Q202 (see Figure 6.9). The model calibration and verification depended on good statistical performance between computed piezometric to observe piezometric heads at five wells named: Q102; N2; BD06; BD11; Q202 (as Table 6.3). The mean errors range is from 0.07 meters to 0.61 meters. The maximum error is from 0.37 meters to 2.5 meters. The R-squared error is in the ranges of 0.6-0.86. According to the different head between groundwater level and river stage, the Saigon River Basin can be divided into 2 zones at 60 km distance from the dam (Figure 6.9). In the upstream from the 0 km to 60 km, the groundwater level is above the river stage, whereas the groundwater level is below the river stage at the downstream river stretch from 60 km to 120 km. The groundwater use activities are mainly for urban areas of the downstream. The R-squared in downstream still satisfies goodness of fit, though lower than in the upstream because the groundwater abstraction is partially uncontrolled, and the pumping rate may be underestimated. The conductance at 0km, 35km, 60km, 80km, 120km are 4.5 m^2/day/m, 4.2 m^2/day/m, 2.5 m^2/day/m, 1.7 m^2/day/m, 0.25 m^2/day/m, respectively. The conductance values derived reduce from upstream to downstream in accordance with riverbed materials, which changed from sand in the upstream to silt in the downstream. Moreover, the results from inverse groundwater modelling also show good agreement with field seepage measurements.

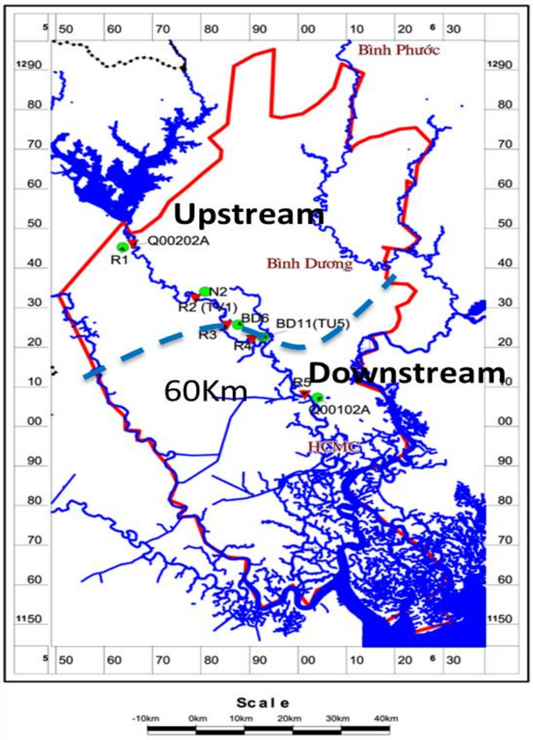


Figure 6. 9: Location of river – groundwater calibration

Table 6. 3: Statistic performance of calibration and verification

Section name	R1 -Q102	R2 - N2	R3 -BD06	R4 -BD11	R5 -Q202	R1 -Q102	R2 -N2	R3 -BD06	R4 -BD11	R5 -Q202
	Calibration (1995 - 2006)					Verification (2007-2017)				
Max Error (m)	1.73	0.15	2.5	0.37	1.99	1.78	0.28	0.68	0.58	1.22
Min Error (m)	0	0.04	0.04	0	0	0.01	0.03	0	0.02	0
Mean Error (m)	0.61	0.12	0.1	0.12	0.02	0.16	0.11	0.06	0.05	0.07
R^2	**0.86**	**0.94**	**0.68**	**0.72**	**0.7**	**0.83**	**0.79**	**0.63**	**0.7**	**0.65**
Conductance (m^2/day/m)	4.5	4.2	2.5	1.7	0.25	4.5	4.2	2.5	1.7	0.25

In summary, the surface – groundwater interaction parameters in Saigon River Basin were measured from the field measurement and were successful calibrated and validated via groundwater modelling. The improved parameters assisted the piezometric head more reliable and reasonable with the previous study. The table 6. 4 and table 6. 5 summarize land recharge function and conductance of riverbed along Saigon river.

Table 6. 4: Summary of land recharge function in Saigon River Basin

	Land Recharge function
Aquifer 1	Re=0, top coverage is thick clay layer (thickness >20m)
Aquifer 2	Re=0.424*$e^{0.118ER}$
Aquifer 3	Re=0.0932*$e^{0.088ER}$
Aquifer 4	Re=1.21*$e^{0.085ER}$
Re: recharge rate (mm/day), ER: effective rainfall (mm/day)	

Table 6. 5: Summary of conductance of riverbed along Saigon River (Tran Thanh Long & Koontanakulvong, 2019)

Distance from Dautieng dam	0	30km	60km	80km	120km
Sand percentage	80%	65%	40%	23%	10%
Conductance (m2/day/m)	4.5	4.2	2.5	1.7	0.25

6.3. Quantifying proportion of fluxes exchange by O^{18}

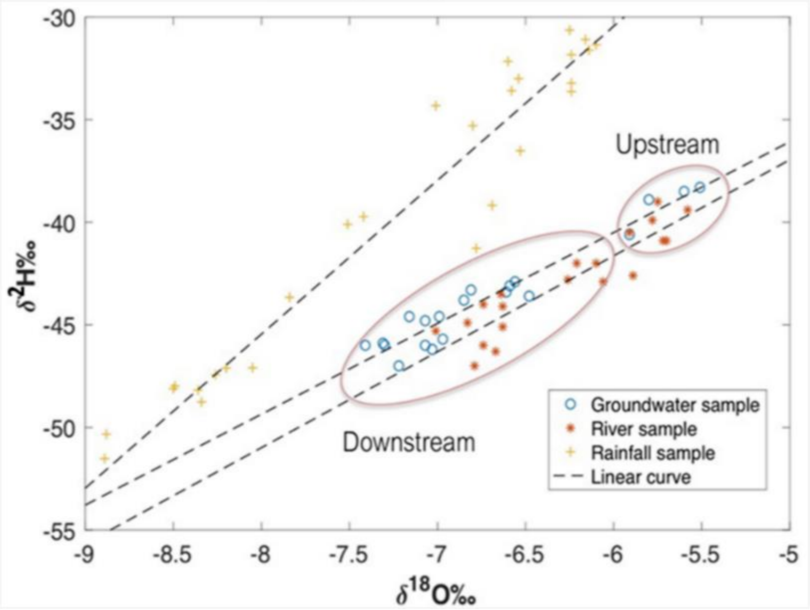


Figure 6. 10: The relationship between δ^3H and δ^{18}O of groundwater, river, and rainfall samples in Saigon River Basin.

To qualify the fluxes exchange of the river into groundwater, the isotope analysis from rain, well and river water samplings were conducted quarterly in year 2018. As shown in Figure 6.10 there exists good correspondence between the hydrogen and oxygen isotope compositions obtained from the groundwater sample of the observation wells and to those of along the Saigon River. The results of stable isotope analysis describe in appendix D. The $\delta^{18}O$ and $\delta\ ^{2}H$ isotopic sample of groundwater collected at five stations varies in range between −7.4‰ and −5.5‰ and -46.3‰ and −38.2‰, respectively. The river consisted of $\delta^{18}O$ from−7‰ to −5.5‰ and $\delta^{2}H$ in range -47‰ and −39‰. Meteoric Water Line was built from isotopic samples of Hochiminh City's precipitation. The $\delta^{18}O$ of precipitation varies from −8.89‰ to −6.57‰, while $\delta^{2}H$ are in range -53.79 ‰ to −32.16‰. In general, the slope isotopic of groundwater, river, precipitation distinguished in three different lines. The isotopic composition of groundwater is inline between land recharge's and river's. The collected isotope samples of groundwater and Saigon River water in upstream exhibit similarity isotopic composition. This shows that the groundwater and river in the upstream would be from same origin. Also, the groundwater level above river stage in upstream drives groundwater leakage along the riverbank (see Figure 6.11). Therefore, the groundwater mainly discharges to Saigon River in the upstream. Contrarywise, the $\delta^{18}O$ of groundwater is lower than the $\delta^{18}O$ of the river but higher than the $\delta^{18}O$ of rainfall in downstream. Besides, the fluctuating of groundwater level corresponds with river stage and rainfall event. The groundwater level also below the river stage downstream (see Figure 6.12). With above evidence, it concluded that groundwater in downstream was dominated by mixing sources of land recharge and Saigon river.

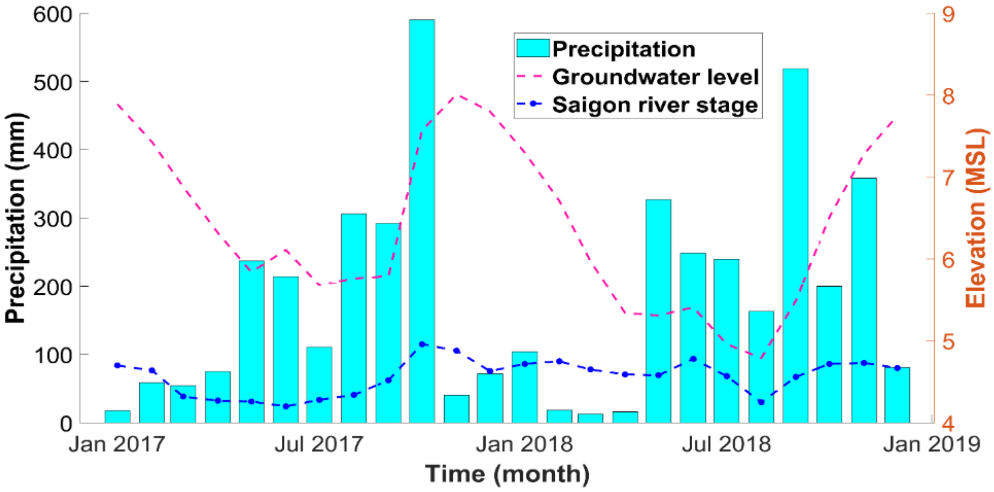


Figure 6. 11: Groundwater level, Saigon river stage and precipitation in upstream Saigon River Basin

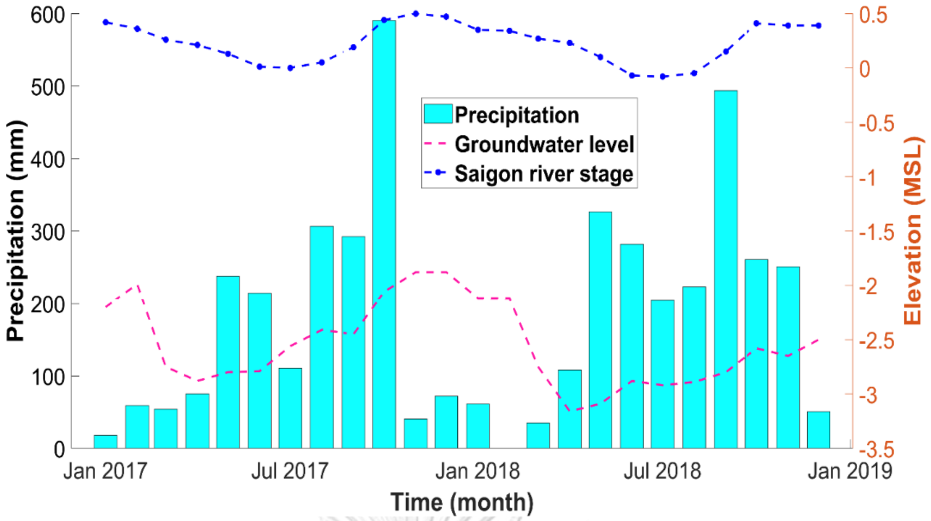


Figure 6. 12: Groundwater level, Saigon river and precipitation in downstream Saigon River Basin

To understand groundwater balance in basin, it was essential to assess the actual recharge of groundwater by rainfall and river water. To correctly understand how groundwater recharges, the meteoric δO^{18}-δH^{2} signature of groundwater, river, and precipitation were used to analyze the ratio mixing both rainfall and surface water in groundwater at five sections. Based on the mass balance calculation of oxygen and hydrogen isotopes, the contribution percentage of each recharge source to groundwater in the study area could evaluate by Ep. IV-10 and Ep. IV-11. At the distance 0km, the water from the groundwater with an enriched isotopic signature is mainly discharged source to Saigon river. Since distance 36km, the composition δH^{3} in surface water and groundwater indicated that river water accounted for around 14%–73% of the total groundwater recharge. While the rainfall archived 27%-86% of total groundwater recharge. The percentage contribution of Saigon river to groundwater recharge gradually increase since distance 60-km to 120-km. Because of the impact of intensive pumping rate downstream, the declining groundwater level below river level drives the recharge aquifers process from river complement. Besides, the ratio between land recharge and river recharge from isotope analysis showed good agreement with exchange fluxes in Saigon regional groundwater model (see table 6. 6). According to Saigon regional groundwater modeling, the land recharge at five field workstations varies 148 - 336 m^3/day, while the river recharge range -1005 - 874m^3/day. Regarding river – groundwater interaction evidence above, Saigon River Basin could be divided into two parts: the upstream where the groundwater relied on rainfall recharge and release to river, and the downstream where the river significant dominated to groundwater recharge (see Figure 6.11).

Table 6.6: Comparison fluxes recharge from modelling and isotope composition in rainy season year 2017

Name section	Distance	Isotope			Groundwater modeling	
		GW (%)	Rainfall recharge (%)	River recharge (%)	Rainfall recharge (m^3/day)	River recharge (m^3/day)
R1-Q102A	0km	100	*0*	*100*	336 *(0%)*	-1005 (100%)
R2-N2	36km	100	*86*	*14*	336 *(91%)*	34 (9%)
R3-BD6	60km	100	*69*	*31*	148 *(70%)*	64 (30%)
R4-BD11	80km	100	*61*	*39*	148 *(64%)*	83 (36%)
R5-Q202A	120km	100	*27*	*73*	268 *(23%)*	874 (77%)

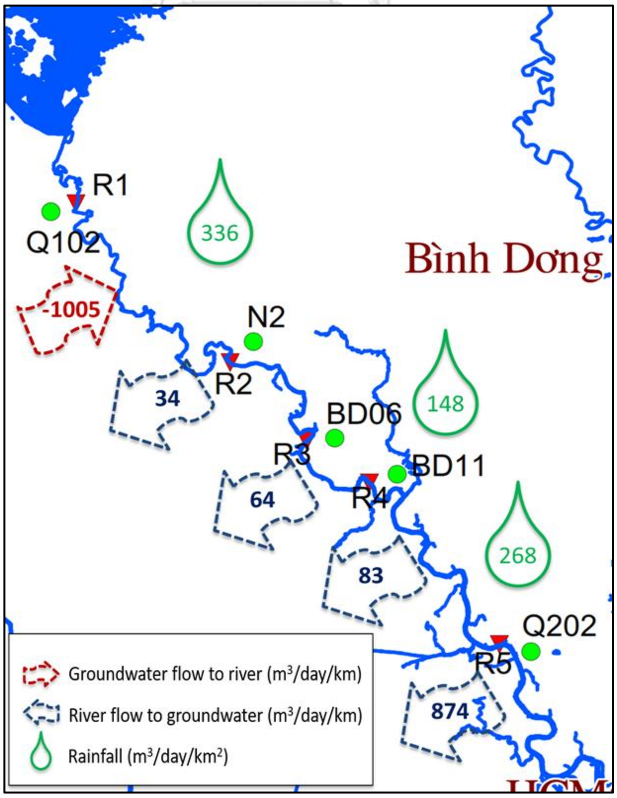


Figure 6. 13: Surface – groundwater interaction in the Saigon River Basin

6.4. Groundwater balance under the surface– groundwater interaction flux

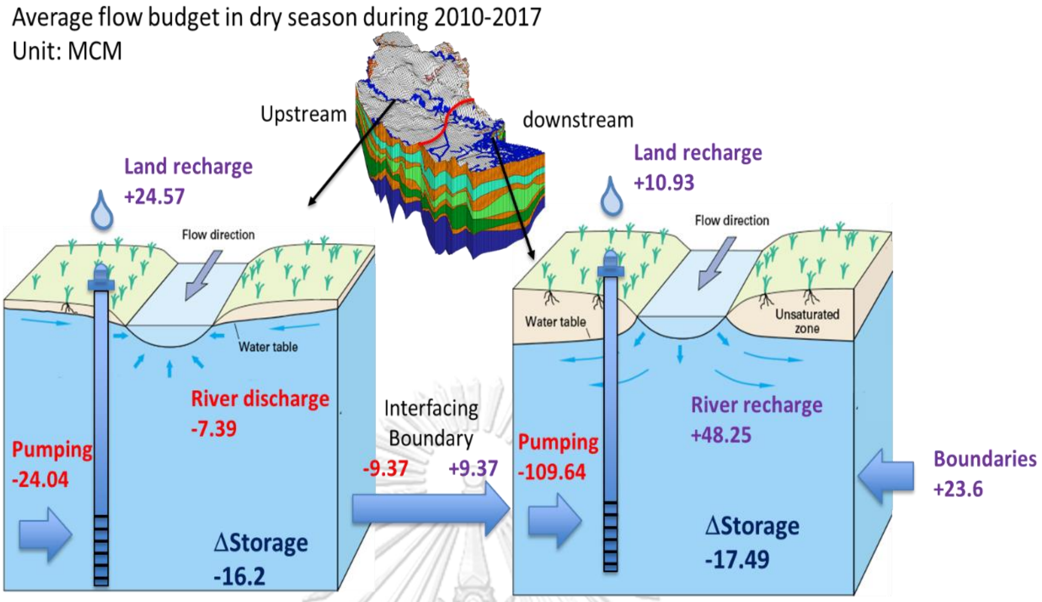


Figure 6. 14: Average groundwater budgets of Saigon River Basin in the dry season during 2010-2017

According to developed groundwater modelling, the monthly flow budget in Saigon River Basin was utilized to compute seasonal water budget in regional scale (see details in Appendix E). Figure 6.14 illustrates the average groundwater budgets of the Saigon River Basin in the dry season during 2010-2017. In upstream, the inflow only comes from rainfall recharge with +24.57 MCM. Meanwhile, the present groundwater abstraction is approximately equivalent to land recharge (-24.04 MCM). Besides, because groundwater level in upstream is higher than river stage and downstream drawdown, the groundwater storage in upstream outflows to river discharge -7.39 MCM and to the interfacing boundary -9.37 MCM. Hence, to balance the groundwater budget in dry season, the groundwater storage upstream was depleted -16.2 MCM. In downstream, the inflow components are +10.93 MCM of rainfall recharge, +48.25 MCM of river recharge, +9.37 MCM of interfacing boundary and +32.97 MCM of the neighboring boundaries. The primary outflow in downstream is the abstraction with amount -109.65 MCM. Under extensive groundwater pumping, the groundwater level was dramatically decreasing. Hence, the groundwater below the river stage 3 meters which enhanced the recharge source from Saigon River into aquifers +48.25 MCM. However, the groundwater recharge is insufficient to balance abstraction and generate negative groundwater storage in downstream (-17.49 MCM).

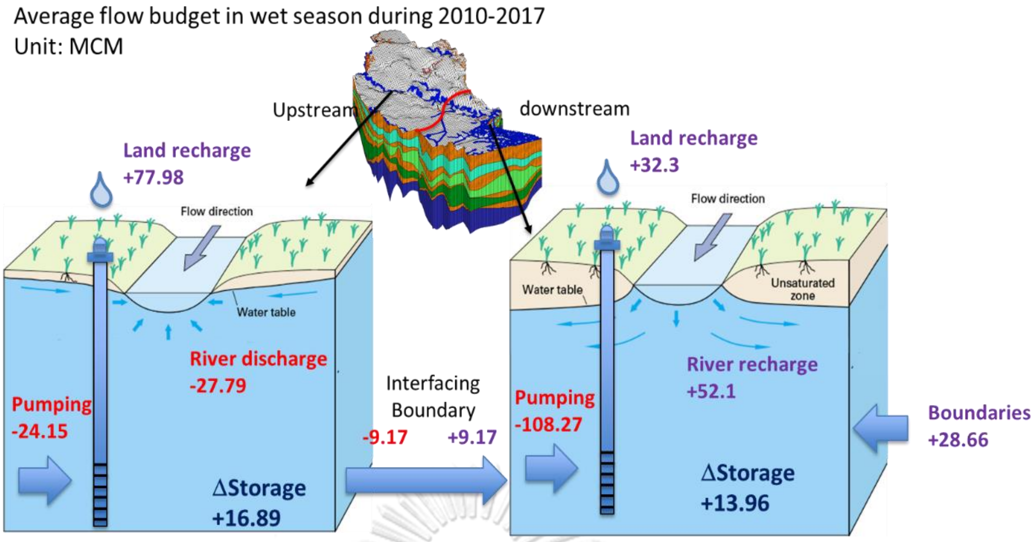


Figure 6. 15: Average groundwater budgets of Saigon River Basin in the wet season during 2010-2017.

The average groundwater budgets in Saigon River Basin in wet season 2010-2017 demonstrate in Figure 6.15. As same as the dry season, the pumping of upstream in the wet season was -24.15 MCM. During the wet season, the groundwater level in upstream raised up because aquifers received +77.98MCM from land recharge. Due to the higher piezometric head, the groundwater discharge to Saigon river -27.79 MCM and the interfacing boundary -9.17 MCM. During the wet season, the total outflows in upstream are lower than total inflows, which leads the groundwater storage to recover +16.89 MCM. In downstream sides, because top coverages are mainly thick clay and concrete of urban areas, the aquifers gained only +32.3 MCM from land recharge. During the wet season, the Saigon river rises water levels up and brings more water from the river to aquifers +52.1 MCM. The interfacing boundary and the neighboring boundaries flows are similar to dry season with +9.17 MCM and +28.66 MCM, respectively. The groundwater pumping in the wet season is approximating to dry season’s with -108.27 MCM. Hence, with the additional amount of land recharge in the wet season, the groundwater storage in downstream increased +13.96 MCM.

In general, the groundwater storage in upstream seems to balance at annual scale. Moreover, the groundwater from upstream discharge to downstream through river and interfacing boundary. Under excessive groundwater pumping, the groundwater storage in downstream was gradually declining annually. The rainfall recharge and river recharge contribute 12-26% and 40-50% of total groundwater budget in Saigon

River Basin, which agrees with (Ha Quag Khai & Koontanakulvong, 2015; Tuan Pham Van & Koontanakulvong, 2018)

6.5 Findings

According to sampling compositions, the stable isotope of groundwater, river, rainfall, the study identified that groundwater discharge to river in upstream and gain recharge from river and rainfall in downstream. According to soil distribution, the rainfall recharge percentage decreases from upstream to downstream — meanwhile, the river recharge percentage increases from upstream to downstream. Due to recharge are limited mainly in upstream, the contribution of rainfall recharge is 12-26% of groundwater storage. Because Saigon river stretches across the plain, the river recharge plays a vital role in balancing the groundwater budget downstream with 40-50% contribution of total groundwater budget in Saigon River Basin. With low abstraction, the groundwater storage in upstream are balancing at annual scales. Meanwhile, the groundwater storage in downstream was gradually declining annually as result of extensive pumping rate.

Because of the critical role of Saigon river in balancing groundwater storage, aquifer management downstream requires functional coupling with river water plan. Particularly, Saigon River Basin surface water supply should expand networks to an area that has not fulfilled the rapid increase of water demand. Besides, this study focused on the river groundwater interaction in Saigon River Basin, Vietnam, with no considerations of salt intrusion in river, as well as rising sea levels projected in the future. Therefore, future studies should investigate the saline condition and sea-level rise to find sustainable groundwater yield for better water resources management in the study area.

CHAPTER VII

PUMPING MANAGEMENT FOR DEVELOPMENT SCENARIOS

This chapter describes the optimal groundwater pumping management for development in Saigon River Basin. The pumping management for developments scenarios included three main parts: 1) the water deficit scenarios are calculated from master plans of provincial, World Bank, and surface water supply plan; 2) The sustainable groundwater yield was explored in existing area and new area via regional groundwater modeling considering drawdown, saline interface, land use; 3) The sustainable groundwater yield and optimal groundwater management was recommended for development scenarios by adapting optimal intensity pumping within drawdown criteria.

7.1. Water deficit scenarios by 2035

7.1.1 Water demand scenarios

In order to access optimal pumping management coupling with development scenarios, this study calculated water demand and water deficits in Saigon River Basin by 2035. To understand the magnitude of water demand, this study utilized data from two scenarios: the forecast water demand with GDP growth by World Bank (2017) and the forecast water demand with master plan land use by provincial (Ministry Of Natural Resources And Environment Vietnam, 2013). The water demand of Saigon River Basin mainly comes from irrigation sector, industry sector, tourism sector and household.

The assumptions of water demand with GDP growth criteria are described as follows:

Irrigation: Agriculture growth (including forest and fisheries) since 2009 is estimated at 3.5%. A third of the growth is attributed to the forest and fisheries. After 2020 rice plant area is not to increase further, the cash and plantation crops are likely to grow. Hence, the annual GDP for agriculture, forest and fisheries are expected rising 3.5% during 2009-2020, and 3% throughout 2020-2030. Henceforth, the annual water demand is projected as increasing 2.25% during 2009-2020, and 1% after 2020.

Domestic: Although Viet Nam’s population growth rate has stabilized at 1.03% since 2017, the urban population has been facing rapid growth due to inward migration. Viet Nam has one of the fastest rates of urbanization in the world, with almost 43% of the country’s population expected to be living in cities and urban areas by 2030. As an economic hub of Viet Nam, the population of Saigon River Basin has been projected approximate 13 million by 2025. The average water use for households from 90 water utilities in Viet Nam is 110-120 l/capita/day. Thus, the projected annual water demand for domestic is with increasing rate 4.5%/year.

Tourism: As one of the development sites in Vietnam, Saigon River Basin attracted a lot of people for tourist activities. Moreover, the growing population in this basin is corresponding to tourist activities. Hence, the annual increase in water demand for tourism is assumed to increase in line with the domestic sector at 4.5%.

Industrial: Industry contributes 39% of the GDP and is growing fast with an average growth rate of 7%. Although industrial water demand is not disclosed or reported, Viet Nam's standards for construction No33:2006 (TCXDVN33:2006) indicate that industrial sectors such as liquid, milk, food processing and paper have an estimated water demand of 45 m^3/hectare/day. Published data indicates that industrial park water demand can be significantly higher at 75 m^3/hectare/day. The annual increase in water demand for the industry is expected by 7% until 2030. The projected water demand in Saigon River Basin of World Bank scenarios is shown in Table 7.1.

Table 7. 1: The projected water demand of World Bank scenario in Saigon River Basin (World Bank, 2017)

No.	Demand	2005	2010	2015	2035
1	**Daily life water**	718,401	1,011,659	1,099,467	2,651,599
2	**Industrial water**	179,600	317,950	345,547	1,337,157
3	**Irrigation**	718,401	953,850	973,814	1,248,165
4	**Tourist**	379,156	578,091	722,507	1,742,482
	Total	1,995,558	2,861,550	3,141,335	6,979,403

Besides, the Vietnam Government also projected water demand based on the master plan of land use in Saigon River Basin through 2030 (Vietnam Government, 2012, 2014). The details of projected assumption by Vietnam Government are described as follows:

Irrigation: The agricultural land will be maintained approximate 238,322 hectares. Agriculture will be restructured toward less cultivation and more husbandry and agricultural services. The proportion of cultivation will be diminished from 66% to 53% through 2035. The proportion of husbandry will be 42% in 2035. Besides, the water demand for husbandry is negligible compared to cultivation's. Therefore, the water demand in 2035 for irrigation was forecasted to increase to 1,283,389m^3/day in 2035 from 1,099,467 m^3/day in 2015.

Domestic: The standard water use for households in Saigon River Basin is 150 l/capita/day. (Gorvernment, 2008). As an economic hub of Viet Nam, the population of Saigon River Basin has been projected approximate 12 million by 2035. Thus, the forecasted water demand through 2035 for domestic is 1,826,361m^3/day.

Tourism: The standard water demand for tourism is 80l/person/day. As one of the attracted areas in Vietnam, Saigon River Basin was forecasted around 16 million tourists forward 2035. Hence, the forecasted water demand through 2035 for tourism is 1,283,389m^3/day.

Industrial: According to Viet Nam’s standards for construction No33:2006 (TCXDVN33:2006), the industrial sectors such as liquid, milk, food processing, and paper have an estimated water demand of 45 m^3/hectare/day. By 2035, the industrial sector is expected reaching 52% of the economic structure. To achieve the target, the industrial land will be fully expanded 16,453 hectares. Henceforward, the forecasted water demand in 2035 for industrial is 740,417m^3/day. The projected water demand in Saigon River Basin provincial scenarios is shown in Table 7.2.

Table 7. 2: The projected water demand of Provincial scenario in Saigon River Basin (Vietnam Government, 2012, 2014)

No.	Demand	2005	2010	2015	2035
1	**Daily life water**	718,401	1,011,659	1,099,467	1,826,361
2	**Industrial water**	179,600	317,950	345,547	740,417
3	**Irrigation**	718,401	953,850	973,814	1,283,389
4	**Tourist**	379,156	578,091	722,507	1,085,944
Total		1,995,558	2,861,550	3,141,335	4,936,111

Figure 7.1 demonstrates the water demand of World Bank and Vietnam Government scenarios. The projected water demand of World Bank scenario is higher than Vietnam Government's. The projected water demand increased 2 – 2.5 times of current water demand by 2035.

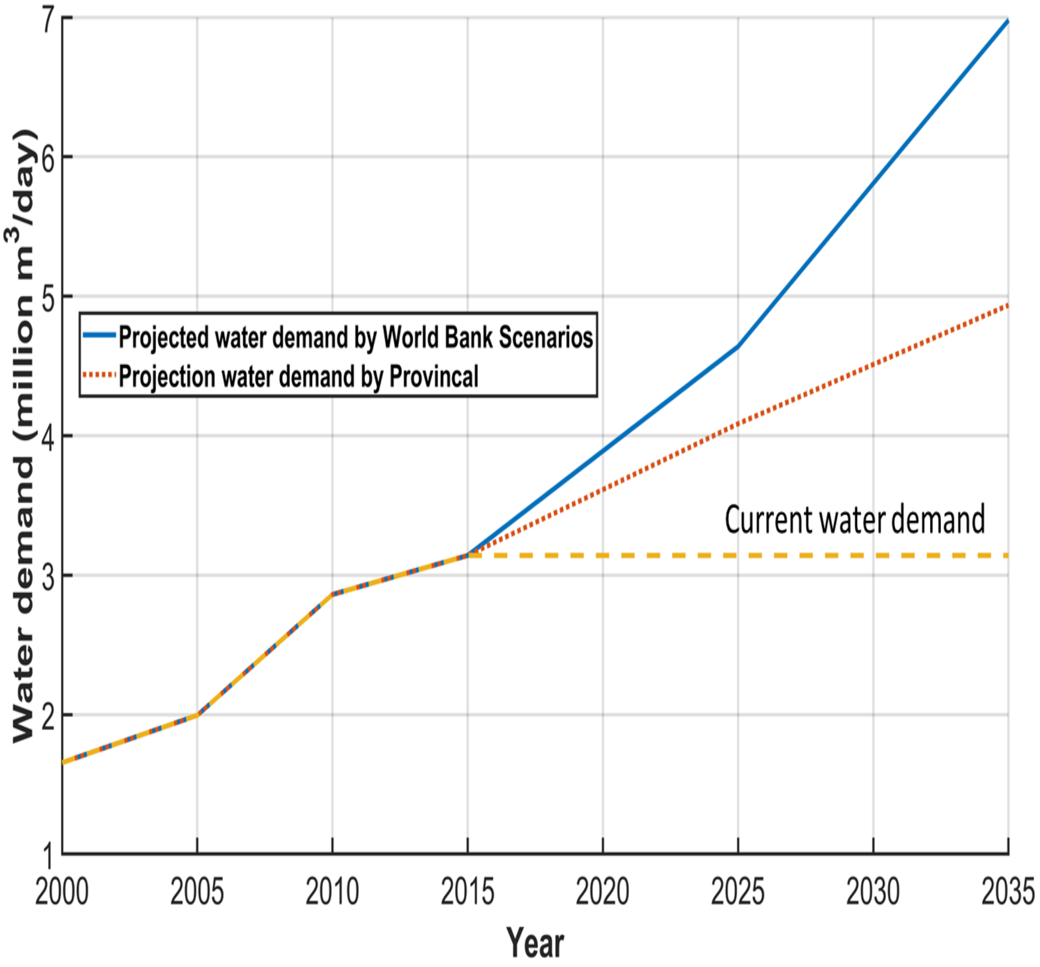


Figure 7. 1: Projected total water demand in Saigon River Basin

7.1.2. Surface water supply capacity

To ensure water supply coupling targets water demand, the surface water system planned to improve production from 1.6 million m^3/day in current to 4.2 million m^3/day by 2035 (Vietnam Government, 2012). The freshwater will be undertaken from following sources:

- Dong Nai river (regulated by Tri An reservoir): The unpurified water from this source will be exploited 2.25 million m^3/day by 2025, and 2.5 million m^3/day by 2035 for supply to water plants designed to use water from this river.

- Sai Gon river (regulated by Dau Tieng and Phuoc Hoa reservoirs): The unpurified water from this source will be employed 0.9 million m^3/day by 2025, and 1.2 million m^3/day by 2035 for supply to water plants designed to use water from this river.

- Dong main canal (regulated by Dau Tieng and Phuoc Hoa reservoirs): The unpurified water from this source will be employed 0.35 million m^3/day by 2025, and 0.5 million m^3/day by 2035 for supply to water plants designed to use water from this canal. Table 7.3 summarizes the surface water capacity in Saigon River Basin:

Table 7. 3: Summary of the surface water capacity in Saigon River Basin

No.	Name	2010	2015	2025	2035
1	**Dong Nai River (Tri An Reservoir)**	1,150,000	1,450,000	2,250,000	2,500,000
2	**Saigon River (Dau Tieng Reservoir)**	300,000	600,000	900,000	1,200,000
3	**Dong Canal (Dau Tieng Reservoir)**	0	150,000	350,000	500,000
	Total	1,450,000	2,200,000	3,500,000	4,200,000

7.1.3. Water deficit scenarios by 2035

In order to access optimal pumping management coupling with development scenarios, this study projected groundwater deficit scenarios by 2035 from water demand scenarios and surface capacity scenarios. The water demand based on two scenarios: forecast water demand with GDP growth by World Bank (2017), forecast water demand with master plan land use by provincial (Ministry Of Natural Resources And Environment Vietnam, 2013). The surface water capacity scenarios consist of three scenarios: current capacity (2.2 million m^3/day), by 2025 capacity (3.5 million m^3/day), by 2035 capacity (4.2 million m^3/day). The water supply scenarios are obviously insufficient to supply developing water demand scenarios. As a result of combining water demand scenarios and surface water capacity scenarios, the projected water deficit by 2035 is 736,111 – 4,779,403 m^3/day. Hence, groundwater becomes a strategic resource to supply water for development social-economic plans. Moreover, the groundwater in Saigon River Basin used to supply mainly for the industry sector and household. However, groundwater is a vulnerability resource under indiscriminate abstraction. Henceforth groundwater exploitation needs proper pumping management to avoid depleting aquifers in the Saigon River Basin. This study attempted to explore sustainable pumping intensity and groundwater yield for Saigon River Basin under developing water demand scenarios. Table 7.4 presents a summary of the estimated water deficit by 2035 in each scenario.

Table 7. 4: Summary of estimated water deficit by 2035 in each scenario

No	Water demand by 2035	Surface water capacity by 2035			Estimated water deficit in 2035
		Total surface water	Saigon River	Dong Nai River	
A.1	4,936,111 by provincial (Government, 2012)	(C.1) 2,200,000	750,000 (present)	1,450,000 (present)	2,736,111
A.2		(C.2) 3,500,000	1,250,000 (by 2025)	2,250,000 (by 2025)	1,436,111
A.3		(C.3) 4,200,000	1,700,000 (by 2035)	2,500,000 (by 2035)	736,111
B.1	6,979,403 by World Bank (World Bank, 2017)	(C1) 2,200,000	750,000 (present)	1,450,000 (present)	4,779,403
B.2		(C2) 3,500,000	1,250,000 (by 2025)	2,250,000 (by 2025)	3,479,403
B.3		(C3) 4,200,000	1,700,000 (by 2035)	2,500,000 (by 2035)	2,779,403

7.2. Sustainable pumping yield in Saigon River Basin

7.2.1. Sustainable pumping yield in the existing area (downstream)

Groundwater sustainable yield is considered as an available exploitation yield for a long time without any adverse effects to the economy, society and environment (Fetter Jr, 1972; Freeze, 1971; Kalf & Woolley, 2005; MA Sophocleous et al., 1999; Marios Sophocleous & Perkins, 2000; T. Yang et al., 2008; Zhou, 2009). Hence, to recommend optimal groundwater pumping management, this study accessed sustainable groundwater yield in the existing area to supply deficit water scenarios in the future.

In current, under intensive pumping rate, Saigon River Basin is facing saline water that occurs in some wells in the existing area. However, there are insufficient record salinity data to simulate the salt intrusion movement. On the other side, the hydraulic gradient of the saline interface corresponds to the lowest drawdown of aquifers (see Figure 5.8). Since the length and area of seawater intrusion in the aquifer are governed by the hydraulic gradient (Guo et al., 2019). In addition, the hydraulic gradient at the salinity interface seems to fluctuate stable when the groundwater levels stabilized in the last five years. Hence, the sustainable groundwater yield in the existing area was estimated with drawdown criteria remained as the current situation to avoid increasing saltwater intrusion into aquifers progress. Regarding Figure 7.2, the drawdown limitation of aquifer 2, aquifer 3 and aquifer 4 in downstream are -35 m. MSL, -30 m. MSL, and -30m. MLS.

According to developed groundwater modeling, water balance in Saigon River Basin under pumping rate of 785,000 m^3/day (current pumping rate) was calculated in three water years: dry year defined as annual rainfall below 1600 mm, normal year considered as annual rainfall between 1600 mm and 2000 mm, and wet year received annual rainfall over 2000 mm. Figure. 7.2 indicates water balance in Saigon River Basin under the current pumping rate. The annual river recharge into aquifers is approximal 147 MCM. The annual rainfall recharge into aquifers varies 115 - 175 MCM depend on water year. The annual boundary flow to aquifers 60 MCM. The annual river discharge range -59 - -71MCM. Regards to flow water budgets, the groundwater storage balanced since the groundwater pumping maintained 785,000 m^3/day during the last three years. The groundwater storage deficit over dry year, while the different of groundwater storage is positive during normal year and wet year.

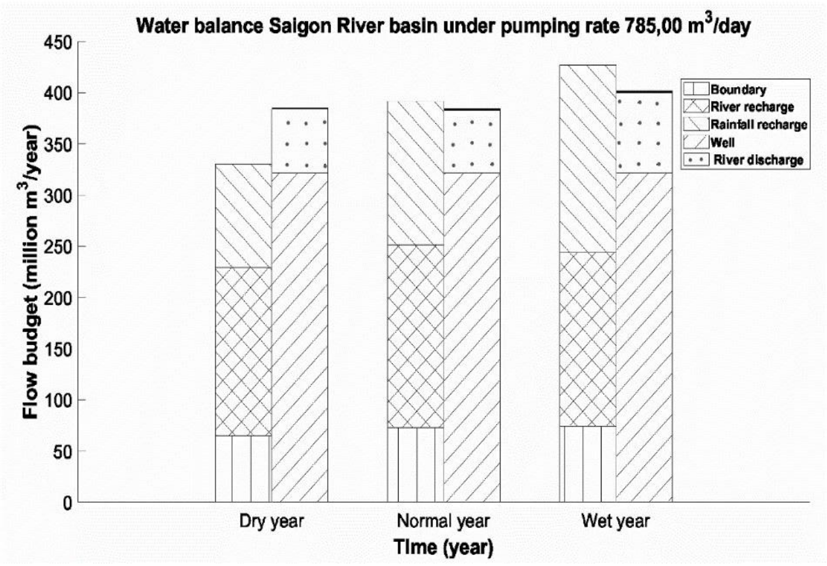


Figure 7. 2: Water balance in Saigon River Basin under pumping rate of 785,000 m^3/day (current pumping rate)

However, the existing groundwater pumping is impossible to supply water deficits in the future. To determine additional sustainable groundwater pumping in existing area, the study analyzed optimal pumping well intensity in downstream to avoid concentrated pumping wells in small area which cause anomalous drawdown in local over drawdown limitation. The appreciate intensity pumping well consist of drawdown above -20 m. MSL for aquifer 2 and -30 m. MSL for aquifer 3 and aquifer 4. According to the intensity pumping in existing area, the sustainable intensity pumping for aquifer 2, aquifer 3 and aquifer 4 was 2000 m^3/day/km^2, 3500 m^3/day/km^2, and 4000 m^3/day/km^2, respectively (see appendix F).

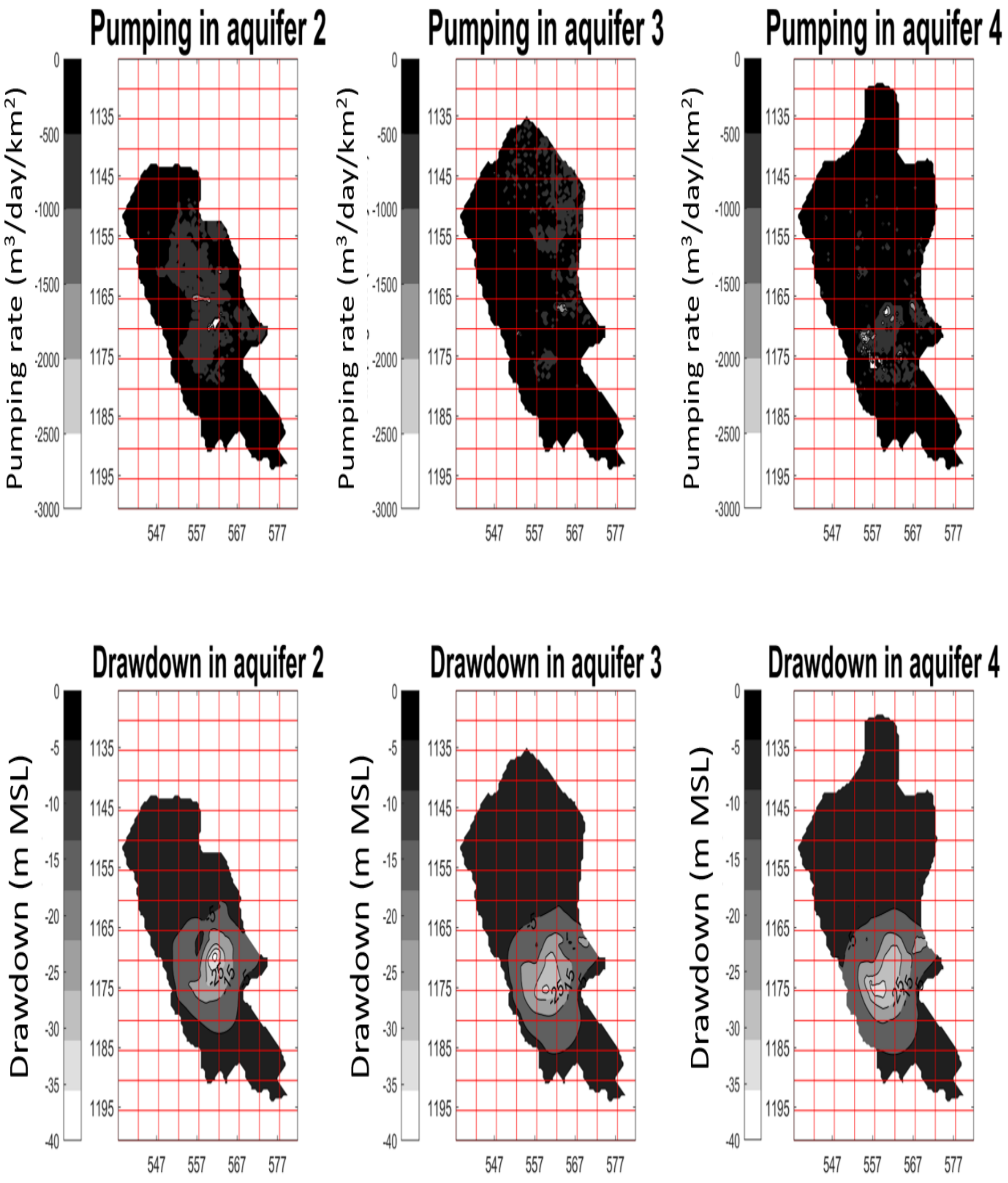


Figure 7. 3: Pumping and drawdown of aquifers under pumping rate 880,000 m^3/day (increase pumping 100,000 m^3/day in existing area)

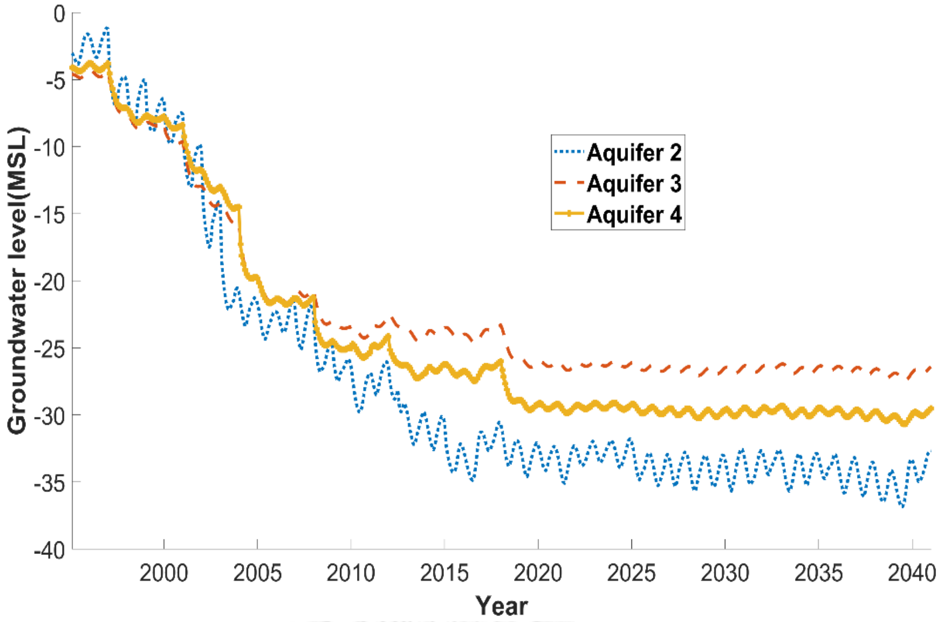


Figure 7. 4: Sustainable drawdown of aquifers in downstream under pumping rate 880,000 m^3/day (increase pumping 100,000 m^3/day in existing area)

The sustainable groundwater yield in downstream was estimated by “increase pumping step by step” approach. The sustainable groundwater yield was defined as the maximum groundwater pumping in the region with drawdown under constraint for 20 years of simulation (see Figure 7.4). In respect to drawdown criteria, appropriate intensity pumping and 20-year climate data, the sustainable pumping yield in the existing area is 880,000 m^3/day. Figure 7.3 and Figure 7.4 present the groundwater levels in aquifers meet drawdown criteria. Figure 7.5 illustrates water balance Saigon River Basin under pumping rate 880,000 m^3/day (increase pumping 100,000 m^3/day in the existing area). The annual river recharge into aquifers is approximal 164 - 178MCM depend on water year. The annual rainfall recharge into aquifers varies 101 - 182MCM. The annual boundary flow to aquifers 64 - 73 MCM. The annual river discharge range -59 - -71MCM. Like the current pumping scheme, the different of groundwater storage is positive during normal year and wet year. Although the river recharge increased under growing pumping, the groundwater budgets are abundantly unbalanced in the dry year. Therefore, in case of pumping over 880,000 m^3/day in the existing area, the groundwater levels rapidly decrease and drive more salt intrusion toward aquifers.

Although the water deficit by 2035 was projected from 0.76 million m^3/day to 4.77 million m^3/day, the current pumping management seems impossible to supply those pumping rates without infringing to drawdown aquifers limitation. While the groundwater in upstream is abundant and consistently discharge to river. Consequently, the groundwater pumping management should expand to upstream.

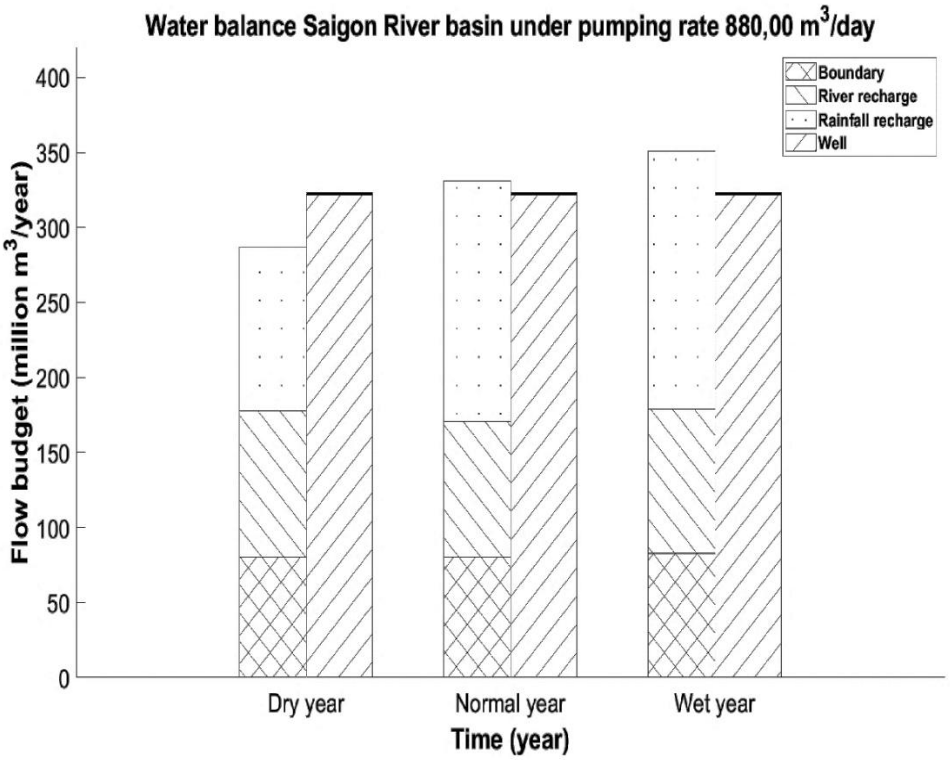


Figure 7. 5: Water balance in Saigon River Basin under pumping rate of 880,000 m^3/day (increase pumping 100,000 m^3/day in existing area)

7.2.2. Sustainable pumping yield in new area (upstream)

The upstream Saigon River Basin is mainly freshwater area. To determine the appropriate for the sustainable yield in the new area, the drawdown criteria in upstream will follow decision 69/2007/QD-UBND of Ho Chi Minh City (2007) on reducing underground water exploitation. The drawdown of aquifer 1 and aquifer 2 limits at -20 m. MSL. The groundwater levels of aquifer 3 and aquifer 4 remain not lower than -40 m. MSL. Because of effective groundwater – river interaction flux and large thickness of aquifers at locations near Saigon river, the groundwater model inserted pumping well along Saigon river to determine sustainable yield in the new area.

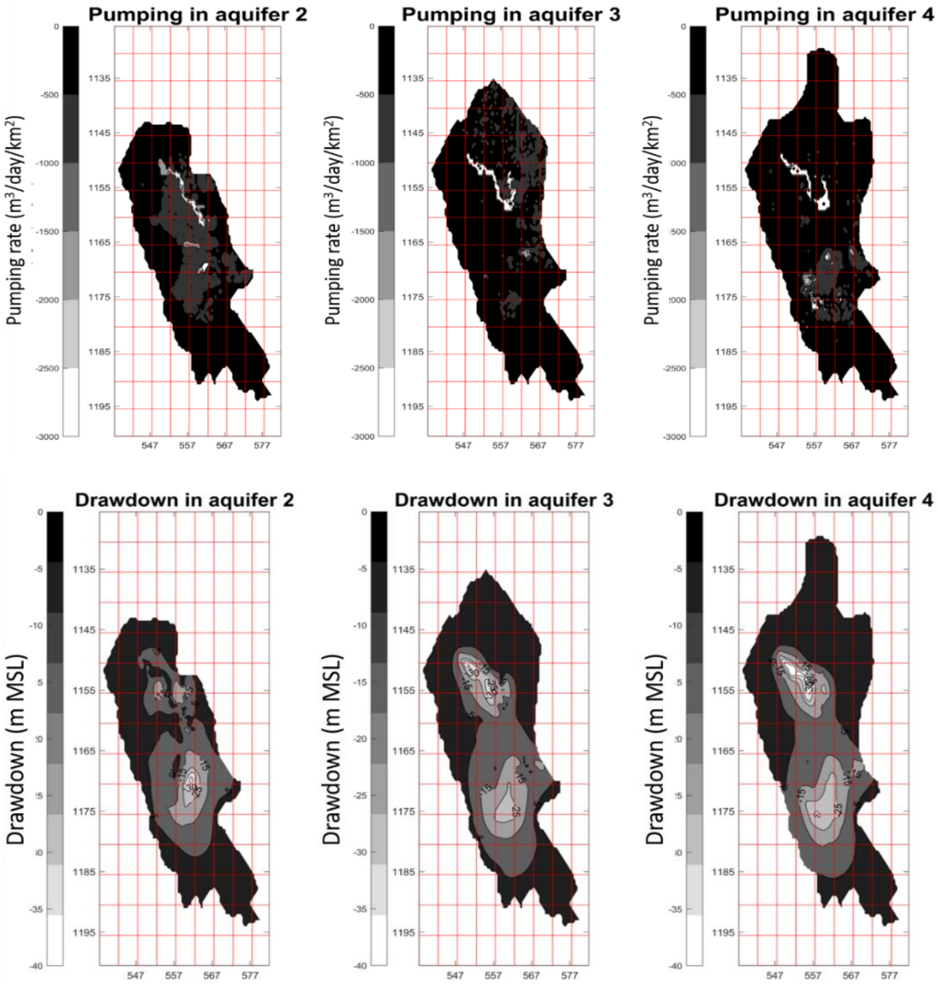


Figure 7. 6: Pumping and drawdown of aquifers under pumping rate 1.9 MCM/day (0.88 MCM/day in existing area + 1.02 MCM/day in new area)

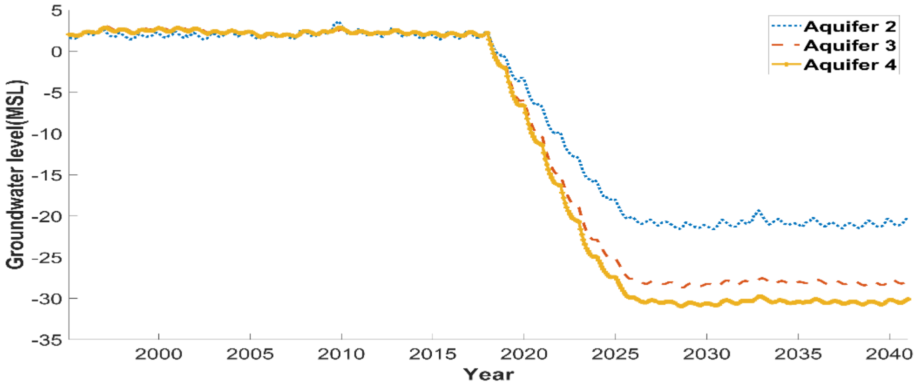


Figure 7. 7: Sustainable drawdown of aquifers at upstream during 20 year simulation under pumping rate 1.9 MCM/day (0.88 MCM/day in existing area + 1.02 MCM/day in new area)

Regards to drawdown criteria, appropriate intensity pumping and 20 years climate data, the developed groundwater modeling estimated the sustainable pumping yield in new area is 1.02 MCM/day. Figure 7.6 and Figure 7.7 present drawdown of aquifers under pumping rate 1.9 MCM/day (880,000 m^3/day in the current area and 1.02 million m^3/day in new area). The drawdown under the sustainable pumping rate is higher than 30 m. MSL which meet drawdown criteria. Figure 7.8 demonstrates water balance Saigon River Basin under pumping rate 1.9 MCM/day (0.88 MCM/day in the existing area and 1.02 MCM/day in new area). The annual river recharge into aquifers is approximal 427 - 436MCM depend on water year. The annual rainfall recharge into aquifers varies 101 - 182MCM. The annual boundary flow to aquifers approximal 91 MCM. Under increasing groundwater pumping, the groundwater model indicates that the amount from river flows into groundwater up 3 times higher current situation. Moreover, groundwater cannot discharge to the river since the drawdown is lower than the river stage 5 meters during increasing pumping rate of 1.9 MCM/day. In terms of groundwater balance, the different of groundwater storage is negative in dry year and positive during normal year and wet year. Figure 7.9 illustrates cross-section water level along Saigon River. Under increasing pumping rate 1.9 MCM/day, the groundwater level along Saigon river decrease 2-5 meters.

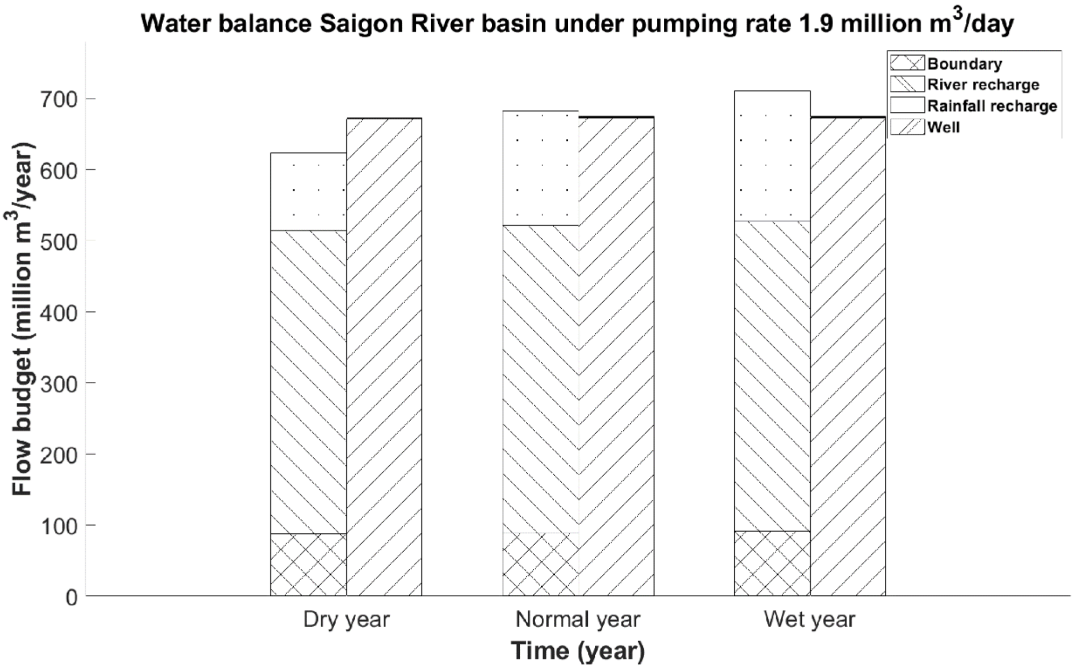


Figure 7. 8: Water balance in Saigon River Basin under pumping rate of 1.9 MCM/day (0.88 MCM/day in existing area + 1.02 MCM/day in new area)

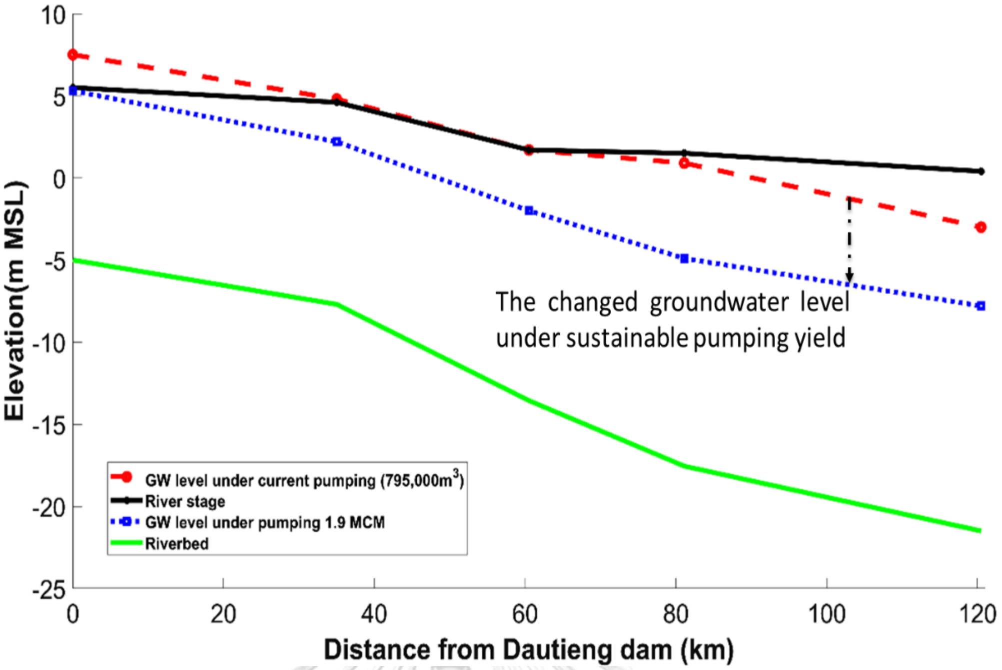


Figure 7. 9: Cross section water level along Saigon river

Figure 7.10 describes groundwater budget components considering surface - groundwater interaction of Saigon River Basin under pumping rate 1.9 MCM/day (0.88 MCM/day in the existing area + 1.02 MCM/day in the new area). The upstream absorb more rainfall recharge than the downstream. The annual rainfall recharge in upstream includes 18.33 MCM to aquifer 1, 60.98 MCM to aquifer 2, 25.865 MCM to aquifer 3 and 231.185 MCM to aquifer 4. The rainfall recharge to aquifer 1, aquifer 2, aquifer 3 and aquifer 4 of downstream are 31.765 MCM, 7.64 MCM, 0.115 MCM and 1.725 MCM, respectively. The river recharge to groundwater through 4 aquifers in upstream and 2 aquifers in downstream. The annual river recharge to upstream groundwater consist of 5.55 MCM to aquifer 1, 231.045 MCM to aquifer 2, 76.54 MCM to aquifer 3, -18.47 MCM to aquifer 4. The annual river recharge to aquifer 1 and aquifer 2 in downstream are 6.235 MCM and 126.86 MCM, respectively. The river – groundwater interaction occurs mainly in aquifer 2. The deeper aquifers recharged through leakage from upper aquifers. The total groundwater recharge of upstream is greater than downstream’s. Generally, the developed groundwater model expresses that the groundwater storage attainable balanced in both upstream and downstream under pumping rate of 1.9 MCM/day. Therefore, the sustainable pumping yield management in Saigon River Basin is 1.9 MCM/day (0.88 MCM/day in the existing area + 1.02 MCM/day in the new area).

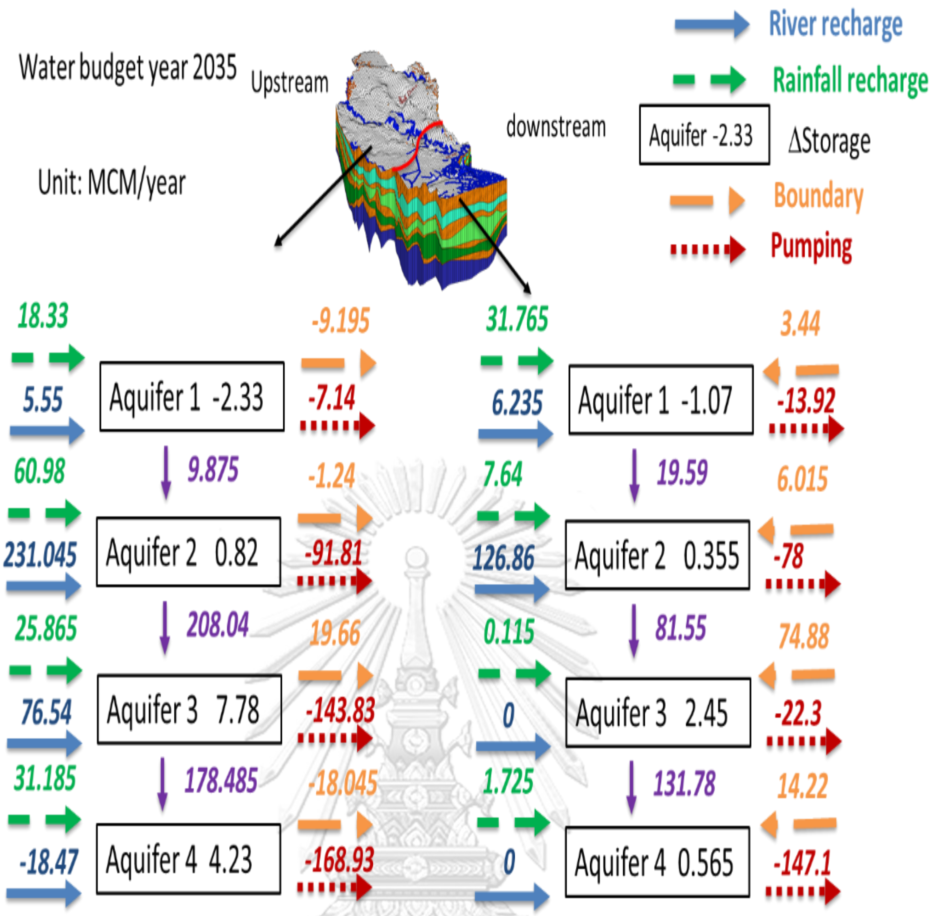


Figure 7. 10: Groundwater budget components of Saigon River Basin under pumping rate 1.9 MCM/day (0.88 MCM/day in existing area + 1.02 MCM/day in new area)

As a result of groundwater budgets associated surface – groundwater interaction, the sustainable pumping yield in Saigon River Basin summarizes in Table 7.5. In existing pumping area, the sustainable pumping yield of aquifer 1, aquifer 2, aquifer 3, and aquifer 4 are 57,699 m^3/day, 263,699m^3/day, 61,096 m^3/day and 497,822 m^3/day, respectively. Because of narrow thickness, the aquifer 3 in the existing area contribute less abstraction than other aquifers. Meanwhile, in the new area, the thickness of aquifers is over 20 meters. Plus, aquifer 2 gained large recharge from Saigon river. Therefore, the sustainable pumping yield was estimated 201,534m^3/day, 394,055m^3/day and 428,014m^3/day, respectively, for aquifer 2, aquifer 3, and aquifer 4. Figure 7.11 describes the sustainable groundwater pumping management map in Saigon River Basin.

Table 7. 5: Summary of sustainable pumping yield in Saigon River Basin

Pumping (m^3/day)	Aquifer 1	Aquifer 2	Aquifer 3	Aquifer 4	Subtotal	Total
Existing area	57,699	263,699	61,096	497,822	880,315	1,903,918
New area	0	201,534	394,055	428,014	1,023,603	

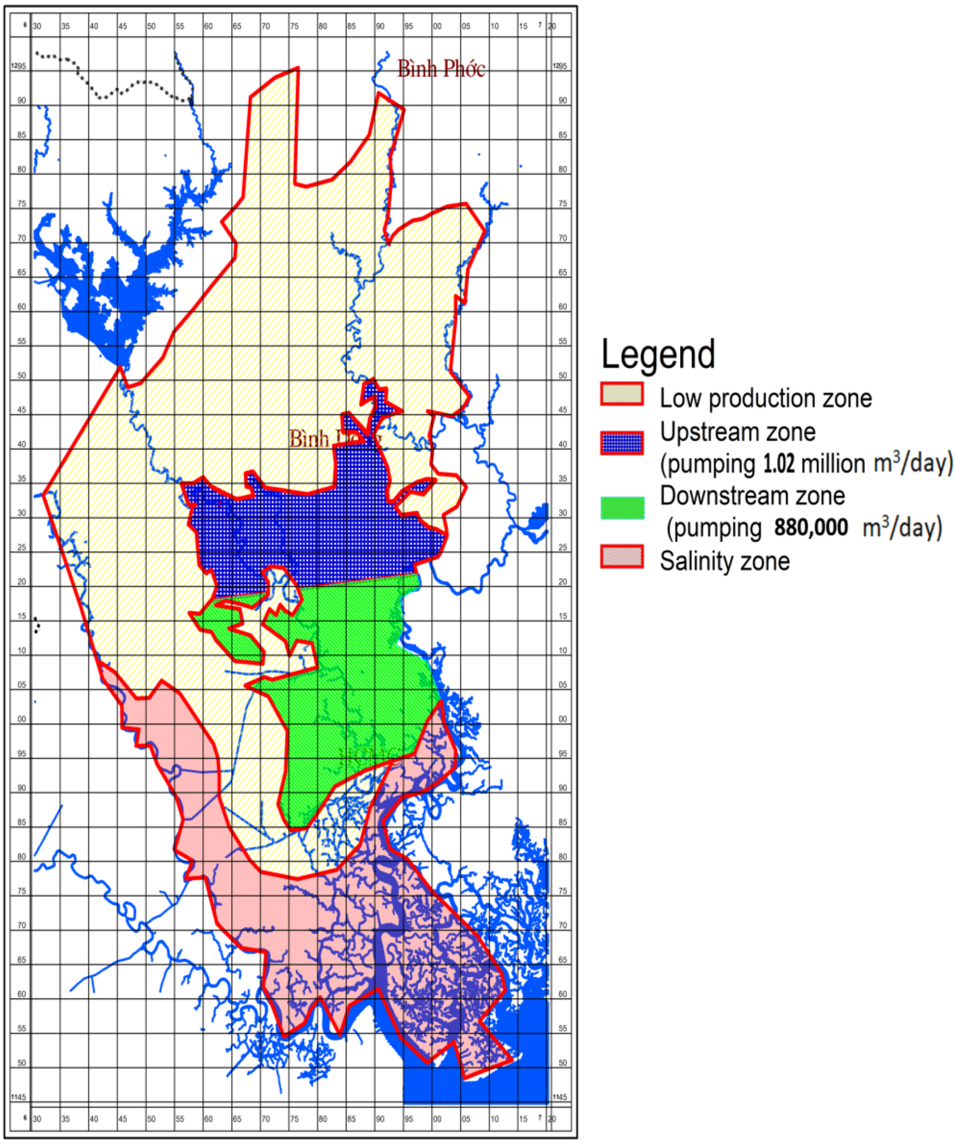


Figure 7. 11: Sustainable groundwater pumping management map

7.3 Optimal pumping management in Saigon basin for development scenarios

7.3.1. Optimal pumping management for projected water demand by provincial scenarios

Since the improvement of surface water supply required large investments on time and money, the surface water supply plan may not be accomplished when water demand increasing by 2035. Hence, the optimal pumping management was recommended based on the minimum capacity of surface water supply plan and the sustainable pumping yield in Saigon River Basin, which can meet the development water demand. According to surface water supply plan until 2025 and sustainable pumping yield, the water demand of Saigon River Basin by 2035 can be supplied by 3.5 million m^3/day from surface and 1.4 million m^3/day from aquifers. By year 2020, the projected water demand under the provincial scenario is 3,472,778 m^3/day. By improving the Dautieng reservoir capacity to 3.5 million m^3/day, the surface water supply of Saigon River Basin is possible to cover water demand by 2020 without using groundwater. The projected water demands by 2025, 2030 and 2035, are 3,960,556 m^3/day, 4,448,333 m^3/day and 4,936,111 m^3/day, respectively. To supply the increasing water demand, the groundwater of Saigon River Basin requires to exploit 460,556 m^3/day by 2025, 948,333 m^3/day by 2030, and 1,436,111m^3/day by 2035. Table 7.6 presents conjunctive water supply for the provincial scenario.

Table 7. 6: Conjunctive water supply for provincial scenario

Pumping (m^3/day)	2020	2025	2030	2035
Water demand	3,472,778	3,960,556	4,448,333	4,936,111
Surface water supply	3,500,000	3,500,000	3,500,000	3,500,000
Groundwater supply	0	460,556	948,333	1,436,111

In Saigon River Basin, the groundwater used to be supplied for industry and household. Since the urban and industry area located mainly in downstream, the optimal pumping management attend to extract groundwater in downstream first and expand abstraction to upstream later. With less groundwater use by 2025, the abstraction could explore 460,556 m^3/day in existing area. After the groundwater use excess over sustainable pumping yield in existing area by 2030, the groundwater pumping could expand 555,796 m^3/day in new area to meet future water consumption. To avoid unbalancing groundwater storage in each aquifer, the ratio pumping of each aquifer remains as the ratio of sustainable groundwater yield. Because the thickness of aquifer 1 is narrow, the aquifer 1 can pump 30,186 - 57,669 m^3/day in downstream. The aquifer 2 with a strong association with Saigon river can pump 137,960 - 263,699 m^3/day in downstream and 13,392 - 109,429 m^3/day in upstream. The thickness of aquifer 3 is high in upstream and low in downstream. Then, the aquifer 3 can pump 31,964 - 61,096 m^3/day in downstream and 26,185 - 213,964m^3/day in upstream. The aquifer 4, consist large coverage area and high thickness, which can exploit 260,446 - 497,822m^3/day in downstream and 28,441 - 232,403m^3/day in upstream. The details of optimal groundwater pumping management under provincial scenarios are shown in Table 7.7.

Table 7. 7: Optimal groundwater pumping management under provincial scenario

Pumping (m^3/day)		2020	2025	2030	2035
Groundwater demand		0	460,556	948,333	1,436,111
Existing area	Aquifer 1	0	30,186	57,699	57,699
	Aquifer 2	0	137,960	263,699	263,699
	Aquifer 3	0	31,964	61,096	61,096
	Aquifer 4	0	260,446	497,822	497,822
Subtotal		0	460,556	880,316	880,316
New area	Aquifer 1	0	0	0	0
	Aquifer 2	0	0	13,392	109,429
	Aquifer 3	0	0	26,185	213,964
	Aquifer 4	0	0	28,441	232,403
Subtotal		0	0	68,018	555,796

7.3.2. Optimal pumping management for projected water demand by World Bank scenario

The projected water demand for World Bank scenario is 6,979,403 m^3/day by 2035. Meanwhile, the total water supply of Saigon River Basin is only 6.1 million m^3/day, which includes 4.2 million m^3/day from maximum surface water supply plan, 1.9 million m^3/day from sustainable groundwater yield. Hence, the water shortage by 2035 is 875,485 m^3/day. Then, the maximum surface water supply plan (4.2 million m^3/day) employed into optimal pumping management for projected water demand by World Bank scenarios. By year 2020, the projected water demand for World Bank scenario is 3,472,778 m^3/day. Under maximum development capacity of surface water supply to 4.5 million m^3/day, the surface water supply of Saigon River Basin is sufficient to cover water demand by 2020 without using groundwater. The projected water demands by 2025 and 2030 are 4,982,202m^3/day and 5,980,802m^3/day, respectively. To supply the increasing water demand, besides surface water supply capacity, the Saigon River Basin requires to exploit groundwater 460,556 m^3/day by 2025 and 948,333 m^3/day by 2030. By 2035, due to intensive developing water demand, Saigon River Basin requires to use 4.2 million m^3/day from maximum surface water supply plan, plus 1.9 million m^3/day from sustainable groundwater yield and backup plan for 875,485 m^3/day water shortage. Table 7.8 indicates conjunctive water supply for World Bank scenario. Groundwater abstraction is utilized mainly by the industrial sector and domestics. Hence, without conjunctive water supply coupling to water demand, groundwater becomes an alternative source for water shortage. However, groundwater is a vulnerability resource under indiscriminate abstraction. To regulate groundwater pumping sustainable under the water demand of the World Bank scenario, groundwater management scheme and groundwater tax should be implemented. As the experience of groundwater management in three Asian mega-cities, namely Bandung (Indonesia), Bangkok (Thailand) and Osaka (Japan) by Kataoka and Kuyama (2008), the groundwater level has recovered in recent years in the Bangkok City and Osaka City due to more stringent groundwater management policy. Besides, water recycling can be an alternative to reduce water use in the industrial sector. However, the strategy for water recycling needs to be elaborated considering the structure of industries.

Table 7. 8: Conjunctive water supply for World Bank

Pumping (m^3/day)	2020	2025	2030	2035
Water demand	3,983,601	4,982,202	5,980,802	6,979,403
Surface water supply	4,200,000	4,200,000	4,200,000	4,200,000
Groundwater supply	0	782,202	1,780,802	1,903,918
Water shortage	0	0	0	875,485

Since the urban and industry area located mainly in downstream, the optimal pumping management attend to extract groundwater in downstream first and expand abstraction to upstream later. With less groundwater uses by 2025, the abstraction could explore 782,202 m^3/day in the existing area. By 2030, to meet development future water consumption, the groundwater pumping supply 880,316m^3/day in the existing area and 900,487 m^3/day in the new area. By 2035, the total sustainable yield of Saigon River Basin is not able to supply increasing water demand. To meet the projected future water demand, Saigon River Basin pumping 880,316m^3/day in the existing area, 1,023,603m^3/day in the new area and improve surface water capacity or water recycle technology to cover water shortage 875,485 m^3/day.

Because the thickness of aquifer 1 is narrow, the aquifer 1 can pump 51,268- 57,669 m^3/day in downstream. The aquifer 2 with a strong association with Saigon river can pump 234,309 - 263,699 m^3/day in downstream and 177,294 - 201,534 m^3/day in upstream. The thickness of aquifer 3 is high in upstream and low in downstream. Then, the aquifer 3 can pump 54,287 - 61,096 m^3/day in downstream and 376,534 - 394,055 m^3/day in upstream. The aquifer 4, consist of large coverage area and high thickness, which can exploit 442,338- 497,822 m^3/day in downstream and 376,534 - 428,014 m^3/day in upstream. The details of optimal groundwater pumping management for scenarios B are shown in Table 7.9.

Table 7. 9: Optimal groundwater pumping management under World Bank scenario

Pumping (m^3/day)		2020	2025	2030	2035
Groundwater demand		0	782,202	1,780,802	1,903,918
Existing area	Aquifer 1	0	51,268	57,699	57,699
	Aquifer 2	0	234,309	263,699	263,699
	Aquifer 3	0	54,287	61,096	61,096
	Aquifer 4	0	442,338	497,822	497,822
Subtotal		*0*	*782,202*	*880,316*	*880,316*
New area	Aquifer 1	0	0	0	0
	Aquifer 2	0	0	177,294	201,534
	Aquifer 3	0	0	346,659	394,055
	Aquifer 4	0	0	376,534	428,014
Subtotal		*0*	*0*	*900,487*	*1,023,603*

7.4 Findings

The projected water demand of provincial scenario by 2035 is 4,936,111 m^3/day (Vietnam Government, 2012, 2014). In other sides, the projected water demand of World Bank scenario is 6,979,403 m^3/day (World Bank, 2017). The surface water capacity scenarios consist of three scenarios: surface water in current capacity (2.2 million m^3/day), surface water capacity by 2025 (3.5 million m^3/day), surface water capacity by 2035 (4.2 million m^3/day). Hence, the projected water deficit by 2035 are 736,111 – 4,779,403 m^3/day. However, the existing groundwater pumping is only 785,000 m^3/day, which is impossible to supply water deficits scenario in future. Besides, the groundwater storage in upstream is abundant and discharge to river in upstream in both dry season and wet season. To supply growing water demand in future, the groundwater has to expand pumping area to upstream.

According to the intensity pumping in the existing area, the appropriate intensity pumping for aquifer 2, aquifer 3 and aquifer 4, which avoid high concentrated pumping wells in small areas, are 2000 m^3/day/km^2, 3500 m^3/day/km^2 and 4000 m^3/day/km^2, respectively. The groundwater sustainable yield in the existing pumping scheme is 880,000 m^3/day. Meanwhile, according to the fluxes exchange surface – groundwater, the north part of Saigon River Basin is the new potential groundwater pumping area. The addition of sustainable groundwater yield in the new area is 1.02 MCM/day. Due to the distribution of urban areas locates along Saigon river, the pumping scheme was designed near Saigon river. The sustainable groundwater yield was estimated under drawdown limitation and saline interface criteria. Besides, to abstract groundwater with an extensive rate of 1.9 MCM/day, Saigon river should maintain flows 436 MCM/year (~ 13 m^3/second) for river recharge to aquifers.

According to groundwater yield in Saigon River Basin, to supply water demand in Saigon River Basin for provincial scenario (4.9 MCM/day), the water resources may collect 3.5 MCM/day from surface and 1.4 MCM/day from aquifers, which are sufficient for sustainable abstraction. For water demand of World Bank scenario (6.9 MCM/day), Saigon River Basin is possible to supply 6.1 MCM/day, which include 4.2 MCM/day from surface water, 1.9 MCM/day from groundwater. Hence, Saigon River Basin could be facing water shortage 875,485 m^3/day. Groundwater abstraction is utilized mainly by the industrial sector and domestics. Then, groundwater abstraction will be abused to supply for water shortage. To regulate groundwater pumping more sustainable, groundwater management scheme and groundwater fee should be implemented. As the experience of groundwater management in three Asian mega-cities, namely Bandung (Indonesia), Bangkok (Thailand) and Osaka (Japan) by Kataoka and Kuyama (2008), the groundwater level has recovered in recent years in the Bangkok City and Osaka City due to more stringent groundwater management policy. Besides, water recycling can be an alternative to reduce water use in the industrial sector. However, the strategy for water recycling needs to be elaborated considering the structure of industries.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Interaction parameters

The study found the percolation rate is the highest for sand clay loam and the lowest for clay. The average monthly percolation rate of sand clay loam, sand clay, and clay varies 2-4.5 mm/day, 1.5-3.5 mm/day, and 0.5-2 mm/day, respectively to rainfall intensity 4-14mm/day. Besides, grain size of soil and percentage of sand has strong relationship with percolation flux, i.e., the higher sand percentage gives higher percolation rate.

The groundwater-river interaction parameters were measured via field measurements and validated through development groundwater modeling. The conductance values at distance 0km, 30km, 60km, 80km, and 120km are 4.5 m^2/day/m, 4.2 m^2/day/m, 2.5 m^2/day/m, 1.7 m^2/day/m, and 0.25 m^2/day/m, respectively. The conductance in the riverbed relies on the sand percentage of sediment. In fact, the grain sized of riverbed sediment is finer in downstream, that cause the conductance value gradually decreases from upstream to downstream.

8.2 Surface groundwater interaction fluxes

According to sampling compositions stable isotope of groundwater, river, rainfall, the study identified that groundwater discharge to river in upstream and gain recharge from river and rainfall in downstream. According to soil distribution, the rainfall recharge percentage decreases from upstream to downstream — meanwhile, the river recharge percentage increases from upstream to downstream. Due to recharge are limited mainly in upstream, the contribution of rainfall recharge is 12-26% of groundwater storage. Because Saigon river stretches across the plain, the river recharge plays a vital role in balancing the groundwater budget downstream with 40-50% contribution of total groundwater budget in Saigon River Basin. With low abstraction and high land recharge, the groundwater storage in upstream are balancing at annual scales. Furthermore, the groundwater discharge to river in upstream in both dry season and wet season. Meanwhile, the groundwater storage in downstream was gradually declining annually as result of extensive pumping rate. The river recharge flows into aquifers in downstream in both dry season and wet season.

The approach measurement surface – groundwater interaction parameters via field experiment and qualification of surface groundwater interaction fluxes through isotope composition was successfully to provide better-understanding surface – groundwater interaction in Saigon River Basin. As result of developed groundwater modeling, the study figured the groundwater recharge in Saigon River Basin, which was employed to recommend groundwater pumping management for the study area.

8.3 Groundwater pumping management

The projected water demand of the provincial scenario by 2035 is 4,936,111 m^3/day (Government, 2012; Vietnam Government, 2014). In other sides, the projected water demand of World Bank scenario is 6,979,403 m^3/day (World Bank, 2017). The surface water capacity plan by current, by 2025, and by 2035 are 2.2 million m^3/day, 3.5 million m^3/day, and 4.2 million m^3/day. Consequently, the projected water deficit by 2035 are 736,111 – 4,779,403 m^3/day. However, the existing groundwater pumping is only 785,000 m^3/day, which is insufficient to supply water deficits scenarios in the future. Therefore, the groundwater has to expand the pumping area to upstream to supply growth water demand in the future.

According to the intensity pumping in existing area, the appropriate intensity pumping for aquifer 2, aquifer 3 and aquifer 4, which avoid high concentrated pumping wells in small area, are 2000 m^3/day/km^2, 3500 m^3/day/km^2 and 4000 m^3/day/km^2, respectively. The groundwater sustainable yield in existing pumping scheme is 880,000 m^3/day. Due to the extensive exchange flux surface – groundwater, the addition of sustainable groundwater yield in new area is 1.02 MCM/day. Because the distribution of urban area locates along Saigon river, the pumping scheme was designed near Saigon river. The sustainable groundwater yield was estimated under drawdown limitation and saline interface criteria.

With the integrated approach, the study shows clearly the available water resources supply and the water demand in the future. According to groundwater yield in Saigon River Basin, to supply water demand in Saigon River Basin for provincial scenario (4.9 MCM/day), the water resources may collect 3.5 MCM/day from surface and 1.4 MCM/day from aquifers, which are sufficient for sustainable abstraction. For water demand of World Bank scenario (6.9 MCM/day), Saigon River Basin is possible to supply 6.1 MCM/day, which includes 4.2 MCM/day from surface water, 1.9 MCM/day from groundwater. Hence, Saigon River Basin could be facing water shortage 875,485 m^3/day. Groundwater abstraction is utilized mainly by the industrial sector and domestics. Then, groundwater abstraction will be abused to supply for water shortage.

As the experience of groundwater management in three Asian mega-cities, namely Bandung (Indonesia), Bangkok (Thailand) and Osaka (Japan) by Kataoka and Kuyama (2008), the groundwater level has mitigated in recent years in the Bangkok City and Osaka City by achieving groundwater management policy. The successes groundwater pumping management in Thailand depends on the availability of water substitute, socio-economical driven situation, ratio of groundwater charge and surface water supply charge, water supply coverage, and policy/campaign push from the Government (DGR (Department of Groundwater Resources), 2008). Besides, water recycling can be another alternative to reduce water use in some structures of industries. To regulate groundwater pumping sustainable, groundwater management scheme and groundwater fee could be considered to implement from the successful experiences in Thailand and Japan.

8.4 Recommendations

Although the monitored soil moisture approach was successfully determined land recharge function for the Saigon river regional, the land recharge applied under some constraints. Since the soil composition map in Saigon River Basin has not been established, the spatialization of the groundwater recharge potential was produced by employing the outcrop of the hydrogeology map. Therefore, the future study should collect more soil type composition to improve distribution land recharge in Saigon River Basin.

Thus, aquifer management downstream will require good coupling with river water plan, especially HCMC surface water supply expansion works, an area which has not fulfilled the rapid increase of water demand. Such as, the Saigon river should maintain flows above 57m^3/second, which includes 18m^3/s (436 MCM/year) for river recharge to aquifers, plus 20m^3/s for salinity control in downstream, and 19 m^3/s for surface water supply).

Besides, this study focused on the impact of groundwater and river interaction on the aquifers in Saigon River Basin, Vietnam without considering movements of salt intrusion, as well as rising sea level as projected in the future. Therefore, future study should investigate the saline condition and sea-level rise to improve groundwater yield estimation for better water resources management in the study area.

Although the leakage between aquifers was calibrated via piezometric head in this study, the magnitude of exchange fluxes between aquifers have not been evaluated. Henceforth, the further study should archive pumping test to improve exchange fluxes between aquifers.

Since there a limited subsidence record data, the study will not consider land subsidence issue. For better groundwater management, the further study should measure subsidence data and consider subsidence as criteria.

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APPENDIX

A. Field monitoring of soil moisture

A. Field monitoring of soil moisture

In order to calibrate soil moisture in HYDRUS 1D model, the study modified soil moisture sensor by resistance from Kojima et al. (2016). The soil moisture sensor was created by connecting Arduino board with copper sensor (Long & Koontanakulvong, 2019). The soil moisture sensor measure soil moisture from 1-5 meters depth from the ground. The location of the soil moisture experiment was selected in outcrop of three aquifers. The monitored soil moisture installed in the forestry area without any irrigation activity. The soil sample in the fields was classified soil type by ASTM (see Figure A.2) and calibrate with moisture of sensor. Figure A.1 show the step of soil moisture sensor set up. The soil moisture was monitored from Oct, 2017 to Dec, 2018. The data was recorded hourly. The rainfall and evaporation data were collected at Thu Dau 1 station from Southern Regional Hydrometeorology Center Department of Resources and Environmental. Table A.1 shows the rainfall and evaporation data. Figure A.3 presents the monitored soil moisture at 3 boreholes.

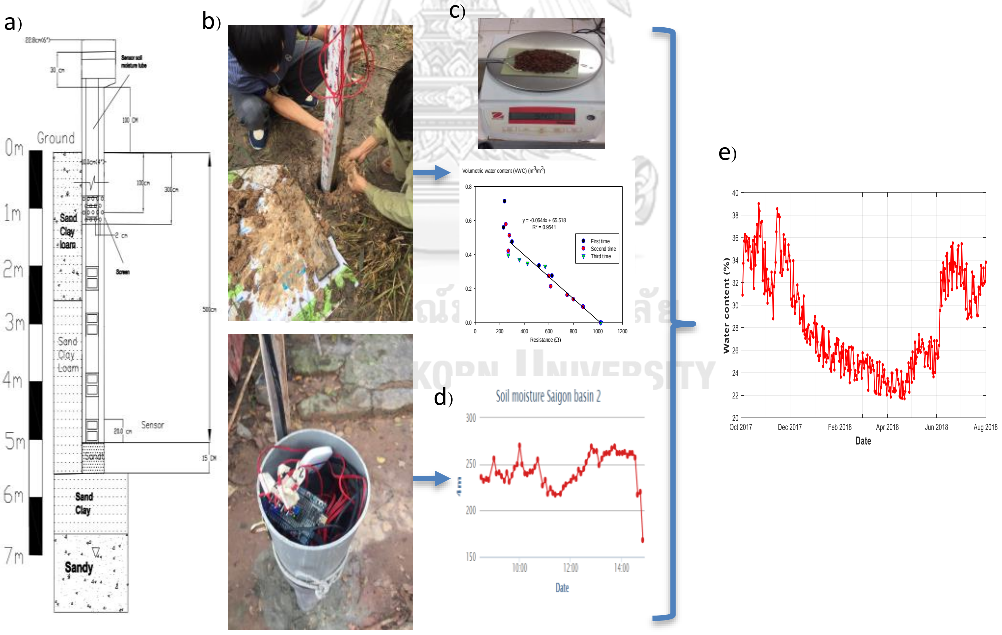
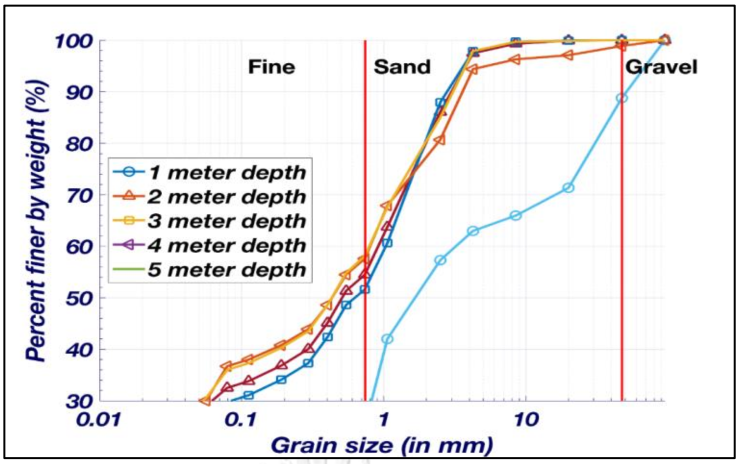
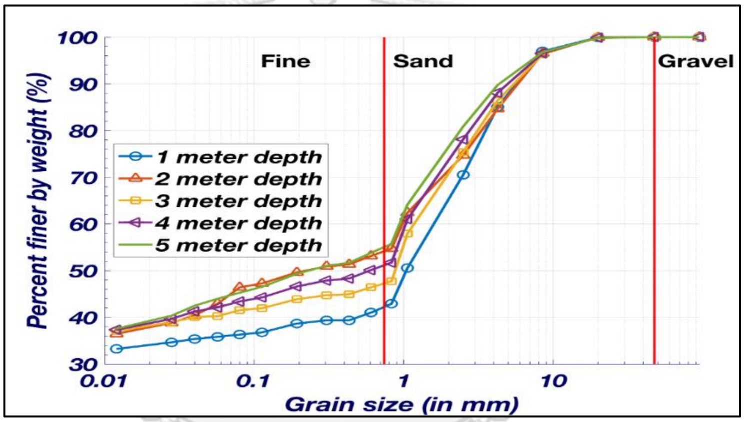


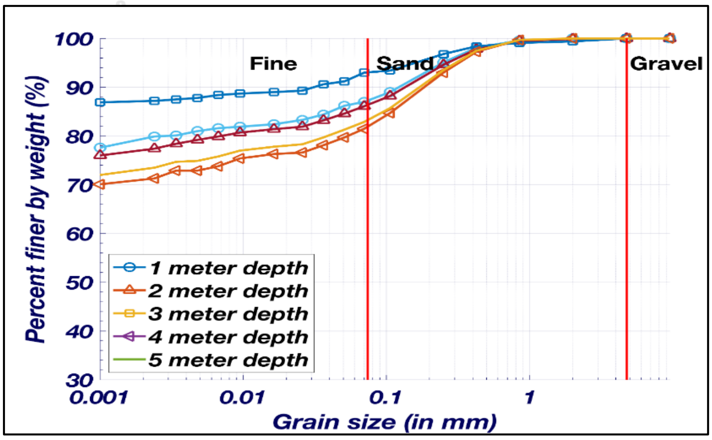
Figure A. 1: The field measurement set up: a) Bore log soil moisture, b) Install soil moisture sensor, c) Calibrate soil moisture with sensor, d) Monitor resistance sensor, e) Convert observed soil moisture



a) Grain sizes distribution of soil sample at B1 (sandy clay loam)

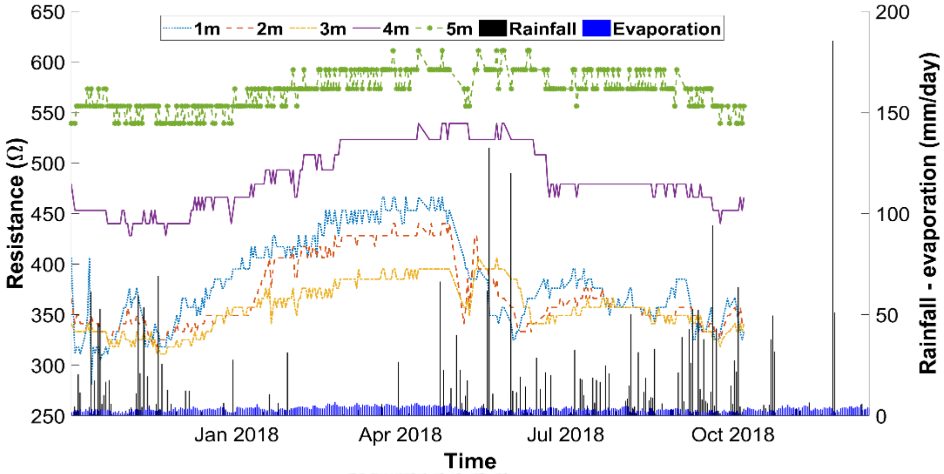


b) Grain sizes distribution of soil sample at B2 (sandy clay)

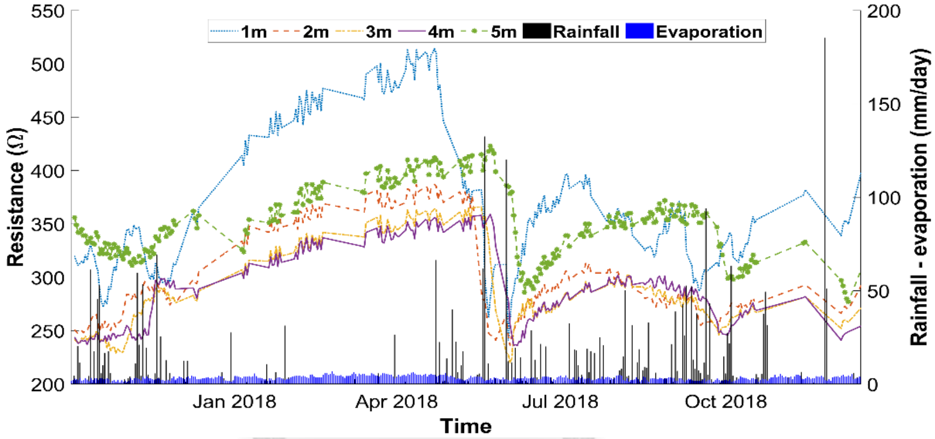


c) Grain sizes distribution of soil sample at B3 (clay)

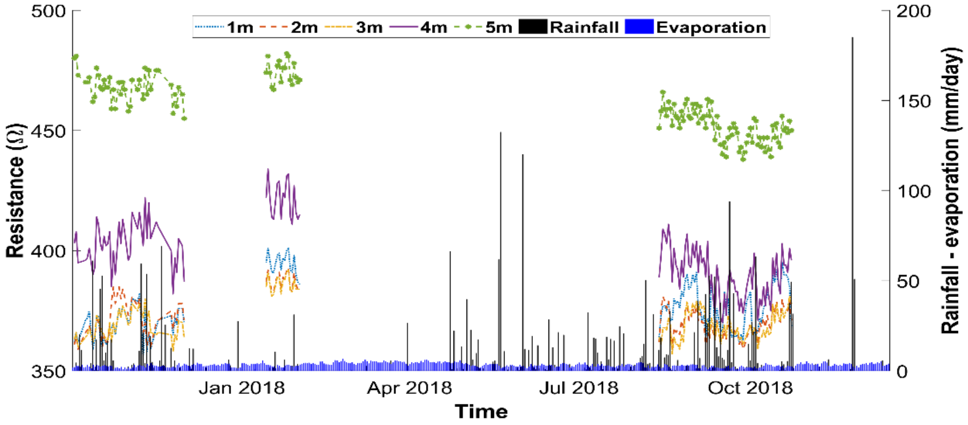
Figure A. 2: Grain sizes distribution of sandy clay loam, sandy clay, clay sample



a) Monitored soil moisture at B1(sandy clay loam)



b) Monitored soil moisture at B2 (sandy clay)



c) Monitored soil moisture at B3 (clay)

Figure A. 3: Monitored soil moisture at 3 fields and rainfall- evaporation during August 2017- December 2018

A.2 Hydrus 1D simulation

Respect to monitored soil moisture, the HYDRUS 1D simulated vertical water flow from 1 meter to 5 meters in topsoil layer. Hence, the input boundary condition of vertical flow remained as atmosphere boundary. The groundwater level varied from 6-10 meters depth. So, the output boundary condition vertical flow at 5-meter depth was set as free flow boundary to aquifer. The water retention parameters (α,n,K) were estimated by inverse modeling until the computed soil moisture matching with monitor's in the field. The deep percolation function of three soil type was analyzed to determine rainfall recharge to groundwater in regional. Figure A.4 demonstrates the boundary conditions of percolation simulation via Hydrus 1D. Figure A.4 presents the percolation fluxes after calibration.

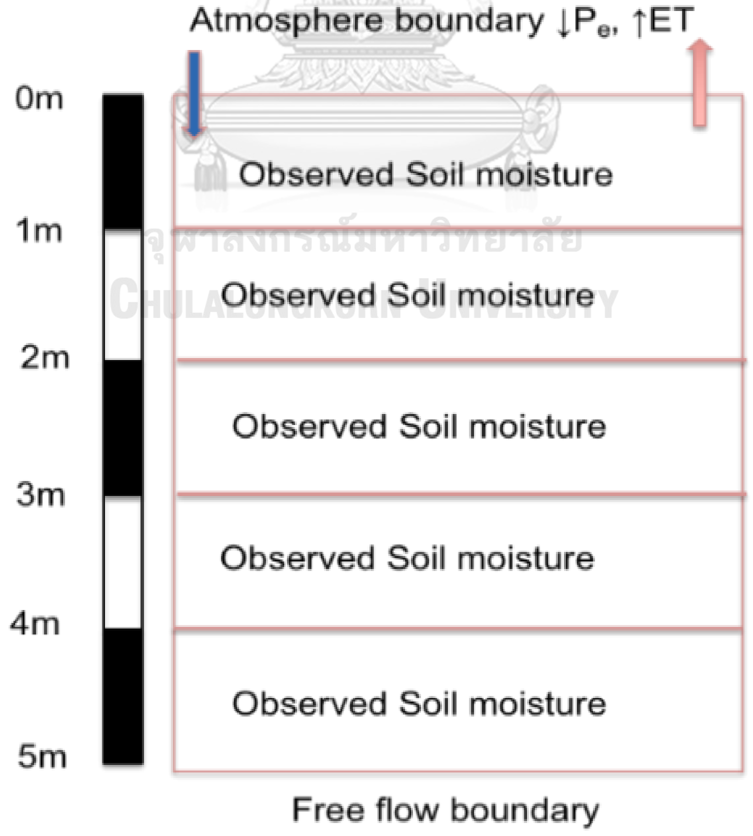
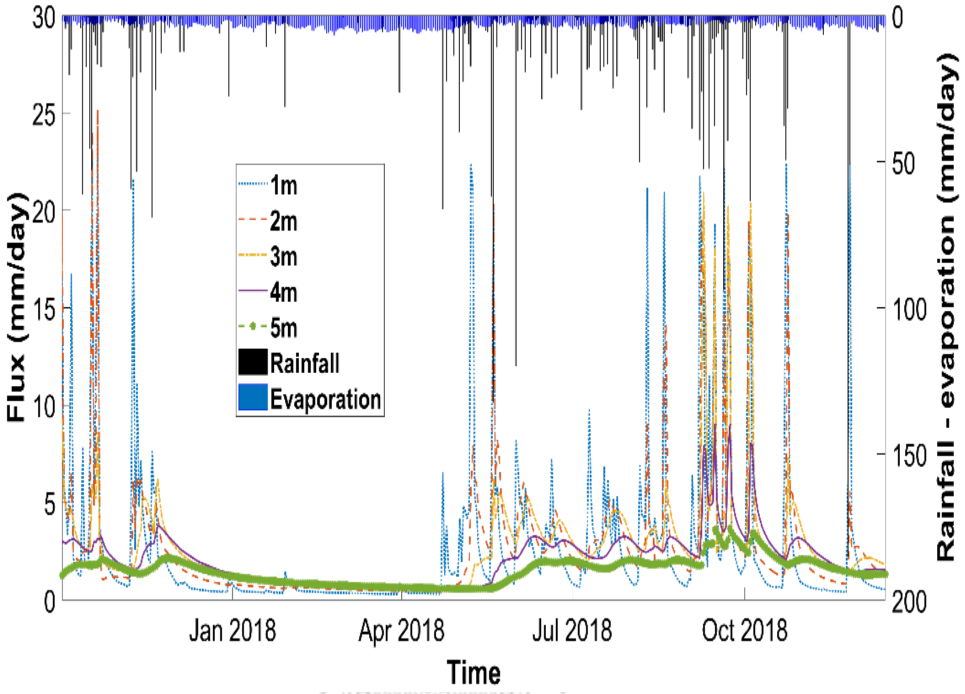
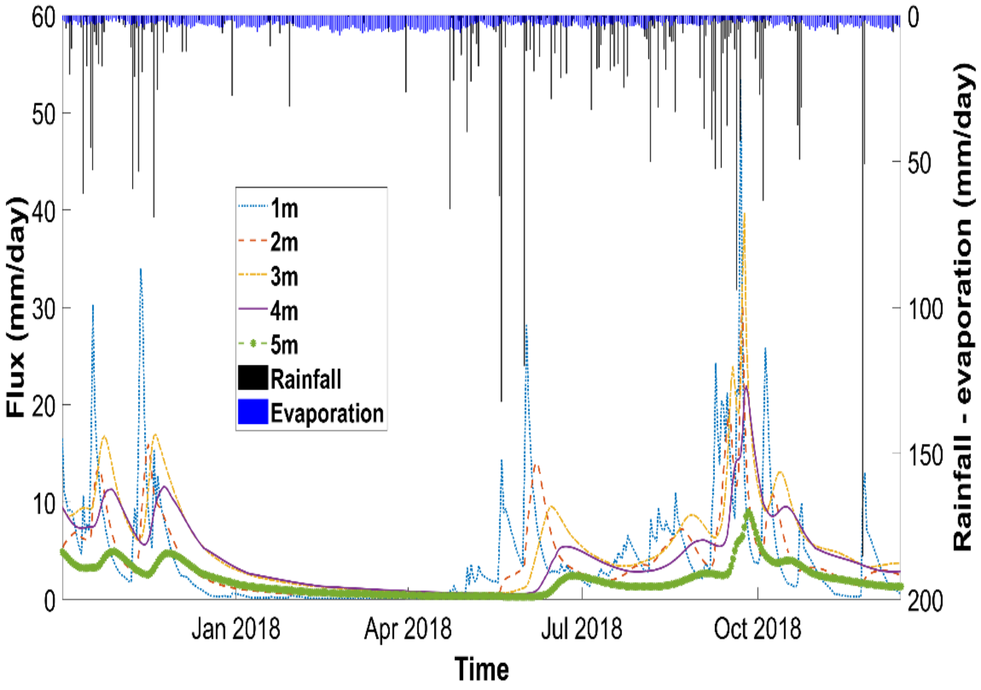


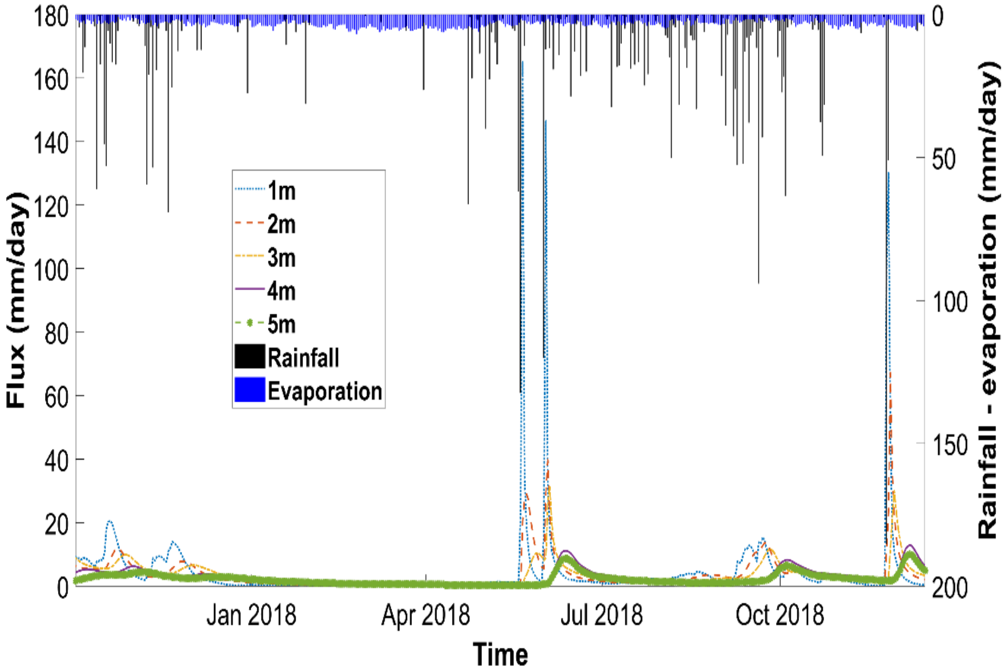
Figure A. 4: Boundary conditions of percolation simulation via Hydrus 1D



a) Percolation flux of sandy clay loam



b) Percolation flux of sandy clay



c) Percolation flux of clay

Figure A. 5: Computed percolation flux of three soil type

B. Field measurement seepage fluxes

B1. Field measurement seepage fluxes

This part will describe field seepage measurement along Saigon River. In order to understand the fluxes exchange between river – groundwater, the seepage meters were measured at 5 stations along Saigon River Basin. The locations of the experiment are shown in Figure B.1. The distance of 5 stations to Dautieng dam are 0km, 35km, 60km, 80km, and 120km. The cross section of 5 stations are demonstrated in Figure B.2. According to cross section, the river – groundwater interaction process mainly in aquifer 2.

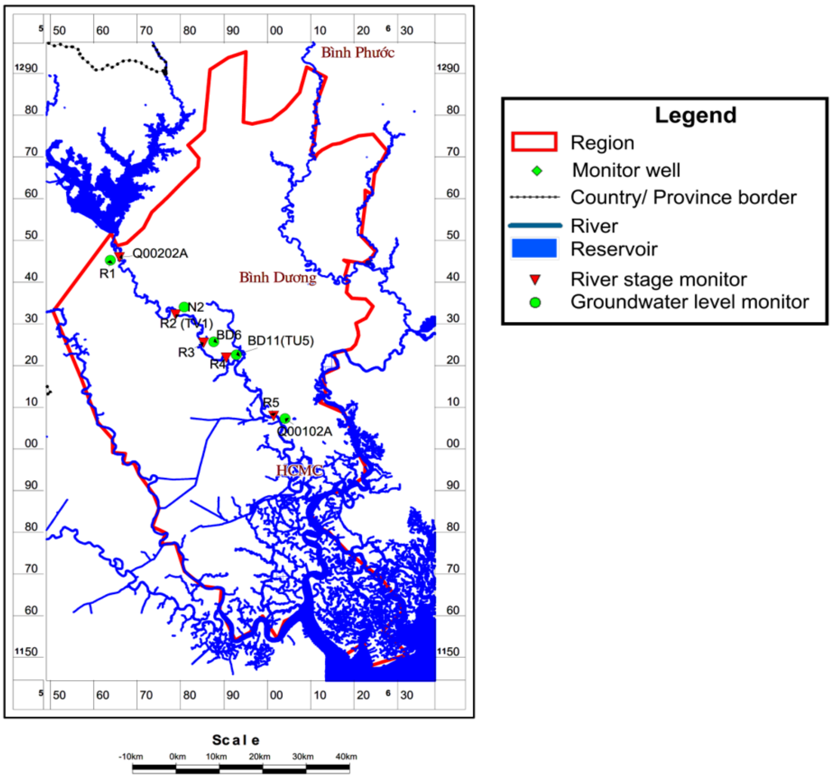
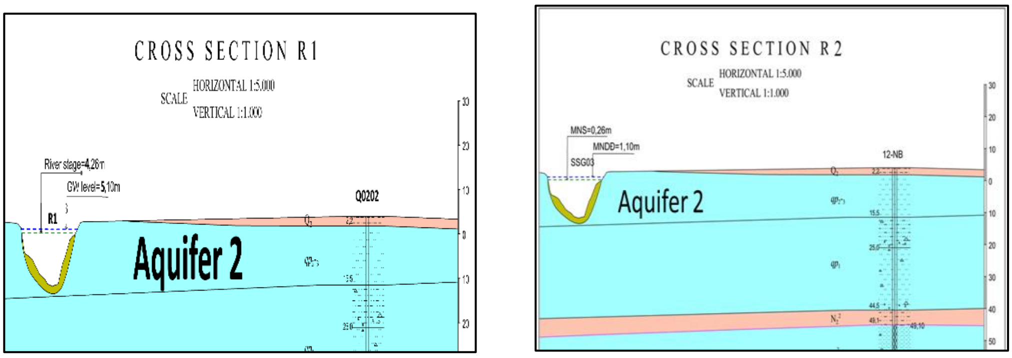
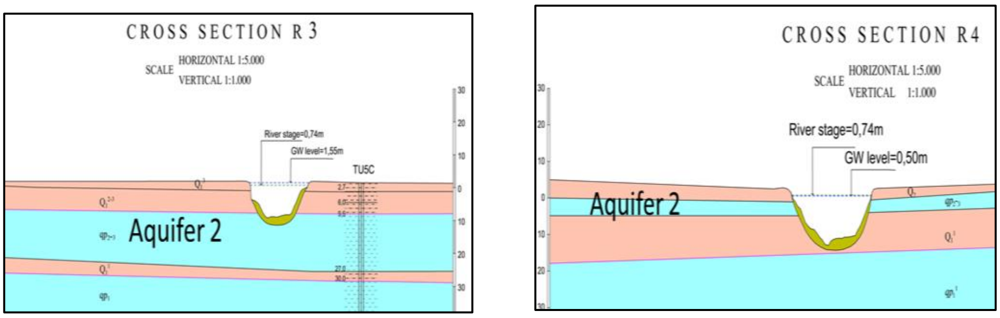


Figure B. 1: Locations of five seepage measurement stations



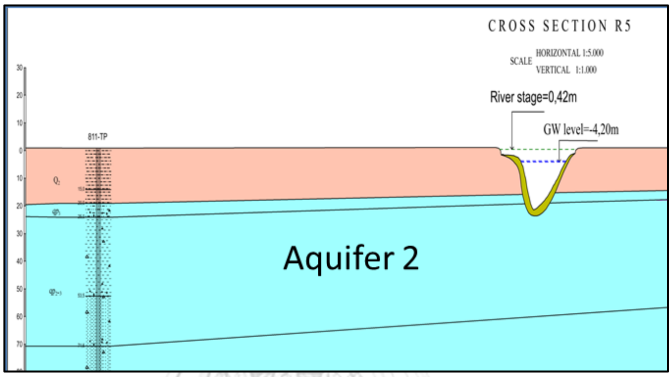
a) Cross section R1

b) Cross section R3



c) Cross section R3

d) Cross section R4



e) Cross section R5

Figure B. 2: River cross section measured seepage along Saigon river

The hydraulic conductivity of sediments riverbed is estimated using the equation from (B. P. Kelly & Blevins, 1995; S. E. Kelly & Murdoch, 2003; Lee & Cherry, 1979)

$$k_v = \frac{Q\Delta z}{A_b\Delta h} \qquad ; \quad C = k_v * w$$

Where Q is flow rate(L^3T^{-1}), which can be measured by seepage meters through inserted container into riverbed 40cm. (see Figure B.3)

Δz is thickness of sediments (L), measured by the field

Δh is the difference piezometers (L) between river stage and observed well nearby,

w is the width river cross section (L), which obtained from Division for Water Resources Planning and Investigation for the South of Vietnam,

A_b is the cross-section area of seepage meters (L^2), which obtained from Division for Water Resources Planning and Investigation for the South of Vietnam,

K_v is the vertical hydraulic conductivity of sediment (LT^{-1}),

C is the conductance of riverbed (L^2T^{-1}), Table B-1 summarized the results of seepage meters along Saigon river.

Figure B. 3: Field measure seepage of riverbed along Saigon river

Table B. 1: Summary results seepage measurement along Saigon river

Name	ΔV(ml)	t(min)	A (m^2)	w(m)	Q(m^3/day/m)	ΔH(m)	C(m^2/day/m)
R1	130	15	0.26	100	4.8	1.2	4
	200	20	0.26	100	5.54	1.2	4.62
	140	15	0.26	100	5.17	1.2	4.31
	90	10	0.26	100	4.98	1	4.98
	75	10	0.26	100	4.15	1	4.15
	94	10	0.26	100	5.21	1	5.21
R2	60	30	0.26	169	1.87	0.5	3.74
	105	60	0.26	169	1.64	0.5	3.28
	70	30	0.26	169	2.18	0.5	4.36
	75	30	0.26	169	2.34	0.5	4.68
	135	60	0.26	169	2.11	0.5	4.22
	68	30	0.26	169	2.12	0.5	4.24

Name	ΔV(ml)	t(min)	A (m^2)	w(m)	Q(m^3/day/m)	ΔH(m)	C(m^2/day/m)
R3	42	30	0.26	175	1.36	0.5	2.72
	39	30	0.26	175	1.26	0.5	2.52
	71	60	0.26	175	1.15	0.5	2.3
	85	60	0.26	175	1.37	0.5	2.74
	34	30	0.26	175	1.1	0.5	2.2
	45	30	0.26	175	1.45	0.5	2.9
R4	-23	30	0.26	180	-0.76	-0.5	1.52
	-26	30	0.26	180	-0.86	-0.5	1.72
	-25	30	0.26	180	-0.83	-0.5	1.66
	-49	60	0.26	180	-0.81	-0.5	1.62
	-37	45	0.26	180	-0.82	-0.5	1.64
	-18	30	0.26	180	-0.6	-0.5	1.2
R5	-220	1440	0.26	200	-0.17	-0.8	0.21
	-290	1440	0.26	200	-0.22	-0.8	0.28
	-300	1440	0.26	200	-0.23	-0.8	0.29
	-240	1440	0.26	200	-0.18	-0.8	0.23
	-190	1440	0.26	200	-0.15	-0.8	0.19
	-270	1440	0.26	200	-0.21	-0.8	0.26
	-260	1440	0.26	200	-0.2	-0.8	0.25

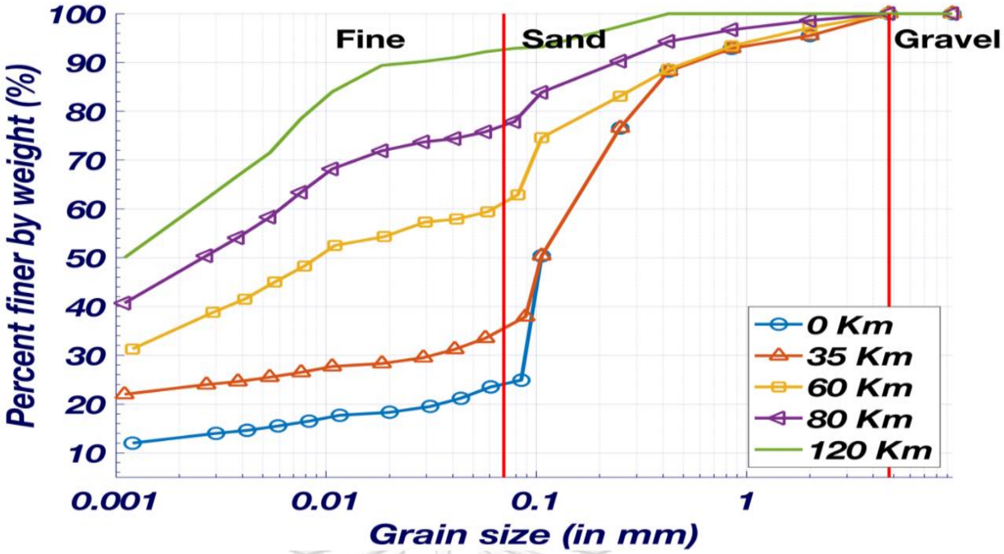


Figure B. 4: Grain sizes distribution of riverbed sample along Saigon River Basin

C. Development of groundwater modeling

C.1 Hydrogeology spatial 3D grid

This part will describe conceptual to build groundwater modelling for aquifers system in Saigon River. The conceptual of groundwater modelling includes 3D hydrogeology spatial, distribution hydraulic conductivity, boundary conditions, land recharge function, pumping well (see Figure 6.1). According to hydrogeology map, the aquifers system consists of 4 aquifers and 4 interwoven aquitards. The grid size 1km x 1km was selected to build 3D hydrogeology spatial. The elevation of each layer was interpolated by inverse distance weighed from 403 boreholes data (see Figure C.1). The table C.1 shows sample of boreholes data.

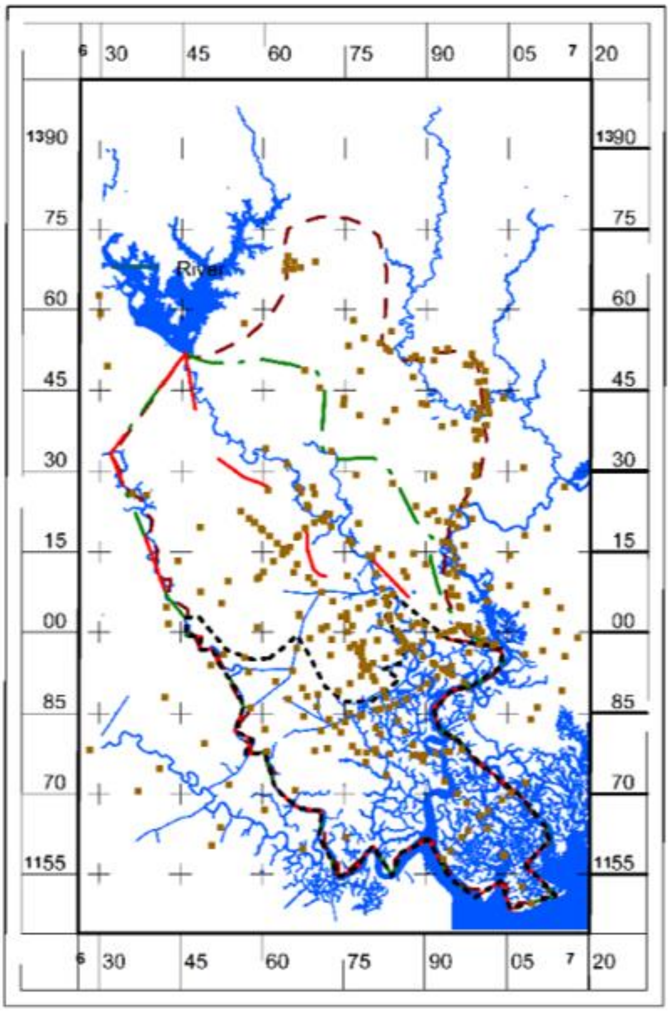


Figure C. 1:The boreholes data used to interpolate hydrogeology spatial

Table C. 1: Sample of boreholes data

id	Name	X	Y	Top	Bottom layer 1	Bottom layer 2	Bottom layer 3	Bottom layer 4	Bottom layer 5	Bottom layer 6	Bottom layer 7	Bottom layer 8
1	203	670751.0	1207694.0	0.9	-12.2	-17.0	-57.3	-95.2	-115.1	-152.5	-169.5	-190.6
2	801_TP	658188.3	1220620.6	9.7	-10.3	-16.3	-39.3	-53.3	-63.8	-63.8	-65.3	-87.3
3	802_TP	658729.5	1210104.6	0.8	-41.9	-41.9	-68.2	-68.2	-74.9	-120.2	-128.2	-157.2
4	803_TP	661719.1	1213437.8	9.1	-11.9	-16.6	-42.9	-62.1	-70.9	-102.9	-113.9	-137.9
5	804_TP	664176.5	1215200.9	10.4	3.4	-17.6	-30.8	-54.4	-96.6	-96.6	-125.6	-125.6
6	805_TP	666076.7	1217885.0	3.0	-21.5	-21.5	-32.0	-47.0	-54.0	-83.0	-92.0	-127.0
7	806_TP	670639.8	1221373.8	1.8	1.8	1.8	-4.7	-15.2	-22.7	-52.7	-68.2	-116.9
8	807_TP	668287.3	1210392.3	8.5	-9.5	-9.5	-45.5	-62.5	-118.5	-118.5	-140.5	-140.5
9	Q808050	665349.3	1193027.8	0.4	-32.1	-76.6	-86.5	-133.1	-144.1	-168.6	-173.1	-207.1
10	809_TP	672406.9	1195955.0	1.8	-8.2	-32.2	-34.2	-72.5	-76.5	-133.2	-138.2	-198.2
11	810_TP	675572.2	1200268.7	7.2	-7.8	-22.8	-38.3	-71.7	-81.5	-123.8	-140.8	-172.5
12	811_TP	682681.9	1206801.2	0.9	-52.6	-52.6	-70.7	-70.7	-108.1	-108.1	-156.6	-156.6
13	812_TP	673275.1	1182780.5	1.4	-74.1	-74.1	-80.9	-92.9	-107.9	-125.1	-139.8	-210.6
14	813_TP	675944.3	1185112.0	1.0	-41.1	-41.1	-70.0	-70.0	-114.0	-134.0	-149.0	-209.0
15	814_TP	678059.0	1192111.0	4.0	-9.0	-36.8	-45.5	-82.5	-90.5	-138.0	-148.0	-204.0
16	815_TP	679209.7	1193935.8	2.9	-3.1	-30.6	-36.1	-73.9	-81.1	-131.1	-140.1	-191.1
17	816_TP	686831.1	1197388.5	2.6	-36.4	-63.9	-86.9	-86.9	-100.9	-125.4	-148.4	-150.4
18	817_TP	693633.6	1200057.2	28.8	28.8	28.8	1.3	1.3	-11.5	-13.3	-25.7	-38.1
19	819_TP	686540.6	1187812.8	1.3	-50.2	-55.7	-62.7	-90.7	-111.7	-128.7	-134.7	-177.7
20	819_1	689663.7	1176241.3	0.8	-31.2	-54.2	-84.2	-90.2	-96.2	-154.2	-186.2	-186.2
21	819_3	681702.5	1181301.0	0.8	-54.9	-54.9	-97.2	-127.2	-140.2	-151.2	-190.0	-192.0
22	820_TP	693721.7	1193115.4	1.0	-10.0	-10.0	-21.6	-42.0	-49.5	-68.5	-109.0	-109.0
23	821_TP	694584.5	1178007.3	2.1	-41.0	-54.9	-54.9	-94.9	-94.9	-116.9	-116.9	-143.9
24	822_TP	709869.5	1149791.0	1.3	-47.7	-73.7	-117.7	-117.7	-122.7	-135.7	-141.7	-191.7
25	826_TP	680784.9	1182374.8	2.4	-31.7	-39.7	-60.3	-80.2	-99.7	-107.7	-112.7	-192.2
26	BSG_K1	682255.7	1189403.3	2.0	-6.5	-42.0	-49.5	-83.0	-87.0	-145.0	-154.0	-213.0
27	827_TP	700344.3	1166107.9	0.8	-34.1	-49.2	-64.2	-126.5	-153.2	-153.2	-170.2	-199.8
28	Q00204B	679458.2	1214345.1	1.7	-16.3	-22.2	-23.3	-47.3	-49.2	-105.3	-111.3	-155.3
29	Q09902C	667652.8	1219631.5	12.0	12.0	12.0	6.0	-34.0	-46.0	-77.0	-83.0	-132.0
30	Q011040	676402.4	1201396.7	7.8	-0.2	-24.2	-40.2	-62.2	-75.2	-122.2	-129.2	-166.2
31	Q004030	683143.7	1202844.3	1.3	-5.7	-28.7	-55.2	58.9	-94.9	-102.2	-120.3	-128.7
32	Q015030	675698.3	1186374.3	1.2	-34.3	-57.8	-92.5	-118.8	-999.0	-999.0	-999.0	-999.0
33	Q007030	671447.0	1197950.6	3.4	-5.6	-20.6	-22.6	-80.6	-999.0	-999.0	-999.0	-999.0
34	Q019340	678138.5	1199287.0	1.7	-33.3	-33.3	-37.8	-95.3	-96.3	-125.3	-999.0	-999.0
35	Q018030	673916.0	1191017.9	1.9	-3.6	-31.6	-39.9	-63.5	-999.0	-999.0	-999.0	-999.0
36	Q003340	670743.8	1200879.8	4.9	-13.1	-35.1	-45.1	-79.5	-85.1	-127.2	-132.1	-191.1
37	9616III	688972.3	1177252.7	0.8	-54.1	-54.1	-80.5	-88.2	-91.2	-158.2	-159.2	-183.0
38	LK172	705964.0	1170298.0	0.7	-30.3	-30.3	-43.3	-60.3	-73.3	-94.3	-110.3	-110.3
39	CT668	693380.0	1157960.0	1.1	-35.9	-54.9	-68.9	-126.9	-146.9	-157.9	-177.9	-219.9
40	A1	675714.6	1186232.4	1.4	-32.1	-55.6	-89.6	-119.6	-999.0	-999.0	-999.0	-999.0
41	A2	674473.8	1182876.4	1.2	-45.3	-64.3	-75.8	-79.3	-109.7	-123.8	-999.0	-999.0
42	A4	680918.7	1185763.1	1.5	-49.5	-74.5	-80.5	-141.2	-149.5	-160.5	-165.1	-226.5

C.2 Hydraulic conductivity distribution

Then, the hydraulic conductivity of 4 aquifers was distributed from 200 well log data through Ordinary Kriging method. Figure C.2 shows the location of estimated hydraulic conductivity by pumping test. Table C.2 presents the sample of hydraulic conductivity from pumping test

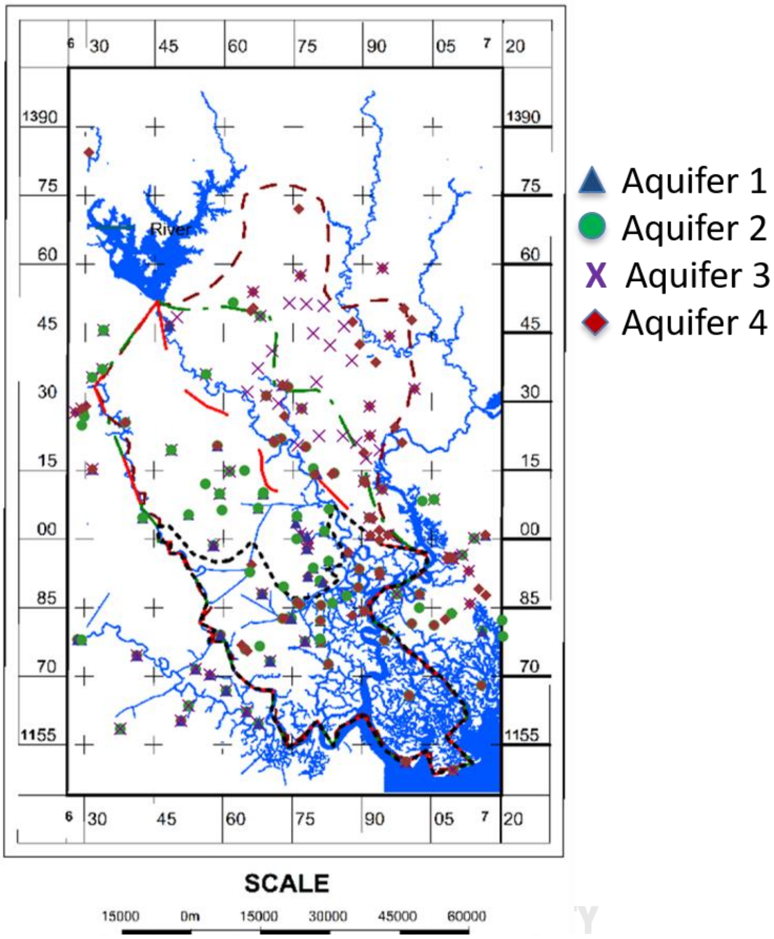


Figure C. 2: The hydraulic conductivity from pumping test in 4 aquifers

To find a function that best fits the points of the empirical variogram, the study carried out the following steps (Pesquer, Cortés, & Pons, 2011):

1. Choose the function that visually best fits the empirical variogram.

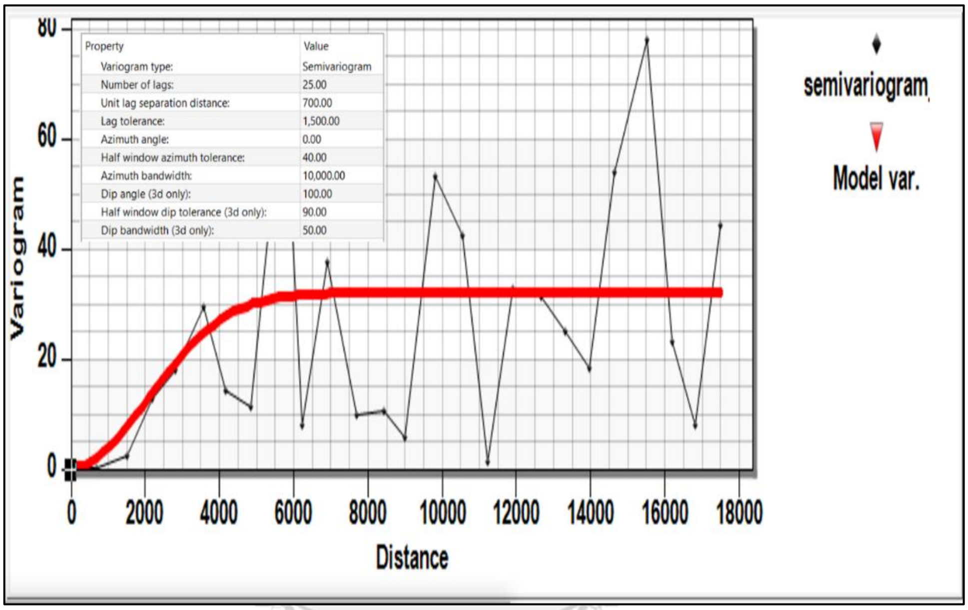
2. Determine the approximate parameters of the chosen function, which identify the aimed for structure: nugget effect, slope for the lineal model, range and sill for the rest.

3. Visually compare the variogram model to the empirical variogram.

4. Repeat point 3 until an appropriate solution is found. If the parameters chosen are close to an optimal solution, some software (e.g. Idrisi and Surfer) provide tools to finish fitting them, but this is not always possible.

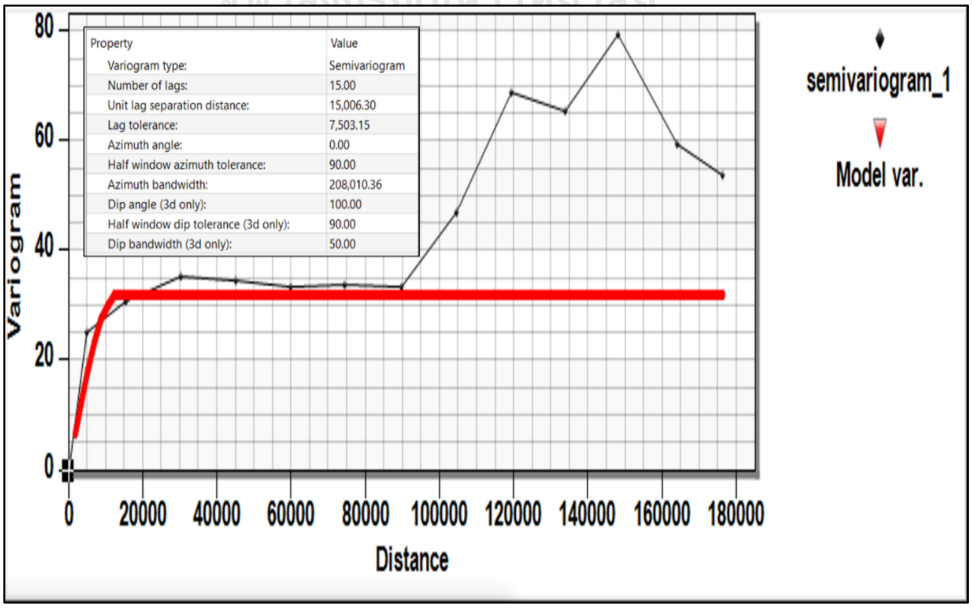
5. Choose a different function and repeat steps 3 and 4.

6. Choose the model solution that the semi variogram match with the major of measured data. The fitting variogram ordinary kriging of aquifer 1-4 are presented in Figure C.3.



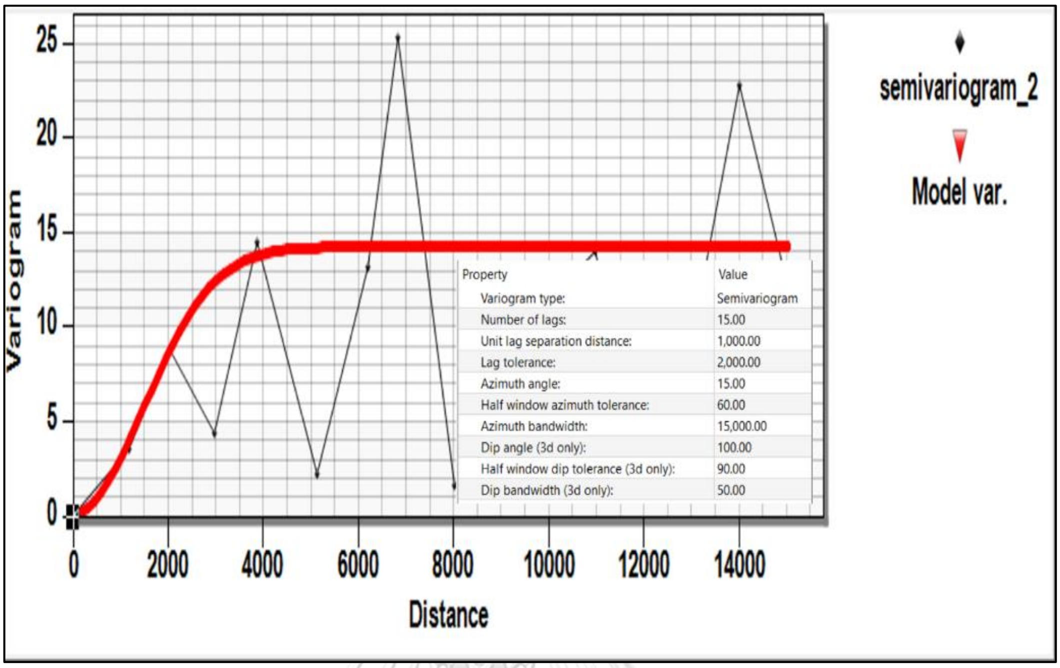
Property	Value
Variogram type:	Semivariogram
Number of lags:	25.00
Unit lag separation distance:	700.00
Lag tolerance:	1,500.00
Azimuth angle:	0.00
Half window azimuth tolerance:	40.00
Azimuth bandwidth:	10,000.00
Dip angle (3d only):	100.00
Half window dip tolerance (3d only):	90.00
Dip bandwidth (3d only):	50.00

a) Variogram ordinary kriging of aquifer 1)qp$_3$(



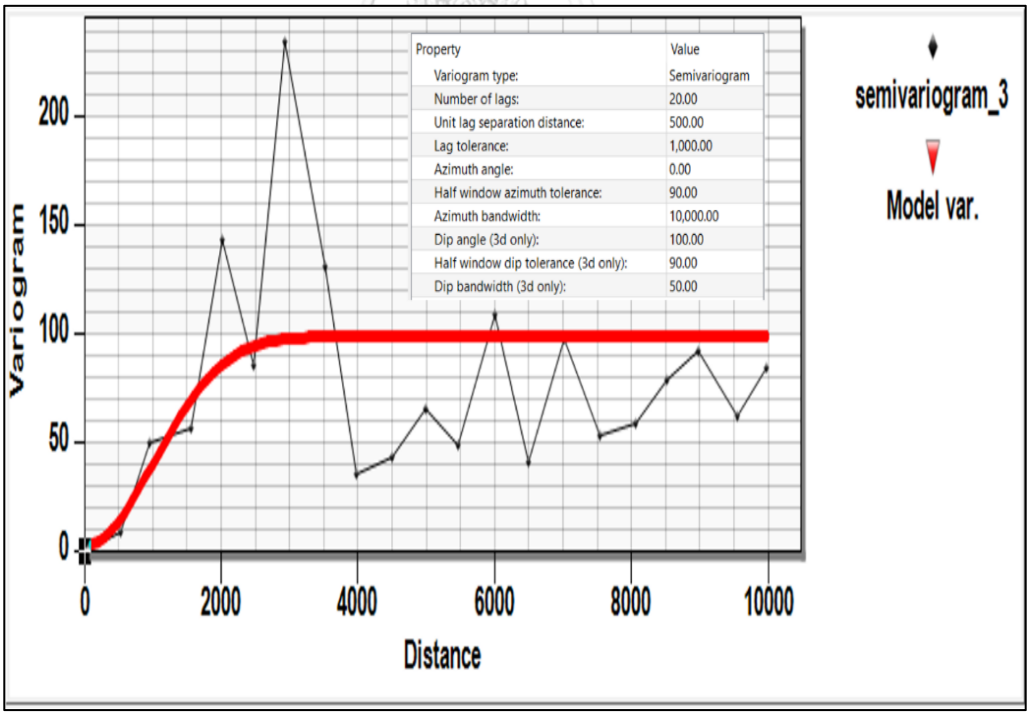
Property	Value
Variogram type:	Semivariogram
Number of lags:	15.00
Unit lag separation distance:	15,006.30
Lag tolerance:	7,503.15
Azimuth angle:	0.00
Half window azimuth tolerance:	90.00
Azimuth bandwidth:	208,010.36
Dip angle (3d only):	100.00
Half window dip tolerance (3d only):	90.00
Dip bandwidth (3d only):	50.00

b) Variogram ordinary kriging of aquifer 2)qp$_{23}$(



Property	Value
Variogram type:	Semivariogram
Number of lags:	15.00
Unit lag separation distance:	1,000.00
Lag tolerance:	2,000.00
Azimuth angle:	15.00
Half window azimuth tolerance:	60.00
Azimuth bandwidth:	15,000.00
Dip angle (3d only):	100.00
Half window dip tolerance (3d only):	90.00
Dip bandwidth (3d only):	50.00

c) Variogram ordinary kriging of aquifer 3)qp$_1$(



Property	Value
Variogram type:	Semivariogram
Number of lags:	20.00
Unit lag separation distance:	500.00
Lag tolerance:	1,000.00
Azimuth angle:	0.00
Half window azimuth tolerance:	90.00
Azimuth bandwidth:	10,000.00
Dip angle (3d only):	100.00
Half window dip tolerance (3d only):	90.00
Dip bandwidth (3d only):	50.00

d) Variogram ordinary kriging of aquifer 4)n$^2_2$(

Figure C. 3: the empirical variogram of hydraulic conductivity in 4 aquifers

Table C. 2: Sample of hydraulic conductivity from pumping test

#	Well Name	X	Y	Aquifer 1	Aquifer 2	Aquifer 3	Aquifer 4
1	325	574632.57	1170250.90	20.00	-999.00	50.00	4.00
2	327	558677.79	1174457.52	12.00	4.00	12.00	12.78
3	328	568337.81	1160190.20	20.00	20.00	4.00	12.00
4	329	569992.14	1163495.25	12.00	20.00	30.00	12.00
5	330	578179.95	1166795.60	12.00	30.00	20.00	50.00
6	333	555076.26	1158437.31	30.00	50.00	30.00	22.83
7	336	571517.61	1171494.05	20.00	4.00	20.00	4.00
8	9614	617429.65	1151151.44	4.00	20.00	4.00	16.92
9	9615	576941.00	1178973.73	30.96	30.00	27.07	40.64
10	9617	559958.20	1204588.15	10.09	52.74	52.83	50.00
11	01C	586261.15	1209805.67	0.25	12.00	4.00	12.00
12	02D	593664.07	1204945.65	12.00	4.00	3.79	3.49
13	03D	595909.51	1200519.26	6.12	-999.00	16.07	10.93
14	04D	600587.88	1195106.30	11.48	18.72	18.22	8.63
15	05C	598673.01	1190842.16	13.38	7.03	12.94	8.40
16	08C	590750.84	1189498.89	30.00	4.00	2.04	15.23
17	09-02A	611666.24	1201841.98	-999.00	4.00	2.86	38.63
18	10B	613558.10	1200805.66	-999.00	4.00	20.00	23.83
19	10-TH	631465.28	1185746.69	-999.00	28.46	18.75	7.76
20	11-TH	634940.62	1187619.53	-999.00	-999.00	50.00	18.00
21	12A	618208.05	1165633.40	4.00	8.14	10.00	28.64

C.3 Land recharge

In the study, the land recharge area was defined as outcrop area of 4 aquifers. In same aquifer, the soil type is homogeneous. Because the topmost clay layer near the sea has a thickness varying from 20 to 30 meters, the recharge in this zone is basically zero. The study applied the land recharge function from field measurement (Long & Koontanakulvong, 2019). Hence the land recharge initial input to groundwater systems in the Saigon River Basin can be defined in 4 zones: sandy clay loam, sandy clay, clay, and no recharge zone (thickness of clay is over 20 meters). Then, the land recharge was calibrated to generate computed piezometric in the zone far river matching with observation. The land recharge flux was calculated by multi recharge area with recharge rate each soil type. During the calibration, the land recharge area was minor adjust from hydrogeology map to fit the computation groundwater with the observation's. The distribution of land recharge input to the conceptual groundwater model in the Saigon River Basin is demonstrated in Figure C.4

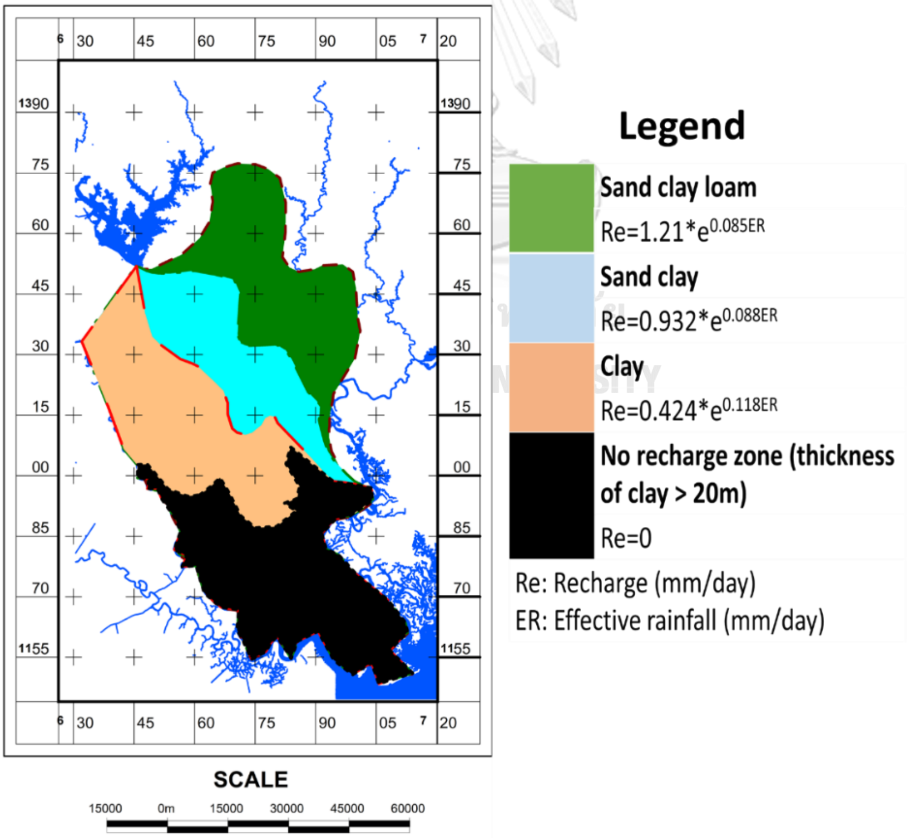


Figure C. 4: Land recharge function input into groundwater model

C.4 River – groundwater interaction parameters

The flux exchange between river – groundwater was estimated by multi the different head between river and piezometric head of aquifer with the conductance of riverbed. The different head between river and piezometric head of aquifer was obtained from observed river stage and computed hydraulic head for finite difference. In this study, the conductance of riverbed was initial employed seepage measurement data along Saigon river. Later, the conductance was calibrated to match piezometric head at 5 stations with observation data. Figure C.5 presents results of calibration piezometric heads long Saigon River Basin.

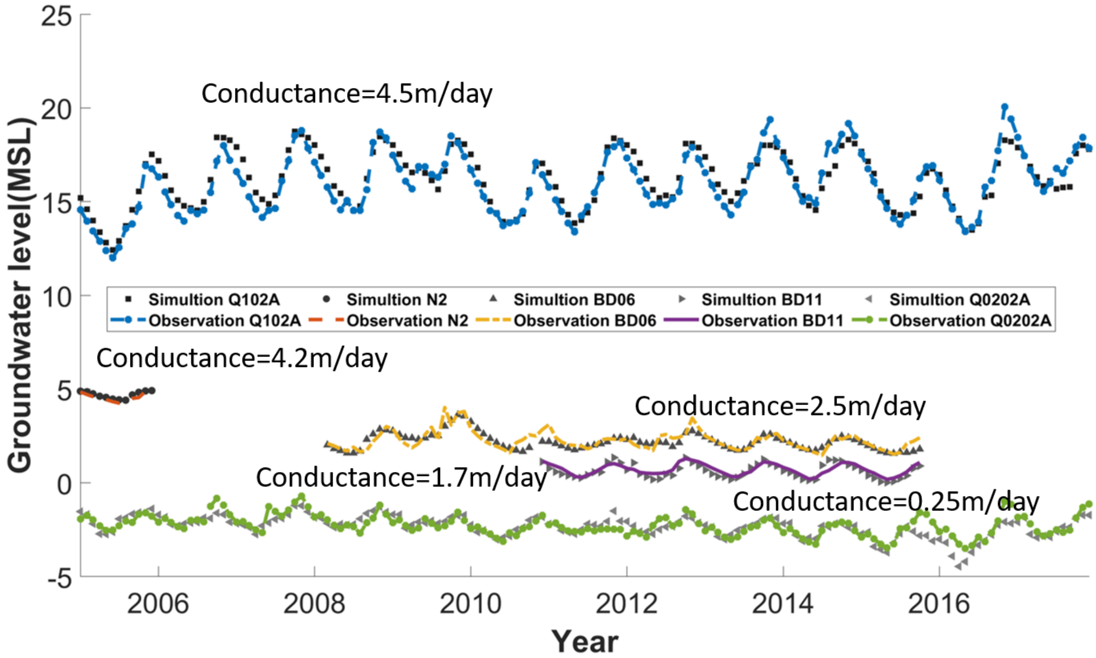


Figure C. 5: Results of calibration piezometric heads long Saigon River Basin

C.5 Pumping well

The pumping rate and hydrogeology parameters were extracted from survey hydrogeology map data of Vuong and Chan (DNRE-Binh Duong, 2017; Vuong & Long, 2016). The groundwater pumping input of aquifer 1, 2, 3, 4 during 1995 to 2017 are 19,255 - 55,711m^3/day, 146,655 - 274,224m^3/day, 42,092 - 165,005m^3/day, 59,064 - 424,446m^3/day, respectively. The groundwater pumping installed mainly in downstream, which located big city as Hochiminh and Binh Duong Province.

D. Field sampling of stable isotope

D1. Field sampling of stable isotope

The sample stable isotope of groundwater, river, rainfall was collected quarterly during Dec 2018 to Dec 2019. The “measured” δ value with respect to VSMOW was calculated using the formula below described by (Craig, 1961b)

$$R = \frac{amount\ of\ {H_2}^{18}O}{mount\ of\ {H_2}^{16}O}$$

$$\delta^{18}\mathrm{O} = \frac{R_{sample} - R_{standard}}{R_{standard}} * 1000‰$$

where R_{std} is the isotopic ratio of the Standard Mean Ocean Water" (SMOW). The table D.1 shows the results of isotope at 5 river stations and 5 observed well.

Table D. 1: Results stable isotopic of river and groundwater (R1, R2, R3, R4, R5 are river stations, Q00202A, N2, BD6, BD11, Q00102A are observed well

Date	5/1/2018					
Name	δ^{18}O (‰)-VSMOW			δ^{2}H (‰)-VSMOW		
R1	-5.51	±	0.12	-38.3	±	1
R2	-7.16	±	0.1	-44.6	±	1
R3	-7.3	±	0.14	-46	±	1.1
R4	-6.59	±	0.11	-43.1	±	1.1
R5	-6.97	±	0.1	-45.7	±	0.1
Q00202A	-6.74	±	0.1	-46	±	0.8
N2	-6.64	±	0.08	-43.5	±	0.8
BD6	-6.83	±	0.13	-44.9	±	1
BD11	-6.79	±	0.07	-47	±	1
Q00102A	-6.67	±	0.07	-46.3	±	0.9

Date	27-04-2018					
Name	$\delta^{18}O$ (‰)-VSMOW			$\delta^{2}H$ (‰)-VSMOW		
R1	-5.8	±	0.08	-38.9	±	1.1
R2	-6.85	±	0.11	-43.8	±	0.9
R3	-6.99	±	0.1	-44.6	±	1
R4	-6.48	±	0.11	-43.6	±	0.9
R5	-6.56	±	0.09	-42.9	±	1.1
Q00202A	-5.78	±	0.1	-39.9	±	0.9
N2	-5.58	±	0.09	-39.4	±	1
BD6	-5.7	±	0.11	-40.9	±	1.1
BD11	-5.72	±	0.08	-40.9	±	1
Q00102A	-5.75	±	0.09	-39	±	0.9
Date	20-08-2018					
Name	$\delta^{18}O$ (‰)-VSMOW			$\delta^{2}H$ (‰)-VSMOW		
R1	-5.91	±	0.09	-40.6	±	1.2
R2	-7.07	±	0.11	-44.8	±	0.9
R3	-7.41	±	0.1	-46	±	0.7
R4	-6.61	±	0.1	-43.4	±	0.8
R5	-7.03	±	0.1	-46.2	±	1
Q00202A	-6.1	±	0.11	-42	±	1.1
N2	-5.91	±	0.11	-40.5	±	1.2
BD6	-6.06	±	0.08	-42.9	±	1.1
BD11	-6.21	±	0.11	-42	±	1.1
Q00102A	-5.89	±	0.1	-42.6	±	1.1

Date	4/12/2018					
Name	**δ^{18}O (‰)-VSMOW**			**δ^{2}H (‰)-VSMOW**		
R1	-5.6	±	0.14	-38.5	±	1.2
R2	-7.31	±	0.07	-45.9	±	1
R3	-7.22	±	0.1	-47	±	1
R4	-6.81	±	0.11	-43.3	±	1
R5	-7.07	±	0.1	-46	±	1.1
Q00202A	-6.63	±	0.11	-44.1	±	1.2
N2	-6.74	±	0.11	-44	±	0.9
BD6	-7.01	±	0.12	-45.3	±	1.1
BD11	-6.63	±	0.09	-45.1	±	0.9
Q00102A	-6.26	±	0.14	-42.8	±	1.2

Table D. 2: Results stable isotopic of rainfall

Date	δ^{18}O (‰)-VSMOW	δ^{2}H (‰)-VSMOW
Jan-18	-8.88	-50.33
Feb-18	-6.1	-31.35
Mar-18	-6.14	-31.61
Apr-18	-6	-29.36
May-18	-6.06	-26.97
Jun-18	-6.8	-35.3
Jul-18	-8.26	-47.43
Aug-18	-10.27	-66.03
Sep-18	-9.34	-57.6
Oct-18	-5.96	-27.07
Nov-18	-7.42	-39.73
Dec-18	-6.25	-28.67

E. Exchanged fluxes between river and aquifers

E. Exchanged fluxes between river and aquifers

This part presents the fluxes exchange between river – groundwater and flow budget in both upstream and downstream of Saigon River Basin during 1995 – 2017. Figure E.1 presents the water budget upstream Saigon river basin in dry season. The land recharge is the major inflow for aquifer 1 and aquifer 2 in upstream. The inflows of aquifer 3 and aquifer 4 come from upper aquifer. Since the abstraction is less in upstream, the storage change of aquifer 1 and aquifer 2 is balancing with inflow and outflow. Meanwhile, the storage change of aquifer 3 and aquifer 4 is negative because the aquifer 3 and aquifer 4 discharge to Saigon river. However, the storage change of four aquifers in upstream seems sustainable and relies on rainfall pattern since 1995.

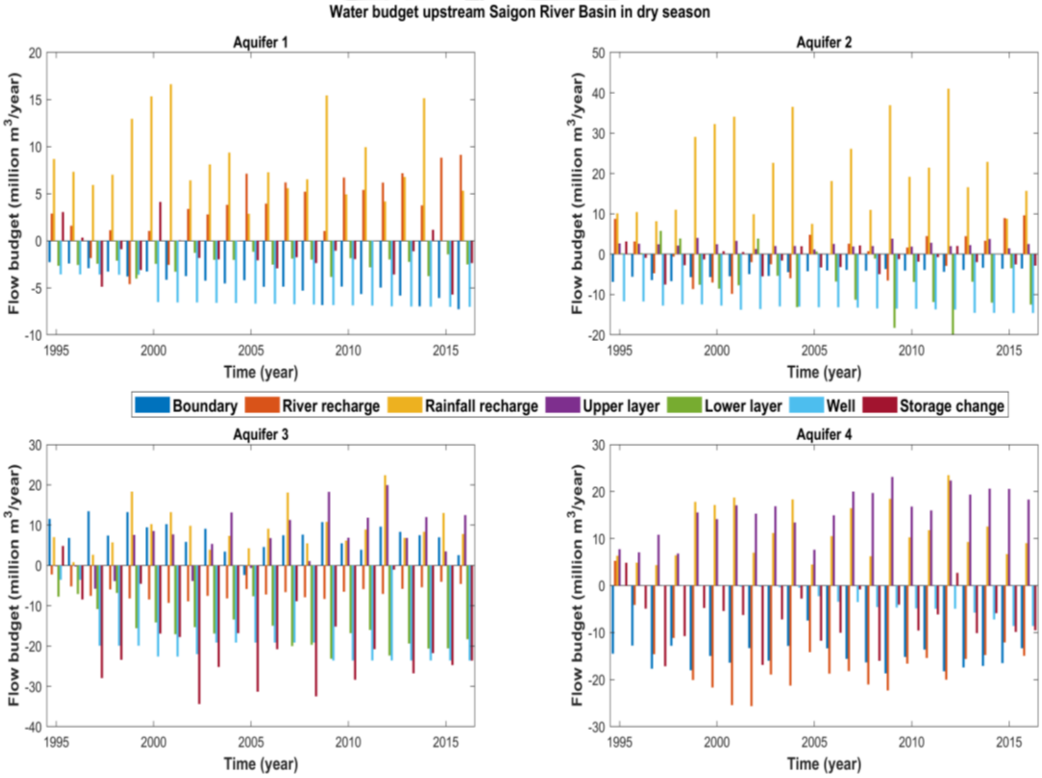


Figure E. 1: Water budget of upstream Saigon River in dry season from 1995-2017

Figure E.2 presents the water budget of upstream Saigon River Basin in wet season. During wet season, four aquifers of upstream Saigon river received 40-80 million m^3/ season. The significant outflows of four aquifers are pumping and river discharge. Since the pumping consumption is less in upstream, the storage change of four aquifers recovers the depleted storage during dry season. Moreover, the pattern of storage change upstream seems stable for 20 years pumping.

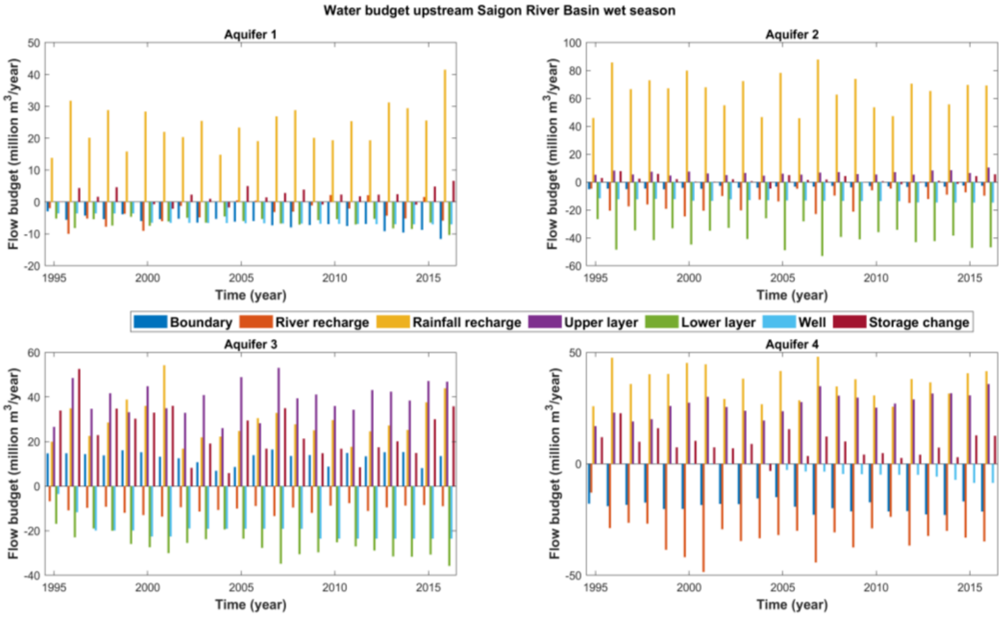


Figure E. 2: Water budget of upstream Saigon River in wet season from 1995-2017

Figure E.3 presents the water budget of downstream Saigon River Basin in the dry season. The land recharge is a small proportion of inflows to aquifers, while the river recharge is the major resource for aquifers downstream. The river recharge seepages directly into aquifer 2. The recharge of aquifer 3 and aquifer 4 come from the leakage of the upper aquifer. Under the excessive pumping rate in downstream, the storage change of four aquifers is negative, especially in aquifer 2 and aquifer 4. The storage change pattern seems to deplete undergrowth pumping.

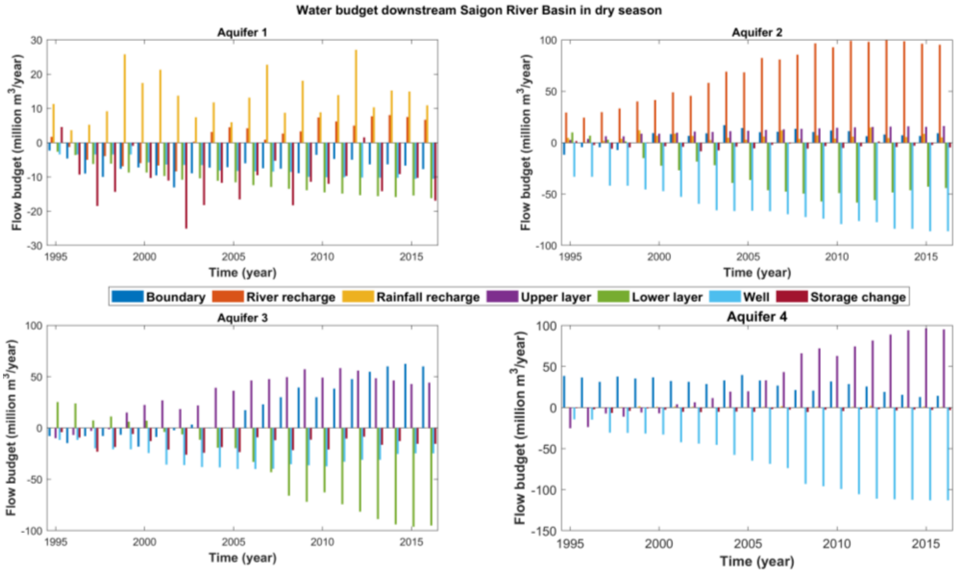


Figure E. 3: Water budget of downstream Saigon River in dry season from 1995-2017

Figure E.4 presents the water budget of upstream Saigon River Basin in wet season. Due to thick clay in top layer, the land recharge in downstream are less than in the upstream. Under the excess pumping rate in downstream, the drawdown of acquires is dramatically decreasing, which enhance river recharge process into aquifer 2. The inflows of aquifer 3 and aquifer 4 relies on leakage from upper aquifers. Although, the river recharge in wet season is higher than in dry season, it is not sufficient to recover the depleted storage change during dry season. Therefore, the annual storage change of aquifers in downstream is negative. Consequently, the drawdown in downstream have been declining since 1995.

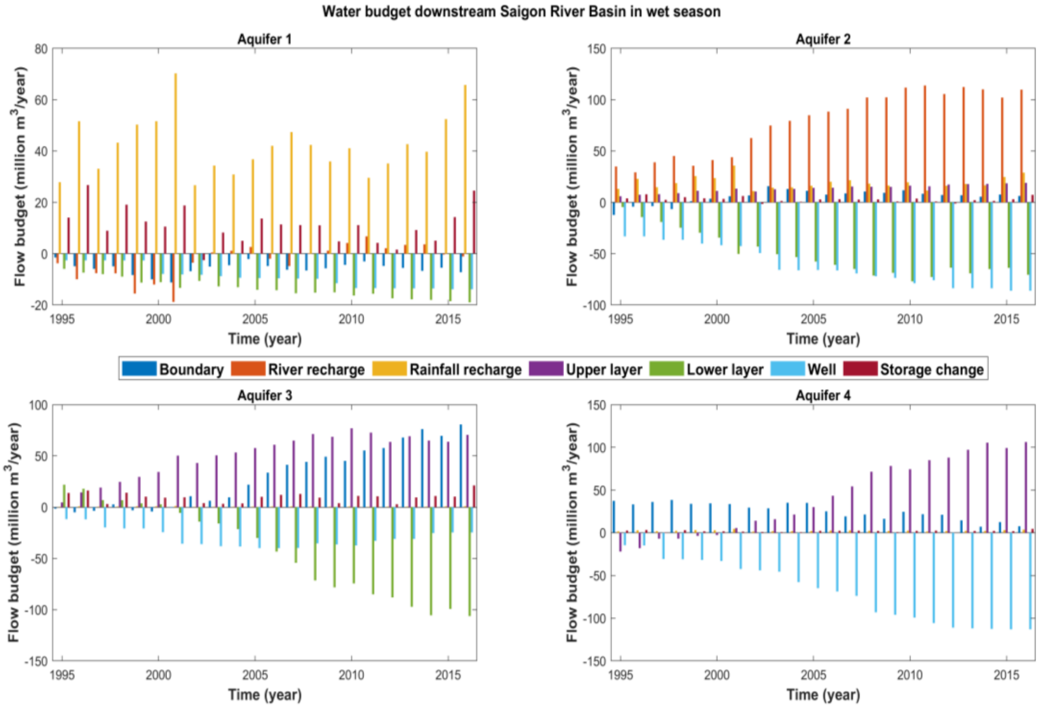


Figure E. 4: Water budget of downstream Saigon River in wet season from 1995-2017

F. Optimal pumping intensity for Saigon River Basin

F. Optimal pumping Intensity for Saigon River Basin

This part describes the optimal pumping intensity for the Saigon River Basin. According to thousands of pumping well in the Saigon River Basin, the study analyzed the histogram of groundwater pumping intensity in each kilometer for four aquifers. The groundwater pumping intensity of 4 aquifers in the Saigon River Basin varies from 0 - -3500 $m^3/day/km^2$ (see Figure F.1). An analysis of the histogram revealed that pumping intensity in aquifer 1, aquifer 2, and aquifer 3 are concentrated from 0 - -500 $m^3/day/km^2$. It is not surprising when the groundwater of three upper aquifers utilized to supply for households in the Saigon River Basin. Meanwhile, the pumping intensity higher 500 $m^3/day/km^2$ distributes approximately 45% of total pumping intensity in aquifer 4. It can be explained that the aquifer 4 was exploited extensively to supply for industries. Besides, aquifer 4 is difficult to receive recharge from rainfall and river. Therefore, the excess groundwater pumping rate in aquifer 4 drives a dramatically declining groundwater level.

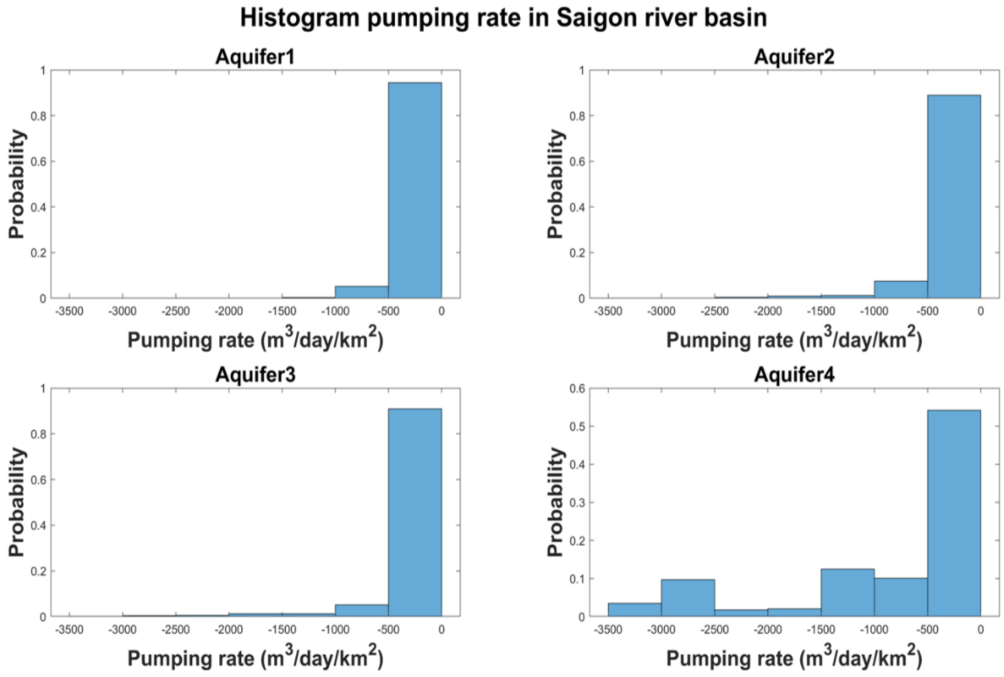


Figure F. 1: Histogram pumping rate in Saigon River Basin

In order to estimate appropriate pumping intensity, the pumping intensity of 4 aquifers was compared with groundwater drawdown in Saigon River Basin. To avoid increasing salt intrusion from growing groundwater pumping, the appropriate intensity of 4 aquifers was selected base on drawdown criteria. According the intensity pumping in existing area, the sustainable intensity pumping for aquifer 2, aquifer 3 and aquifer 4 was 2000 m^3/day/km^2, 3500 m^3/day/km^2 and 4000 m^3/day/km^2, respectively. (see Figure F.2, Figure F.3, Figure F.4)

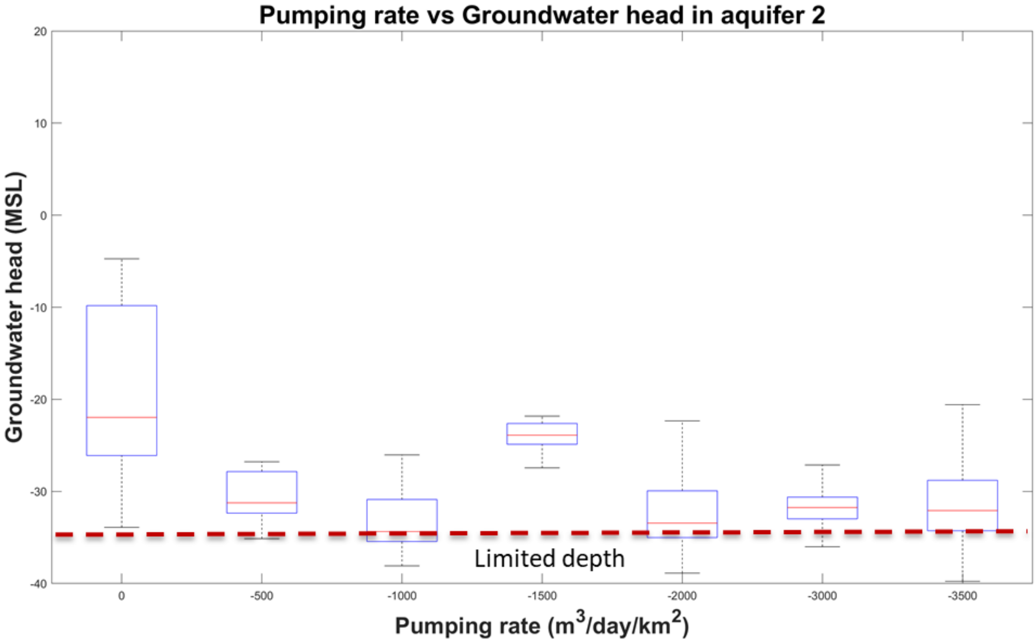


Figure F. 2: Intensity pumping rate and groundwater level of aquifer 2

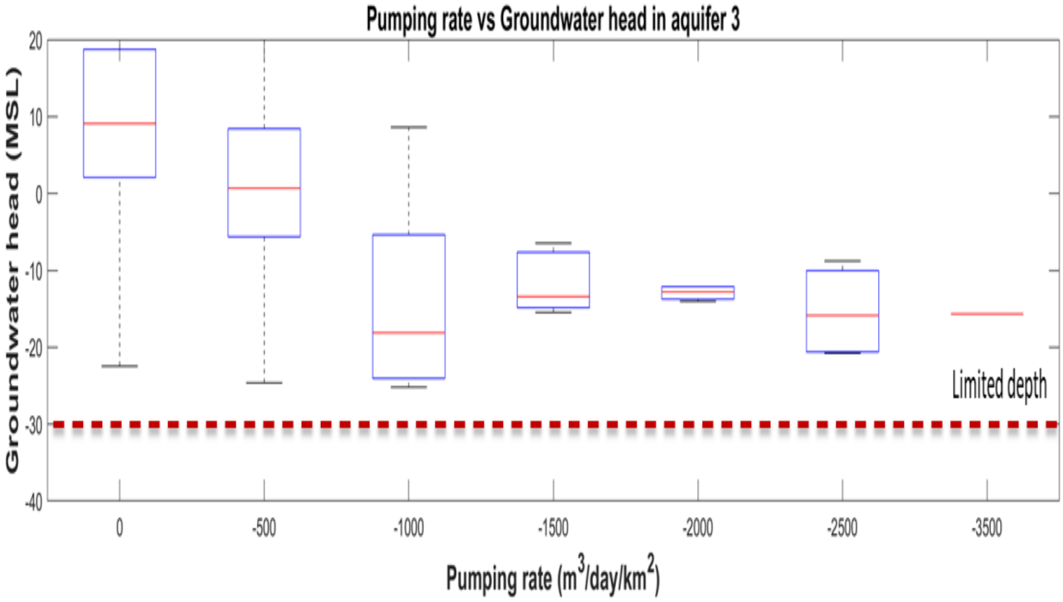


Figure F. 3: Intensity pumping rate and groundwater level of aquifer 3

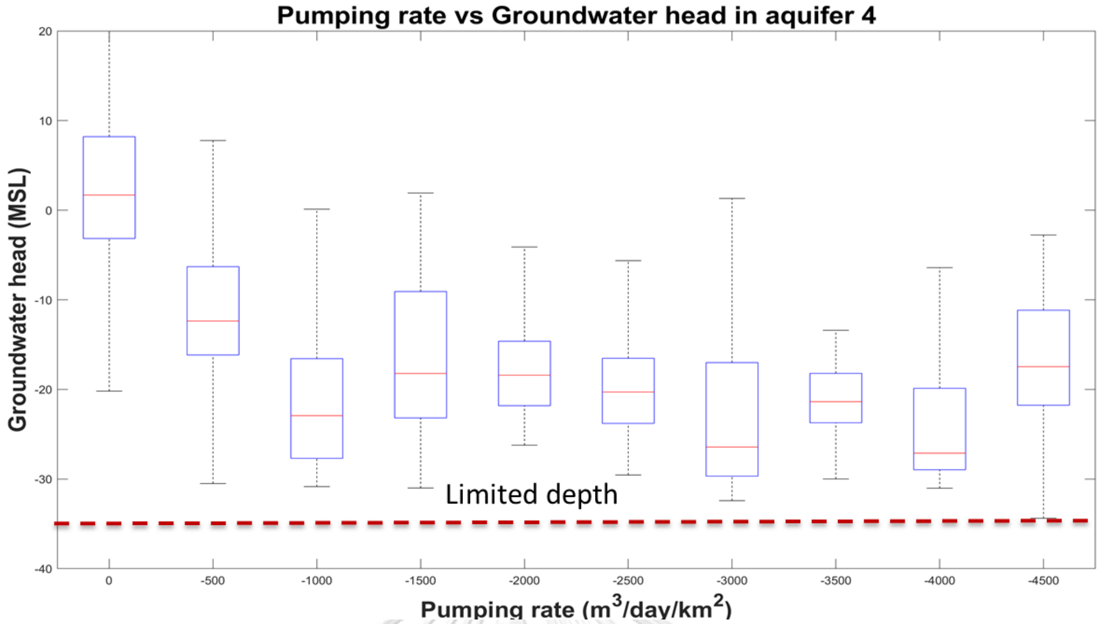


Figure F. 4: Intensity pumping rate and groundwater level of aquifer 4

G. Sustainable pumping yield

G. Sustainable pumping yield

To determine addition sustainable groundwater pumping in existing area, the study increased step by step an amount as optimal pumping intensity until the drawdown meets the limitation. To mitigate the hydraulic gradient of saline intrusion under increasing pumping, the drawdown constraint was set above -35 m. MSL for aquifer 2 and -30m. MSL for aquifer 3 and aquifer 4. According the intensity pumping in existing area, the sustainable intensity pumping for aquifer 2, aquifer 3 and aquifer 4 was 2000 m^3/day/km^2, 3500 m^3/day/km^2 and 4000 m^3/day/km^2, respectively. (see appendix F). As results of invert modeling estimation, Figure G.1 show the relationship between the drawdown and sustainable pumping yield in drawdown. Besides, the drawdown of sustainable groundwater yield was remained drawdown under constraint for 20 years of simulation (see figure G.2). Hence, sustainable groundwater pumping yield for aquifer 2, aquifer 3, and aquifer 4 are 263,699 m^3/day, 61,09 m^3/day, and 6497,822 m^3/day, respectively.

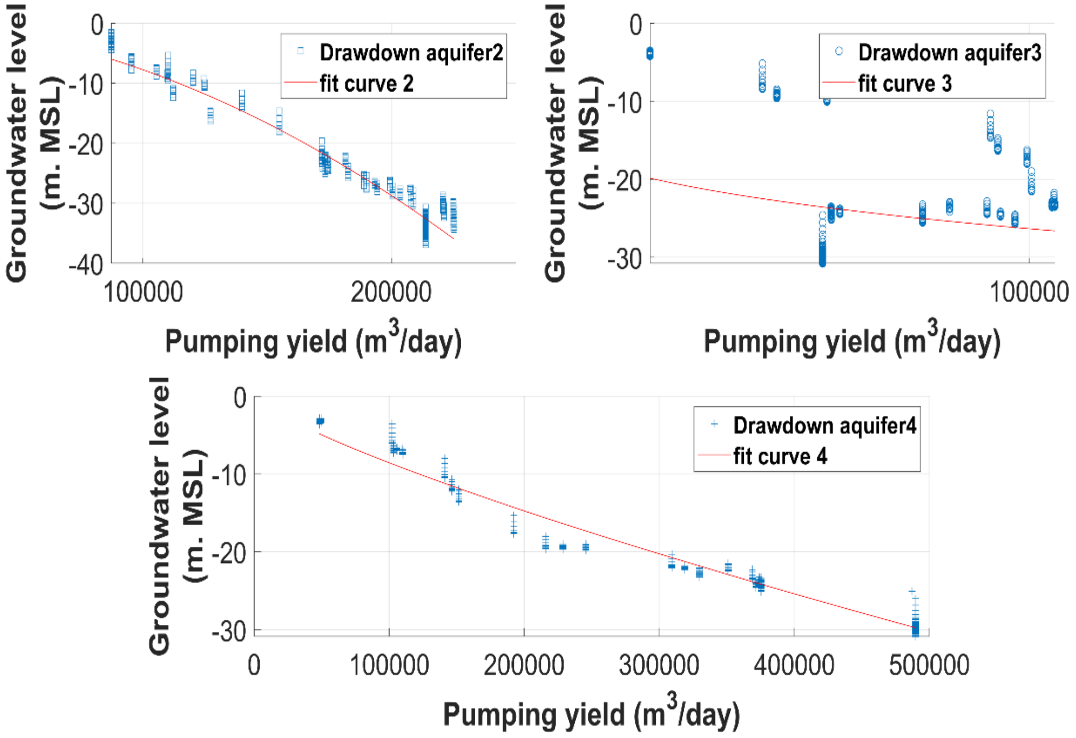


Figure G. 1: The relationship between the drawdown and sustainable pumping yield in drawdown

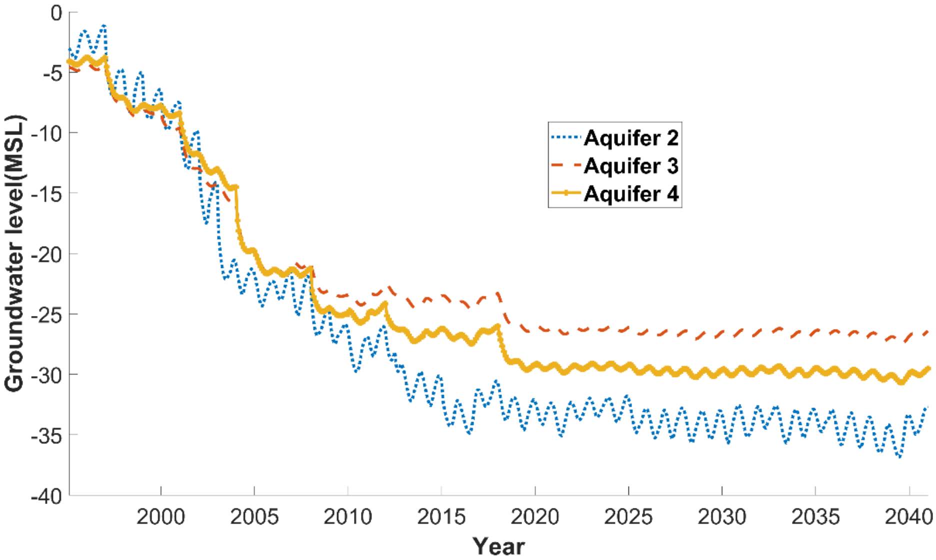


Figure G. 2: Sustainable drawdown of aquifers in downstream under pumping rate 880,000 m^3/day (increase pumping 100,000 m^3/day in existing area)

Since the upstream Saigon River Basin are freshwater area, the sustainable pumping yield in new area was determine by following the drawdown criteria of decision 69/2007/QD-UBND of Ho Chi Minh City (2007) on reducing underground water exploitation. The drawdown of aquifer 1 and aquifer 2 limit at -20 m. MSL. The groundwater levels of aquifer 3 and aquifer 4 remain not lower than -40 m. MSL. Because of effective groundwater – river interaction flux and large thickness of aquifers at location near Saigon river, the groundwater model inserted optimal pumping intensity along Saigon river to determine sustainable yield in new area. Figure G.3 demonstrate the relationship between the drawdown and sustainable pumping yield in upstream. Besides, groundwater model shows the forecast drawdown of sustainable groundwater yield in new area maintains under constraint for 20 years of simulation (see figure G.4). The sustainable groundwater yield for aquifer 2 is 201,534 m^3/day. Because the thickness of aquifer 3 in upstream is approximate 20 meters, the sustainable groundwater yield for aquifer 3 is 394,055 m^3/day. The sustainable groundwater yield for aquifer 4 is 428,014 m^3/day.

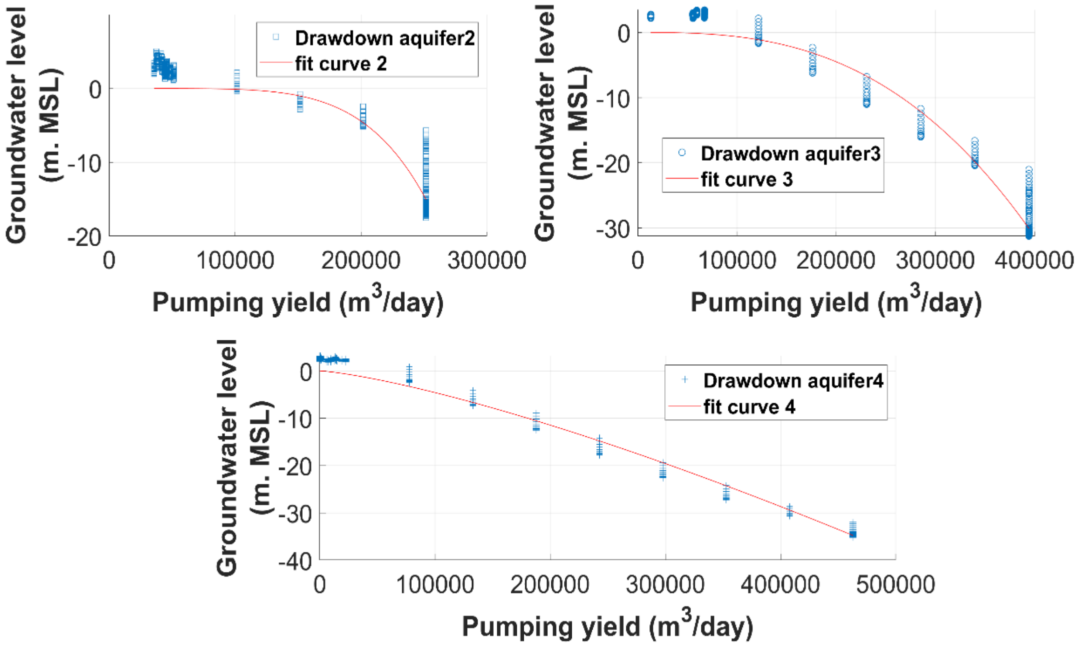


Figure G. 3: The relationship between the drawdown and sustainable pumping yield in upstream

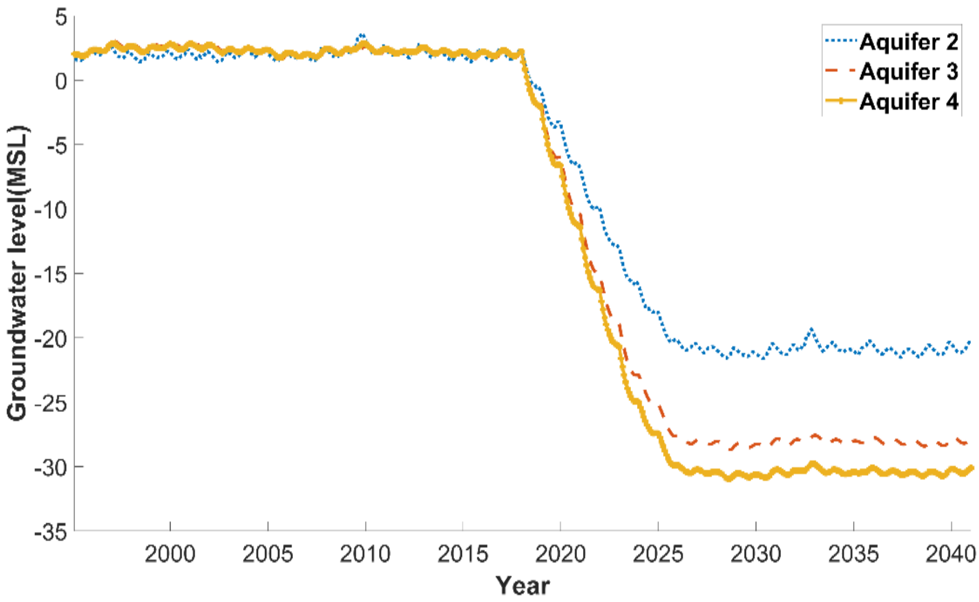


Figure G. 4: Sustainable drawdown of aquifers at upstream during 20 year simulation under pumping rate of 1.9 MCM/day (0.88 MCM/day in existing area + 1.02 MCM/day in new area)

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