ดุลน้ำบาดาลของแอ่งแพร่โดยใช้แบบจำลอง MODFLOW ร่วมกับระบบสารสนเทศทางภูมิศาสตร์
ในจังหวัดแพร่

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GROUNDWATER BALANCE OF PHRAE BASIN USING MODFLOW AND GIS IN CHANGWAT PHRAE

Mr. Jaturon Kornkul

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By	Mr. Jaturon Kornkul
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Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Faculty of Science

(Professor Supot Hannongbua, Dr.rer.nat.)

THESIS COMMITTEE

....Chairman

(Assistant Professor Sombat Yumuang, Ph.D.)

....Thesis Advisor

(Assistant Professor Srilert Chotpantarat, Ph.D.)

....Examiner

(Professor Thanawat Jarupongsakul, Ph.D.)

....External Examiner

(Kannaree Chuangcham, Ph.D.)

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จังหวัดแพร่ประสบปัญหาการขาดแคลนน้ำมาเป็นเวลานานโดยเฉพาะอย่างยิ่งในฤดูแล้ง ดังนั้นการสำรวจและการใช้ประโยชน์จากแหล่งน้ำบาดาลมีความจำเป็นเพิ่มขึ้นอย่างมาก จุดมุ่งหมายของการศึกษาครั้งนี้เพื่อทำการประเมินปริมาณการเติมน้ำลงสู่ชั้นหินอุ้มน้ำ รวมทั้งประเมินระบบการไหลและดุลของน้ำบาลรายจังหวัด ข้อมูลที่ใช้ได้รับมาจากภาครัฐและเอกชน รวมทั้งการสำรวจภาคสนามปี 2555-2556 ผลจากการสร้างโครงร่างแบบจำลองเชิงมโนทัศน์ทางอุทกธรณีวิทยา พบว่าในพื้นที่สามารถแบ่งประเภทชั้นหินอุ้มน้ำได้สามประเภทคือ ชั้นตะกอนตะพักลำน้ำ (Qfd), ชั้นตะกอนเชิงเขา (Qyt และ Qot) และ ชั้นหินแข็งอุ้มน้ำ (TRjik และ PCms) ทิศทางการไหลของชั้นหินอุ้มน้ำทุกชั้นไหลจากทางทิศเหนือไปยังทิศใต้ด้วยค่าความลาดทางชลศาสตร์เฉลี่ยประมาณ 0.0013 ซึ่งสอดคล้องกับแบบจำลองการไหลของน้ำบาดาลโดยใช้โปรแกรม MODFLOW นอกจากนี้ยังพบว่าส่วนกลางแอ่งน้ำบาดาลและแม่น้ำยมเป็นพื้นที่ไหลออกของน้ำบาดาล อัตราการเติมน้ำบาดาลแต่ละฤดูกาลถูกประมาณค่าและแสดงผลในเชิงพื้นที่โดยใช้โมดูล WetSpass ผลการศึกษาพบการเปลี่ยนแปลงตามฤดูกาลของอัตราการเติมน้ำบาดาลมีค่าระหว่าง 0-320 มม./ ปี และพบว่าศักยภาพของพื้นที่เติมน้ำสอดคล้องกับสภาพภูมิประเทศและลักษณะทางอุทกวิทยา ผลจากการประเมินค่าอัตราการเติมน้ำรายฤดูกาลด้วยโมดูล WetSpass ถูกนำมาใช้และปรับเทียบในโปรแกรม MODFLOW ซึ่งผลจากแบบจำลองแสดงถึงดุลของน้ำบาดาลที่เปลี่ยนแปลงตามฤดูกาล โดยอัตราการเติมน้ำบาดาลจะมีปริมาณที่สูงในช่วงฤดูฝน และดุลของน้ำบาดาลรายปีพบว่าปริมาณน้ำไหลเข้าแอ่งจะมีค่าสูงกว่าปริมาณน้ำไหลออกจากแอ่งประมาณ 111,320 ลูกบาศก์เมตร ต่อปี เพื่อกำหนดปริมาณการสูบน้ำที่ปลอดภัยอย่างยั่งยืน แบบจำลองของน้ำบาดาลในจังหวัดแพร่ถูกแบ่งเป็นสามกรณีศึกษา คือ การเพิ่มอัตราสูบน้ำในพื้นที่เป็นร้อยละ 25, ร้อยละ 50 และ ร้อยละ 100 ของปริมาณการสูบเดิม ผลการศึกษาแสดงให้เห็นถึงในพื้นที่จังหวัดแพร่สามารถเพิ่มอัตราการสูบทดสอบได้ไม่เกินร้อยละ 50 จากปริมาณเดิม ซึ่งผลการศึกษาเหล่านี้มีประโยชน์ต่อการพัฒนาและการนำไปใช้ต่อเป็นข้อมูลพื้นฐานสำหรับการบริหารจัดการทรัพยากรน้ำบาดาลที่เหมาะสมอย่างยั่งยืนต่อไป

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Changwat Phrae has faced water shortage problem for a long time. Hence, the aims of this study were to estimate the groundwater recharge of aquifers and assess groundwater movement and groundwater balance. From secondary data incorporated with primary data derived from field investigation during years 2012-2013, the results of hydrogeological conceptual model revealed three aquifer types as follows: floodplain deposited, terraces deposited aquifers, and the consolidated aquifers. The main groundwater direction of the unconsolidated and consolidated aquifers flow from the northern to the southern area with a mean hydraulic gradient approximately 0.0013, which is corresponding to the groundwater flow simulated by MODFLOW, the central part of the region and the Yom river were found as discharge areas. The groundwater recharge rates were spatially determined by WetSpass module for estimating seasonal variability patterns of groundwater recharge which were vary between 0-320 mm/ year. In addition, the results showed that the potentiality of recharge area corresponds to the topography and hydrologic characteristics. Groundwater recharge derived from WetSpass was then imported into MODFLOW for calibration and verification of groundwater modelling. The results revealed that the variations of groundwater balance are seasonal dependent, which found relatively high recharge rates and groundwater inflow during the rainy season. According to groundwater modelling, the groundwater inflow is relatively higher than the groundwater outflow approx. 111,320 cubic meters/year. Finally, in order to determine groundwater safe yield and propose the sustainable groundwater management, the groundwater model was simulated by increasing the pumping rates under three situations: 25, 50 and 100%. The results showed that the availability of the pumping rate is not higher than 50% relatively compared to the base condition. These contributions will be further applied as the fundamental data for appropriately sustainable groundwater management.

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Advisor's Signature ....

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CHAPTER I
INTRODUCTION

1.1 Rationale

The population growth and the expansion of economic activity in Thailand have influenced to the increase demand for resources, especially freshwater for domestic use, industrial, tourist development and agricultural purposes. Moreover, inefficient use of water and deterioration of water quality have influenced more serious problems to availability and sufficiency of surface water resources. Hence, groundwater resource is a secondary freshwater resource, which is developed for conjunctive use with surface water especially in non-irrigated area. However, the over-pumping is much more than groundwater recharge in aquifer, which causes instability of the groundwater balance. Consequently, that has influenced to the depletion of groundwater table, and has taken also a longer period of time to recover back into aquifers [1]. For management of water resources, an approach of management to obtain maximum benefit for economic, environmental and social values, should conjunctively assess and manage the resource for sustainability over a specified management timeframe as well as avoid allocation of the resource twice [2]. Hence, an assessment the groundwater balance for sustainable development is the most important.

Many concepts and methodology are used in the management of groundwater systems to establish the limits of pumpage from an aquifer [3], such as an assessment the groundwater balance. In other word, the relation between inflows and outflows is equal to any changes in groundwater storage [4]. For reliability and accuracy, groundwater balance analysis on large and complex scale is used by mathematical model such like MODFLOW useful for spatial analysis [5] and combination with Geographic information System (GIS) which provides a flexible toolset for resource management, as data pre- and post-processing can be automated to a high level. Moreover, the GIS data permits an efficient data transformation between the spatial distribution and the areal discretization obtained for groundwater modeling, which is calculated by using finite elements or finite differences [6].

Yom watershed is one of the watersheds in the northern of Thailand, which has the water shortage problem in a few decades due to low amount of rainfall and increasing of the population, which resulting in increasing of the water demand level, especially on non-irrigated area in Sukhuthai and Phrae provinces [7]. The study of Amares [7] found that the result of water balance in Yom watershed was found that most of the basin areas were shortage of water in the dry season. The water shortage often occurs in the beginning of wet season in the area with high cultivation which crop water requirements more than the available rainfall, especially in middle and lower part of Yom watershed [8]. Hence, groundwater exploration and exploitation of the Yom watershed are necessary, especially in Phrae province which had the drought in dry season through early rain season [9]. Moreover, to archive the sustainable groundwater management, groundwater balances analysis in Phrae groundwater basin should be really established.

All mentioned above, this study used “WetSPASS” embedded in GIS, which used to spatially estimate for groundwater recharge in Changwat Phrae [10] incorporated with groundwater model, so-called “GMS-MODFLOW” to efficiently assess groundwater flow and groundwater balance. Moreover, this study also presents results in spatial distribution for better understanding, and it can be further used as a database for groundwater balance analysis in other areas, which have similar groundwater characteristics, especially for groundwater basins the north of Thailand.

1.2 Objectives

The purposes of this present study are:

• To assess groundwater recharge in Phrae province using WetSPASS.

• To simulate groundwater flow model in Phrae province using GIS and MODFLOW.

• To investigate groundwater balance system in Phrae province.

1.3 Scope of study

The scope of this research is:

• The study area is located in Phrae province.

• To study the groundwater balance system in Phrae province using secondary data from government and private sectors. In addition, monthly average meteorology data and hydrology data were used to estimation and preparation for modeling during 1988-2007 (30 years).

• The seasonal groundwater recharge rate was estimated by using water balance component method in WetSPASS module. The seasonal precipitation, the seasonal surface runoff and the seasonal evapotranspiration were generated, and they were used to estimate the groundwater recharge in the process. Hence, the precipitation and evaporation data in recharge package (RCH), and runoff data in stream package (STR) in GMS MODFLOW were ignored for groundwater modelling.

• The study was focused on the groundwater system in a regional scale. Hence, shallow groundwater characteristic and shallow groundwater usage in Phrae province not used to establish for groundwater modelling. In addition, block-center flow package (BCF) was used to solve the groundwater flow and groundwater balance.

• GPS navigation device and topological maps were used in field investigate. Normally in modeling of groundwater flow, distributions of wells for analysis are required. However, many wells in the study area are unusable. Additionally, coordinates of wells data from Department of Groundwater Resources (DGR) has geometric error, and many reference wells located far away from the main routes, which usually come with expenditure and safety. Hence, in this study, groundwater wells from field investigation which are possible to reach were used in model analysis.

1.4 Location of the study area

Phrae province is located in the middle part of Yom watershed, which overlaps onto Phrae groundwater basin (Figure 1.1). The total area of approx. 6,483 square kilometers, and its elevation ranges from 85-1633 meters a.s.l. The coordinates of the study area in WGS 1984 datum of approx. 1950000 – 2075000 N from south to north, and 535535000 - 662500 E from west to east. The topographical features compose of high mountainous on the northern part of the area, and alluvial floodplain areas on the center part in the valley of river Yom. The highest elevation of the area, Phi Pan Nam Range runs across the province from north to south in the west and the Phu lueng Range in the east (Figure 1.2).

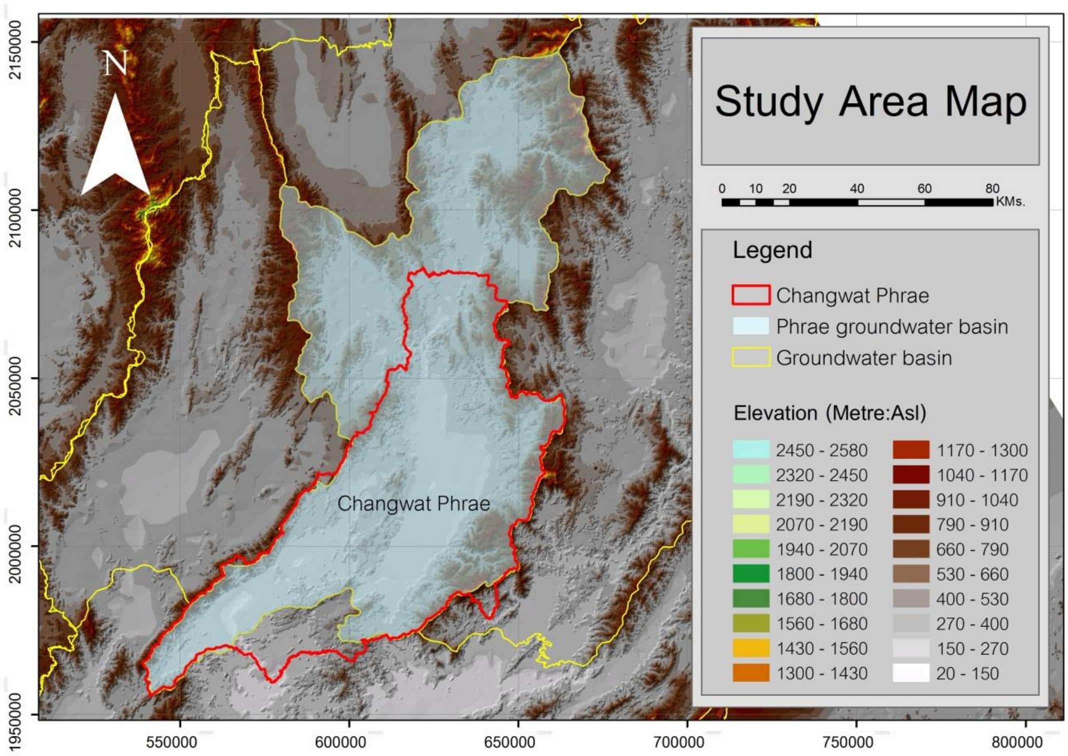

Figure 1. 1 Topographic setting of the study area.

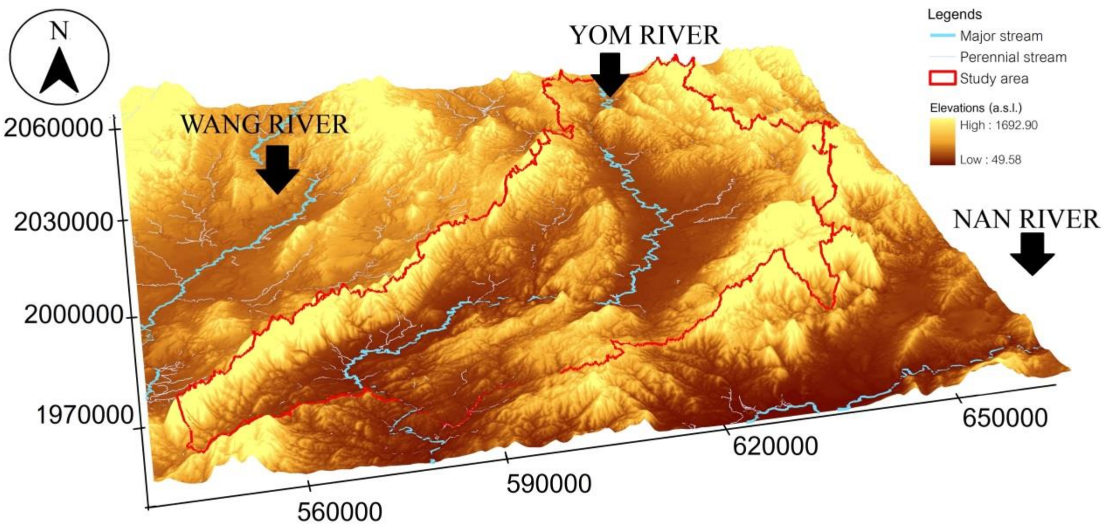

Figure 1. 2 Terrain surface of the study area.

1.5 Expected outputs

The expected outputs of this thesis consist of:

• Groundwater recharge in the study area.

• Simulation of groundwater flow in the study area.

• Groundwater balance for suggestions of groundwater management in the study area.

1.6 Research methodology

To accomplish the aims of the study, four following steps were designed, which that were described, shown on the schematic diagram (Figure 1.3), and as follows:

1.6.1 Preparation

This step includes:

• Previous works of the related researches in the study area, in Yom watershed, in northern Thailand, and other countries were reviewed

• Acquisition and study of the previous basic data acquisition, i.e. topographic map, land use map, soil map, geologic map, hydrogeologic map to understand the topography, geology, and hydrogeologic characteristic of the study area were collected as general background information. In addition, geologic cross-sections were generated from well-logging data in the study area to understand the hydrogeologic characteristics for groundwater modeling.

• Intensive comprehension on the conceptual model of hydrogeologic characteristics was assessed and set-up hydro-stratigraphic layers, initial and boundary condition for groundwater modeling.

1.6.2 Field investigation

This step was carried out as follows:

• Ground surveys were carried out around the surroundings of Phrae province based on the L7018 series 1:50000 map to understand the limitation in the area for associate plan in further steps of the field investigation.

• Groundwater level data were measured with an electric-tape from observation wells surroundings the study area for model calibration and validation as well as recharge estimation.

1.6.3 Laboratorial studies

This step is conducted as follows:

• Data preparation for modeling: These inventory data consisted of digital elevation model (DEM), meteorology, hydrogeology, geology and recharge. Software of GIS and mathematic model (ArcView 3.3, ArcGIS 9.3, CROPWAT 8.0 and GMS MODFLOW 7.1) are applied in storage, manipulating, and analyzing the digital data.

• Developing model: this sub-step was conducted to the set of model conditions specified, such as model grid size and spacing, surface elevations, boundary conditions, hydrogeological characterization, meteorological characterization, recharge etc., which should be selected based upon the model conceptualization. Then, groundwater flow in Phrae province is simulated. This simulation also validated with observation wells from field investigation.

• For model calibration and verification: some parameters are adjusted in a module and the model is repeatedly run until the simulated values match up with field-observed values within an acceptable level of accuracy.

• Groundwater balance analysis and Groundwater simulation were done in Phrae province to assess water budget by MODFLOW. The budget lists were shown the relationship between inflow to and outflow from the aquifer on three scenarios (dry season, rainy season and steady or annual period).

1.6.4 Discussion and conclusions

This step includes:

• Previous results of groundwater flow and groundwater balance system in the study area from step ***1.6.3 Laboratorial studies*** were discussed and concluded.

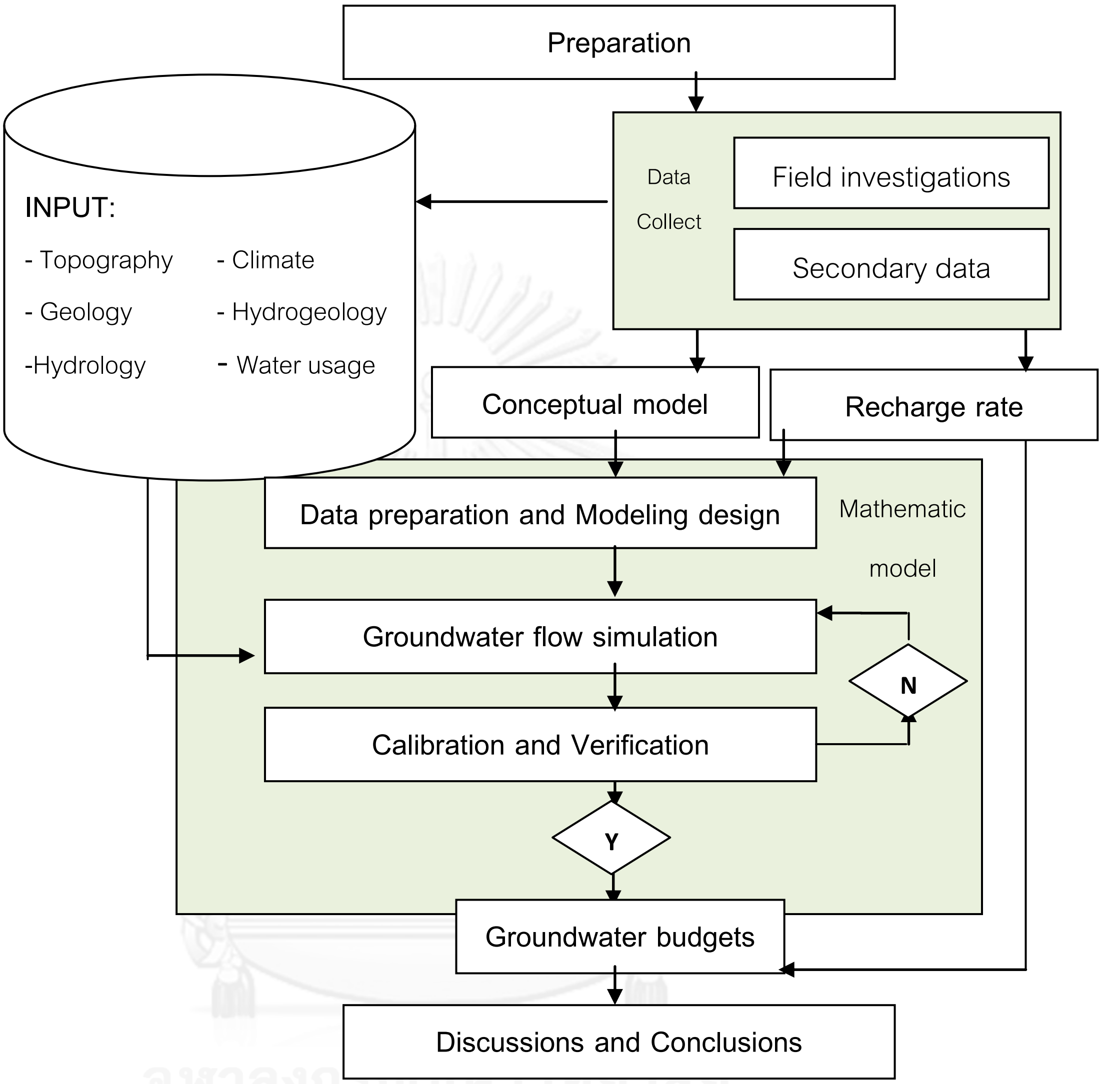

Figure 1. 3 Schematic diagrams of the research methodology.

1.7 Components of the thesis

This thesis composed of six chapters including the introductory in Chapter 1. Chapter 2 is initiated with the definition and theory of groundwater balance and groundwater modeling research. The applications of the geoinformatics (e.g. remote sensing, geographic information system and Global positioning system) in groundwater modeling are also briefly reviewed.

The site description is shown in Chapter 3, including location and topography, climate, geology and hydrogeology. Furthermore, Chapter 4 provides all methods and all data which were used in this study. In this chapter, parameter input from spatial data pre-processed by using GIS techniques are produced and then presents the fieldwork procedures and modeling design. The previous studies from the related technical literatures are hereby also presented.

Following the data preparation and developing model steps, the results are presented in Chapter 5. The modeling approach of the MODFLOW and the resulting output (e.g. groundwater flow analysis, the validation technique) and scenarios of the groundwater balance are proposed in this chapter. In Chapter 6 are focused on discussion of the groundwater flow and water budget results. Finally, the results are summarized and made suggestions in a last of the content of this chapter.

CHAPTER II
LITERATURE REVIEW

2.1 Groundwater

Generally, excess water in a vadose zone is pulled downward by gravity. It passes through the intermediate belt to the capillary fringe, wherewith the pores are filled with capillary water so that the saturation approaches 100 percent, and the water is held in place by capillary force. At some depth, the pores of the soil or rock are saturated with water. The top of the saturated zone is called the water table. Water stored in this zone is known as groundwater [1].

2.1.1 Groundwater flow

Aquifers transmit water from recharge areas to discharge areas. The factors controlling groundwater movement can be expressed in the simple form of a Darcy's law equation as [11] :

$Q = KA\,(dh/dl)$ .... (Equation 2.1)

where Q is the quantity of water (LT^{-1})
K is the hydraulic conductivity (m/d)
A is the cross-sectional area (sq. meter)
dh/dl is the hydraulic gradient (L/L)

From Equation 2.1, it can be rearranged to solve for K as:

$K = Qdl/Adh = (m3d\text{-}1)\,(m)/\,(m^{2})\,(m) = m/d$ .... (Equation 2.2)

Because the hydraulic conductivity is the units of groundwater flow velocity, thus, the hydraulic conductivity depends on the volume of water under a unit hydraulic gradient through a unit area. In addition, the hydraulic conductivity value depends on the pores and fracture sizes of materials, the arrangement, and the dynamic characteristics of the fluid. The relationships between the hydraulic conductivity and rock types are not only varied by different types of rocks, but may by different locations in the same rock. If the hydraulic conductivity values in the aquifer as same as in any area, it is classified as a homogeneous. However, if the hydraulic conductivity values in the aquifer are different, it is classified as a heterogeneous mixture.

Moverover, the hydraulic conductivity may be different because of different directions at any place in an aquifer. If the hydraulic conductivities are the same value in all directions, the aquifer is said to be isotropic. If its values are different in different directions, the aquifer is said to be anisotropic. However, in groundwater flow modelling, it is convenient in boundary setting step when assuming that aquifers are both homogeneous and isotropic in a model, although in the real world, this condition of aquifers are rare. Generally, the hydraulic conductivity of most rocks, unconsolidated deposits and flat-lying consolidated sedimentary rocks in the horizontal direction is greater than the vertical direction. For groundwater modeling, Darcy's law equation (Equation 2.1) used to develop with continuity equation to find the temporal storage change is shown as following equation [12] :

$$\sum Q_t = S_s \frac{\Delta h}{\Delta t} \Delta V \quad \text{............ (Equation 2.3)}$$

where Q_t is the inflow of the cells (LT^{-1})

S_S is the specific storage (L^{-1})

ΔV is the change in the storage (L^{-3}) which depend on change in row, column and vertical of cell i, j, k

Δh is the change in the groundwater table level in each cell per times

Δt is times

In general, the groundwater movement direction can be derived from observations of topography, and gravity is the most important factor in groundwater movement. In natural conditions, groundwater moves in the underground until it reaches the land surface through seeps of stream channels (Figure 2.1). Groundwater in the saturated zone therefore, moves from interstream areas toward streams or the coast by hydraulic gradient of the land surface. Thus, to determine groundwater table and the direction of groundwater movement, the surface elevation of the water level in wells is necessarily determined. Nevertheless, it is difficult to visualize the water movement in the subsurface. This problem can be solved by using flow net simulations, which are one of the most effective techniques for illustrating conditions in groundwater systems [11].

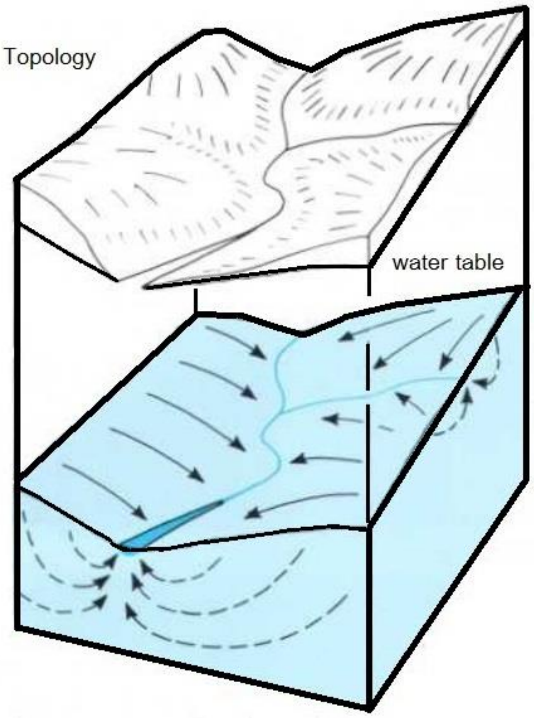

Figure 2. 1 Direction of groundwater movement and topology [11].

2.1.2 Groundwater system

Recharge is the entry into the saturated zone of water which made available at the water table, together with the associated flow away from the water table within the saturated zone [13]. In general, it is expressed in terms of volume per unit of time, per unit of area [11]. When the water from the surface infiltrates and reaches the capillary fringe, in displaces air in the pore spaces and causes the water table to rise. Some environments, especially in arid regions, water may take years to pass through the unsaturated zone. The times may vary from a few days in the zone adjacent to the discharge area to several thousand years. Afterwards, aquifers transmit water from recharge areas to discharge areas that the rate of groundwater movement depends on the hydraulic conductivities and hydrogeologic characteristics of aquifers [1].

The groundwater system has two functions; it stores water to the extent of its porosity, and transmits it from recharge areas to discharge areas. In other words, a groundwater system serves as both a reservoir and a conduit. The assessment of recharge areas and recharge rates are becoming increasingly important because of the land use expanding for human activities. Most recharge occurs when plants are dormant and evaporation rates are small. In the long-term, recharge varies from year to year, depending on the amount of precipitation, its seasonal distribution, temperature, land use, and other factors. According to land use, recharge rates in forests are much higher than those in cities. Natural discharge from groundwater systems includes not only the perennial streams, or springs, or wetlands, but also the adjoining flood plains and other low-lying areas. Natural discharge also includes the evapotranspiration, because large amounts of water can be withdrew from the saturated zone by plants during the growing season (Figure 2.2).

The relationship between recharge areas and discharge areas can be defined by the groundwater movement per areas. The groundwater movement of recharge areas commonly moves in the vertical direction that the hydraulic conductivity is the generally lowest. Conversely, the groundwater movement of discharge areas moves in the horizontal direction that the hydraulic conductivity is the largest. In addition, the difference of area size shows that discharge areas are more efficient than recharge areas. Generally, the discharge area is invariably much smaller area size than that of recharge areas. One of the most significant differences between recharge and discharge is timing. Recharge occurs during and after periods of precipitation and thus is temporal. In the other hand, discharge is a continuous process which occurs as long as groundwater heads are above the seeps level [11] .

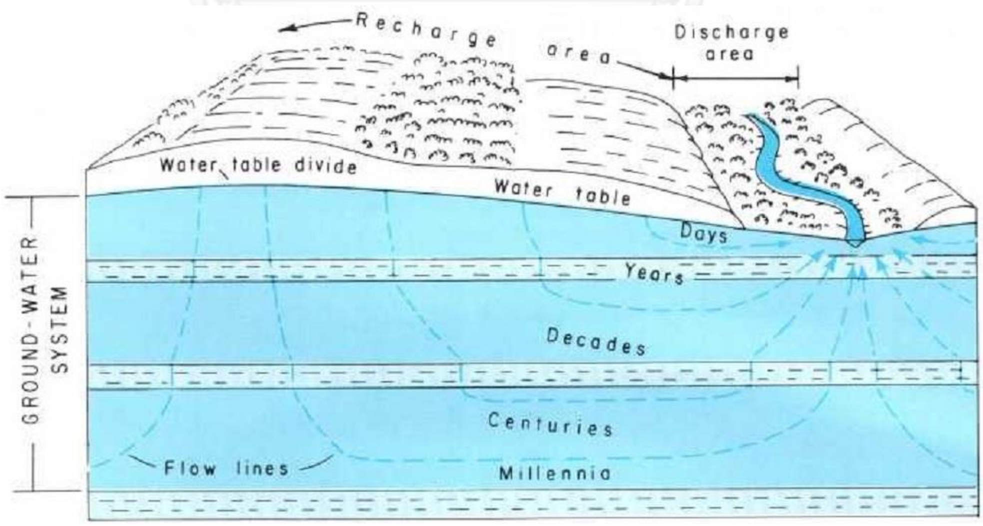

Figure 2. 2 Recharge and discharge areas in groundwater systems [11].

2.1.3 Groundwater budget

In natural conditions, the groundwater system is in long-term equilibrium. The amount of water entering or recharging the system is approximately equal to the amount of water discharging from the system. The groundwater quantity stored in the system is constant or different that depends on annual or longer-term climatic variations. The natural condition budget is schematically shown in Figure 2.3. The groundwater outflow is discharged to streams and rivers are called base flow. The groundwater system inflows and outflows, under natural conditions are showed in Table 2.1. In addition, it can describe the water budget of the pre-development system as [14]:

Recharge (water entering) = Discharge (water leaving) .... (Equation 2.4)

Table 2. 1 Possible sources of inflow and outflow a groundwater system under natural conditions

Recharge	Discharge
1. Areal recharge from precipitation that percolates though the unsaturated zone to the water table. 2. Recharge from losing streams, lakes and wetlands.	1. Discharge to streams, lakes, wetlands, saltwater bodies and springs. 2. Groundwater evapotranspiration

Nowadays, the groundwater system was changed by human activities for domestic use, irrigation, urban development, changing the type of vegetation, etc. The changing in the groundwater system allows water to be withdrawn. This statement is shown in Figure 2.3, and it can be written in terms of rates as:

Pumpage = Increased recharge+Water removed+Decreased discharge (Equation 2.5)

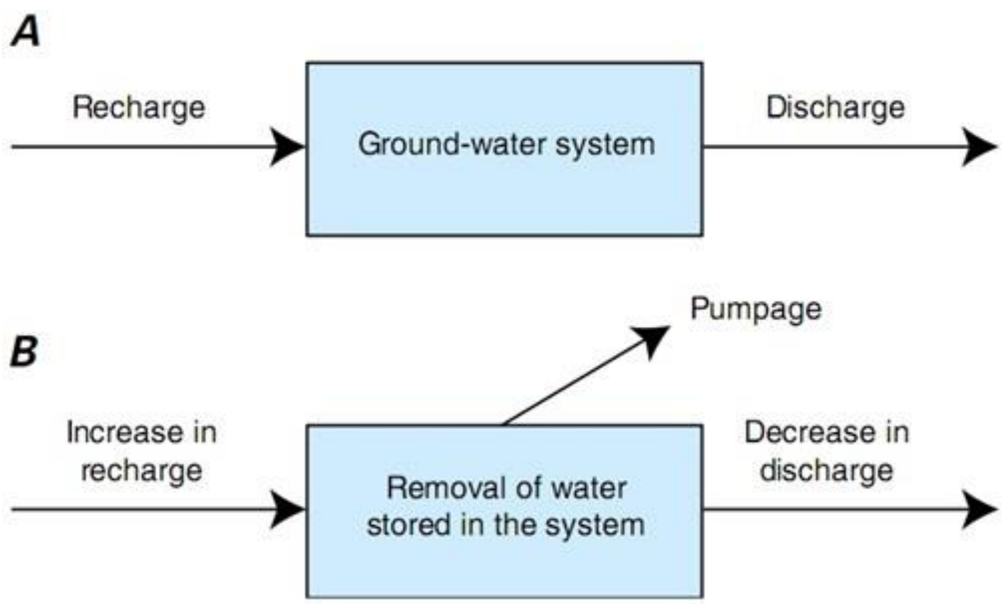

Figure 2. 3 Diagrams illustrating water budgets for a groundwater system for A) predevelopment and B) development conditions [14].

Nevertheless, the storage changing in groundwater system for pumping is a transient phenomenon. If the system can come to a new equilibrium by managing relativity of storage, recharge, and discharge evolve with time. The storage changing will stop and inflows will balance outflows, as shown in following equation:

Pumpage = Increased recharge + Decreased discharge .... (Equation 2.6)

However, it is difficult to determine the water systems in the aquifer. In general, natural inflow is actually recharged from precipitation. Thus, the amount of inflow is relatively fixed. Furthermore, the primary sources of any water pumped from this groundwater system are removal from storage. But some cases, it returns to the groundwater system as irrigation return flow. Most other uses of groundwater are similar in this case. Some groundwater systems can reach a new equilibrium after a period of removing water from storage, by decreased discharge to streams, and decreased transpiration by plants rooted near the water table. If the consumptive use is large, a new equilibrium of the groundwater systems become unstable, water will be removed from storage. In other case, less water will be available for surface water users and the ecological resources dependent on stream flow. The interaction between domestic use water and the effects of withdrawals on the environment often become the driving factor in determining a good management scheme. Thus, the available groundwater estimation becomes necessary for developing sustainable management strategies [14].

2.2 Geoinformatics

Geoinformatics is the science and the technology which develops and uses information science, Raju [15] has described geoinformatics as "the science and technology dealing with the structure and character of spatial information, its capture, its classification and qualification, its storage, processing, portrayal and dissemination, including the infrastructure necessary to secure optimal use of this information". According to Ehlers [16] described as "the art, science or technology dealing with the acquisition, storage, processing production, presentation and dissemination of geoinformation". Main branches of geoinformatics include: geographic information system (GIS), remote sensing (RS), and global positioning system (GPS).

2.2.1 Geographic Information System

2.2.1.1 Definitions

Geographic Information System (GIS) is an information system for collecting, storing, and analyzing. It is capable of searching and updating data, and displaying on spatial data which are linked to attribute data, which make it more accurate [17]. Generally, there are many definitions about GIS, For example, ESRI [18] defined GIS as “an integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information so that it can be displayed and analyzed”. According to USGS [19] , who defined as “a computer system capable of capturing, storing, analyzing, and displaying geographically referenced information; that is, data identified according to location. Practitioners also define a GIS as including the procedures, operating personnel, and spatial data that go into the system”.

These definitions are similar and associated. ITC [20] interpreted three important stages of geographic working as following:

The first stage was data preparation and entry. The data were collected and prepared to be entered into the system.

The second stage was data analysis. The collected data was carefully checked for accuracy and attempts were made to discover patterns.

The final stage was data presentation. The results of earlier analysis were presented in an appropriate way.

2.2.1.2 Components of GIS

ESRI (2012) [18] mentioned that the general components of GIS consist of five keys as:

Hardware: It uses to store data and process software. Some hardware also use to convert data from analog into digital form such as a digitizer, scanner and other device

Software: In GIS software, it consists of the programs and the user interface to generate, store, analyze, manipulate and spatial presentation. It is essential for driving the hardware.

Data: The data is important to GIS. The data collected from field investigation, was converted to spatial data and attribute data. Data can be stored in database, and GIS can integrate data resources in order to use in a database management (DBMS).

People: People are the most important component of GIS. Before GIS processing, people are the only component which is able to design, programming, operating and management for the others GIS component.

Procedure: It was link between people component and others. After an implementation plan and rules, the GIS models and operation in the project was created for work, which has relationship with data, software, hardware, people and other resources in the project.

In addition, some organizations described the network as the sixth key, because in the present, the rapid communication and sharing digital information and data in the internet is necessary. Furthermore, GIS applications in the network and mobile phone are created for simply used in the future [21].

2.2.1.3 GIS techniques and database

GIS uses space and time as the primary key index for all other information. Just as a relational database (string or numbers), it can relate many sub tables using common key index. The key in GIS is the location and/or extent in space-time and it is recorded as dates/times of occurrence. In addition, GIS recorded x, y, and z coordinates representing as longitude, latitude, and elevation, respectively (Bettinger and Wing, 2004). A key index can be classified into two types of the GIS storing data; spatial database and attribute database (Figure 2.4).

Figure 2. 4 The GIS storing data as spatial database [17].

In spatial database, it stores a database as representations of geographic phenomena in the real world which focus on the functions as storage, integration, and querying. Moreover, it provided to support spatial reference system analyzed functionality like geometric computation (distance and area), spatial interpolation, digital elevation model etc. In the spatial database design, it depends on geographic phenomenon. Some object was better represented as a point, as a line, as a polygon or as an image. Then, the spatial data are stored in a spatial database which the relevant in 2D (x, y) or 3D (x, y and z) coordinates as raster data and/or vector data (ITC, 2001). The difference between raster data and vector data was a data characteristic. Raster data were stored as a grid, pixel or cells having digital values, and represented on maps which were continuous across an area such as satellite images and digital terrain modeling. Meanwhile, vector data, was stored as a series of x and y coordinates which was used to represent on maps as, point features are a single location, line features are linear features or un-enclosed area and polygon features are enclosed homogeneous areas [22].

All of the above, spatial data were store in a form of spatial database which related to attribute tables that was called “attribute database” or “relational database”. It has a collection of data tables in the database which were organized using the relational model. In the relational model, a primary column was used to identify a row called the primary key, and a foreign key can relate to the primary key by using ID number or keywords [23].

2.2.2 Remote sensing

2.2.2.1 Definitions

Remote sensing (RS) was the use of an instrument, such as a radar device or camera, to scan the earth or another planet from space in order to collect data about some aspect of it [24]. According to Sanderson [25] , who defined remote sensing as “the collection and interpretation of information about an object, area, or event without being in physical contact with the object”. Thoroughly, remote sensing is a technique used to observe the earth surface or the atmosphere from the space using satellites (space borne) or from the air using aircrafts (airborne). Remote sensing uses a part or several parts of the electromagnetic spectrum. It records the electromagnetic energy reflected or emitted by the earth’s surface. The amount of radiation from an object (called radiance) is influenced by both the properties of the object and the radiation hitting the object (irradiance). The human eyes register the solar light reflected by these objects and our brains interpret the colors, the grey tones and intensity variations [15]. According to the explanation of NASA [26] which defined as “instrument-based techniques employed in the acquisition and measurement of spatially organized (for the Earth, most commonly geographically distributed) data/information on some properties (spectral; spatial; physical) of an array of target points (pixels) within the sensed scene that correspond to features, objects, and materials, doing this by applying one or more recording devices not in physical, intimate contact with the item(s) under surveillance; techniques involve amassing knowledge pertinent to the sensed scene (target) by utilizing electromagnetic radiation, force fields, or acoustic energy sensed by recording cameras, radiometers and scanners, lasers, radio frequency receivers, radar systems, sonar, thermal devices, sound detectors, seismographs, magnetometers, gravimeters and other instruments".

2.2.2.2 Types and data of Remote Sensing

RS sensors are a gadget that measures and records electromagnetic energy. It can be divided into two types; passive sensors and active sensors. The difference between passive sensors and active sensors is a mechanical characteristic. Passive sensors depend on an external source of energy especially the sun, but active sensors have their own energy source because active sensors do not depend upon varying illumination conditions, they are more controllable. However, these RS sensors are different because of applications depending on the data type that the researcher wants to collect, it can be described in terms of spatial, spectral and temporal resolution (Figure 2.5) [25].

• Spatial resolution

The spatial resolution (ground resolution) may be described as the ground surface area that forms one pixel in the satellite image/ or the instantaneous field of view (IFOV) of the gadget sensor. For example, the Landsat Thematic Mapper (TM) sensor has the IFOV /ground resolution which is 30 m. For some satellite types, such as weather satellite, the ground resolution sensors are often larger than a land survey satellite. It can be larger than a square kilometer. In military satellites, they are able to the collect data at less than one meter ground resolution.

• Spectral resolution

The spectral resolution is the number and width of spectral bands in the sensing gadget which rely on a type of satellite, for example, the Landsat TM has seven spectral bands varied in the visible and near to mid infrared spectrum parts. In the simplest form, such as photograph from an aircraft, the sensor has only one band which senses visible light, appearance to a black and white image.

• Temporal resolution

Temporal resolution is a measurement of the frequency of satellite orbit when it repeats a cycle to the same part of the Earth's surface. The frequency will vary from several times per day depending on satellite types. In weather satellite, it varies from 8 to 20 times a year. And in a moderate ground resolution satellite, such as Landsat TM, varies from 20 to 25 times a year (15 days per a time). In conclusion, the satellite sensor design and its orbit pattern determined the frequency characteristics.

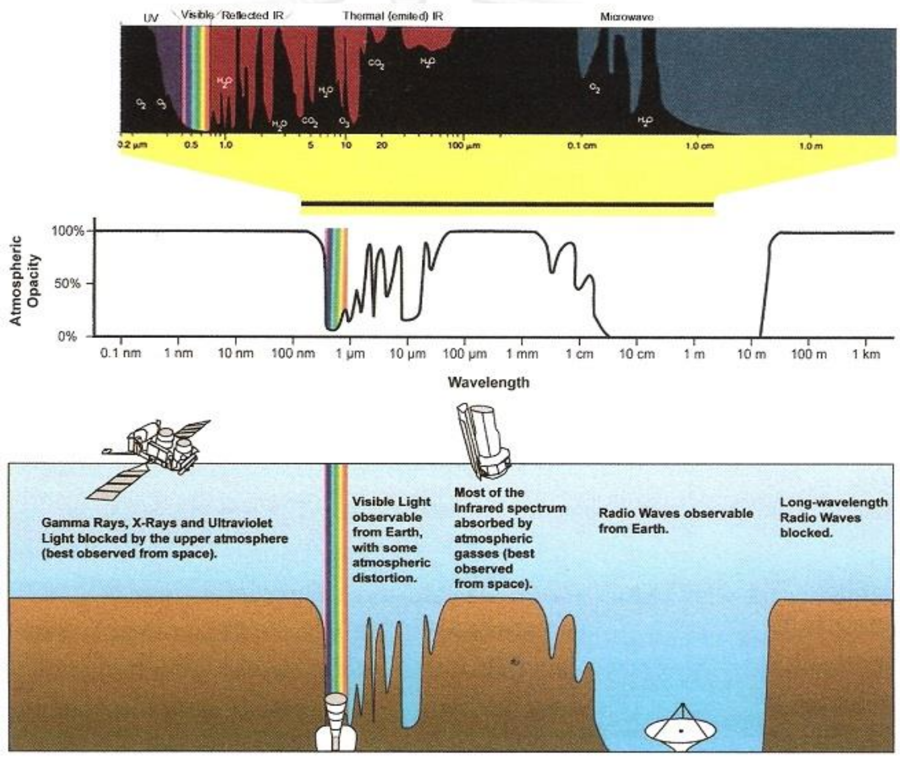

Figure 2. 5 A various wavelength region of the electromagnetic spectrum [17].

2.2.2.3 Remote sensing techniques

Aggarwal [15] described that remote sensing techniques are the techniques that take the earth surface images in various wavelength region of the electromagnetic spectrum (EMS). Stages in RS have briefly reviewed as:

• Emission of electromagnetic radiation (EMR) from the energy sources such as the sun. In active remote sensing, the energy is transmitted from the vehicle itself.

• Transmission of energy from the source to the earth surface such as absorption of a water body platform and scattering of a building platform.

• Interaction of EMR with the surface of the earth by reflection and emission. Some images, it represents reflected solar radiation in the visible wavelength and the near infrared wavelength regions of the EMS.

• Transmission of energy from the surface to the remote sensor.

• Sensor data output to the user.

In RS data, it contains both spatial properties (size, shape and orientation) and spectral properties (tone, color and spectral signature). These properties can be detected by the remote sensor and the interpretation. On interaction, it depends on a number of changes in magnitude, direction, wavelength, polarization and phase in the object of interest. The spectral characteristics of the three main earth surface features are briefly reviewed below (Figure 2.6):

• Vegetation

The wavelength region of the EMS varies with characteristics of vegetation. Chlorophyll in leaves effectively absorbs radiation in the red and blue wavelengths, on the other hand, it reflects green wavelength. Thus, the internal structure of leaves acts as diffuse reflector of wavelengths. The healthy leaves and/or rich plants of land cover acts as diffuse reflector of near infrared wavelengths.

• Water

The interaction between the EMS and the water characteristics can be detected because water body is not reflected the radiation but it absorbed or transmitted. In addition, water can absorb the wavelengths which were longer than visible light and the near infrared radiation more effectively than the visible wavelengths. Thus, water is blue, blue green or darker depending on stronger reflectance at these wavelengths. The factors can be able to determine a water body characteristic such as depth of water, materials within water and surface roughness of water.

• Soil

The soil's characteristics that determine its reflectance properties depend on its moisture content, organic matter content, texture, structure, iron oxide content etc. Thus, the interaction between the EMS and the soil characteristics is either reflected or absorbed, but EMS is hardly transmitted soil.

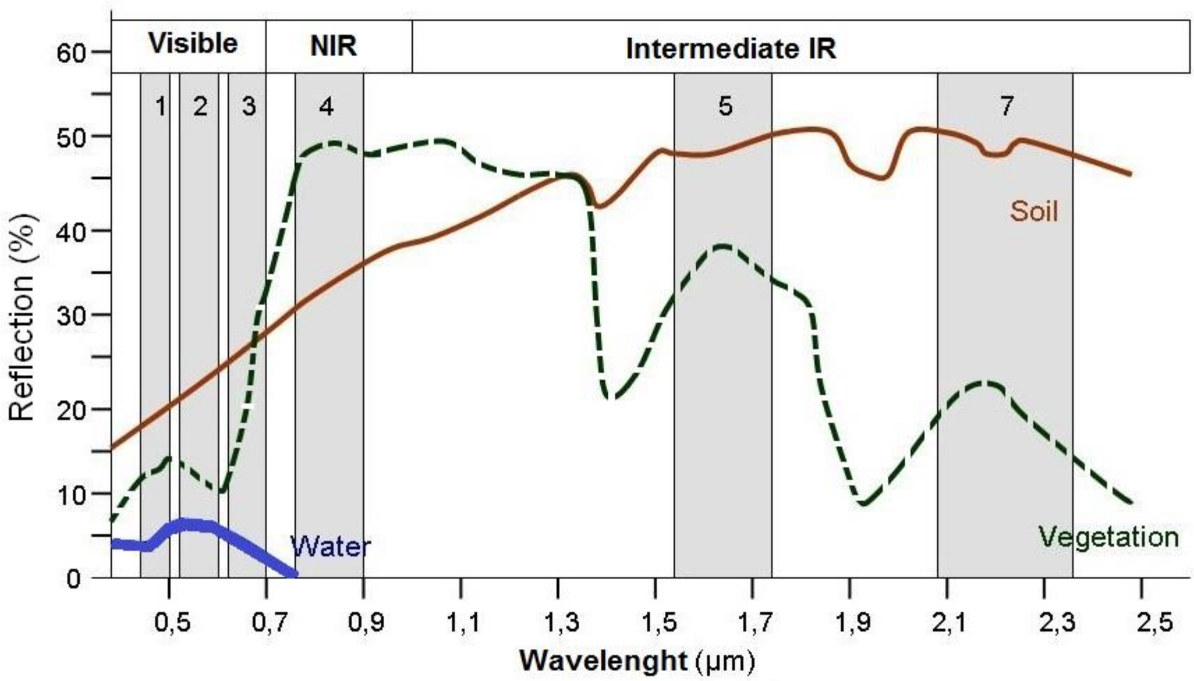

Figure 2. 6 Spectral signatures of soil, vegetation and water, and spectral bands of ETM+ LANDSAT [17].

2.2.3 Global positioning system

2.3.3.1 Definitions

The Global positioning system (GPS) has allowed suitable, inexpensive, and highly accurate measurement of absolute location. GPS has potential to improve remote sensing data. These tools are inexpensive and easy to use. They can be worked in nearby any area on the earth’s surface [27].

Sanderson [25] described GPS that a satellite system gives real times three dimensional X, Y, and Z coordinated at sub-meter accuracy. There are currently twenty-four GPS satellites orbit around the earth. Moreover, the position on earth was calculated by A GPS receiver from radio signals broadcast, which is able to measure a position within centimeters. However, the accuracy suffers due to errors in the satellite signals can be caused by atmospheric interference, proximity of mountains, trees, or tall objects. In addition, differential GPS can be used to improve the accuracy of the real position data.

2.2.3.2 GPS Overview and Techniques

GPS has been developed by the US department of Defense USA since 1973. It consists of 24 satellites at an altitude of 20,200 km above the mean sea level. Four satellites are arranged in six orbits above the horizon anywhere above the earth, at any time of the day. Because of the high altitudes and no atmosphere drag, GPS satellite orbits are stable. However, the impact of the sun and moon on GPS orbit it significant.

GPS Satellites system have two types of transmit code is P-code and C/A code, which frequencies to transmit is L1=1575.42 MHz and L2=1227.6 MHz. In addition, the high frequency L1 and L2 carrier signal is strong enough to pass through the ionosphere to reduce noise effects. Dual frequency observations are necessary for large station separation and for adjusting of the error parameters.

The GPS satellites perform as reference points when receivers on the ground detect their positions, and the distance between the satellite and the GPS receiver plus a little corrective term in pseudo ranging. Ground stations accurately monitor the satellite’s orbit by measuring the transmitting time of the signals from four distances of the satellites, which is necessary for solving clock synchronization error between receiver and satellites, with accurate position, direction and speed. This technique is the fundamental of navigation principle. It is based on the measurement of pseudo ranges between the user and four satellites [15].

2.2.4 Use of Geoinformatics in groundwater resource assessment

Geoinformatics are useful instrument to derive on the spatial-temporal of groundwater resource study, both local and regional scale, both short and long term. Until now, a study has been carried out by organizations and institutions around the world. It has concentrated on the application of groundwater resource management.

For many large sites, a great amount of data were collected, some complicated sites may have 20 to 50 monitoring wells. Each well can have assorted with it a lithological log and data sets, each well may be sampled and recorded for groundwater data in many times perhaps seasonally for several years, each site will also have topographic information and spatial features such as landuse platform, infrastructure platform etc., all of these becomes large data to organize, store, and display as database by GIS. It can be stored, analyzed, and displayed multiple layers of spatial information. In addition, based on maps of the earth, data for analysis can be attached to each well such as depth of groundwater, groundwater table, stratigraphy, soil and groundwater in terms of quality and quantity [1]. Furthermore, GIS can be integrated with mathematical model for groundwater assessment. It can generated three-dimensional views of subsurface data. It can also illustrate the site stratigraphy in three dimensions. It has algorithms that can be used to calculate masses [5].

In RS technique, satellite image data are used to investigate the groundwater, a case study in the probability of groundwater concentration. For example, (1) multispectral images that clearly delineate the surface features and allow the interpretation of their geologic history; (2) thermal images that show the spatial information of hydrologic accumulation both above and below the surface, which may correlate with groundwater aquifers, such as surface runoff, infiltration, groundwater recharge, seepage of groundwater into the water body etc.; (3) radar data that penetrate the landuse/ land cover to interpretation the topography and geomorphology. And (4) elevation data that describe the direction of water flow, both surface water and groundwater. These techniques were used to interpret data. Then, it was correlated with a GIS allow defining the best way to utilize the groundwater resources [28]. In examples and many previous studies, it showed that satellite data has been proven to be very useful for surface study, it was used to define parameters controlling the characteristics and movement of groundwater such as geology, geomorphology, soils, landuse, slope, drainage features etc. The conclusion clearly showed that the RS technique provides suitable, simply, hasty and useful data on the groundwater assessment [29]. Furthermore, in a field investigation, it is necessary to identify the real environment in a study area in order to record the locations of wells or spatial surface pattern for raster classification, and obtain geometric reference data to check the accuracy of result environmental maps. Thus, planning for field investigation should be prepared to represent the physical environments in a study area. GPS is an important component of field investigation, the selection of a suitable system will depend on the project or research objectives and type of geoinformatics data. It is very useful tools to assess the imagery accuracy or spatial location in the real study area [30].

2.3 Mathematical model for groundwater balance assessment

2.3.1 WetSpass module

2.3.1.1 Model description

The spatial-temporal variation in the recharge due to surface feature as distributed land-use, soil type, slope, etc. is necessary and should be used for assessment in the groundwater systems. Many spatial mathematical model were used to analyze groundwater systems, such as WetSpass [31]. WetSpass is an acronym of Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State which was based on the time dependent spatial distributed water balance model “WetSpa”, aiming at water balance component simulation based on distributed data. WetSpass was completely integrated in the GIS as a raster model. Spatial parameters, such as landuse and soil type, are linked to the model as database of the land-use and soil raster maps [32].

The concept of this model shown that the total water balance for a raster cell (Figure 2.7) was separated into four sections: independent water balances for the plant, bare soil, open water and impervious parts of each cell which based on the resolution of the raster cell. The processes in each part of a cell are set on arrange of hydrological occurrence. For example, after the precipitation event, defining such an order as a first step for the steady timescales, another process will be quantified. A mixture of physical and experience relationships is used to describe the processes [32] .

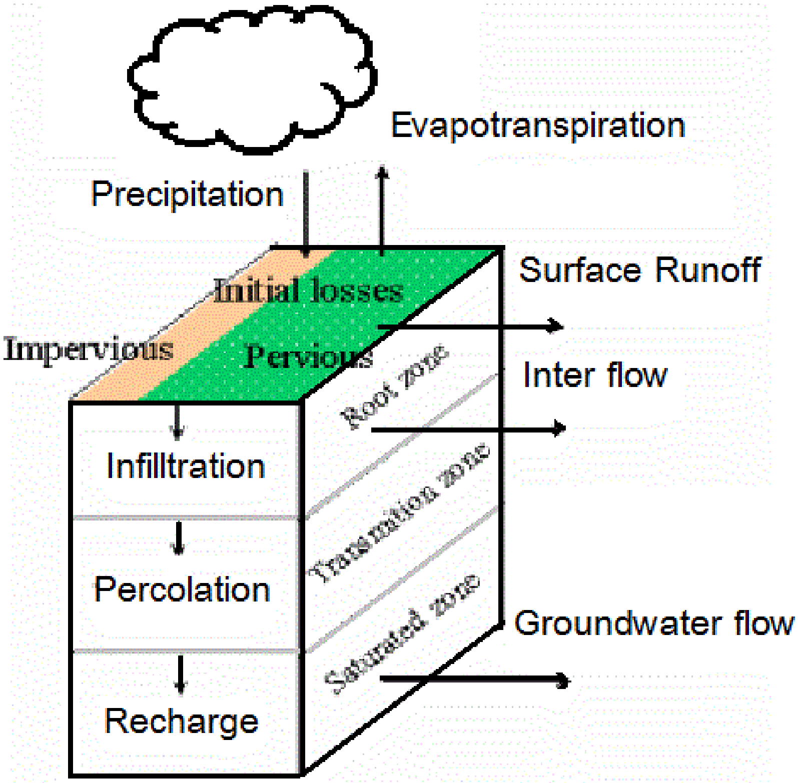

Figure 2. 7 Diagrams illustrating water budgets for a WetSPASS [32].

2.3.1.2 Water balance components

Batelaan and Smedt [32] described that the water balance equation for a vegetated surface in WetSpass module is given by:

$P = I + S_V + T_V + R_V$ .... (Equation 2.7)

where P is the average seasonal precipitation (LT^{-1})

I is the interception by vegetation (LT^{-1})

S_V is the runoff over land surface beneath vegetation (LT^{-1})

T_V is the actual transpiration (LT^{-1})

R_V is the groundwater recharge (LT^{-1})

The actual evapotranspiration (ET_V) is used to calculate the sum of the transpiration (T_V) and the evaporation from the bare soil between the plants (E_S). The total actual evapotranspiration (ET_{tot}) is the sum of the evaporation of water, which was minus by the interception (I) and the actual evapotranspiration. The interception is depending on the vegetation type, which is parameterized as a constant percentage from rainfall. In addition, it shows a compatible decrease with increasing annual rainfall total.

For surface runoff process (S_V), it is calculated in two steps. The potential surface runoff ($S_{V\text{-}pot}$) is calculated in the first step as a coefficient times the precipitation minus the interception under a function of surface types (vegetation, soil and slope). For example, the surface runoff coefficient is very high and assumed to be constant in groundwater discharge areas, generally near to river position because it was reduced dependency by soil and vegetation type. Abovementioned, it is given by:

$$S_{V\text{-}pot} = C_{Sv} (P - I) \quad \text{(Equation 2.8)}$$

where P is the average seasonal precipitation (LT^{-1})
I is the interception by vegetation (LT^{-1})
C_{SV} is the surface runoff coefficient for vegetated infiltration areas
$S_{V\text{-}pot}$ is the potential surface runoff ($L^{-3}T^{-1}$)

In the second step, the potential surface runoff was the differences of spatial rainfall intensities, in relation to soil infiltration capacities. The cumulative high intensity rainfall amount in rainy season was much greater than in summer season. In addition, the high intensities of rainfall contribute to high surface runoff in groundwater discharge areas. For each soil class, the rainfall intensity was also relevant with the infiltration rate. Hence, the surface runoff can be determined as the fraction of the seasonal rainfall when the intensity is higher than the infiltration capacity, which is defined as:

$S_V = C_{Hor}\, S_{V-pot}$ .... (Equation 2.9)

where S_V is the surface runoff ($L^{-3}T^{-1}$)

S_{V-pot} is the potential surface runoff ($L^{-3}T^{-1}$)

C_{Hor} is a coefficient that parameterizes the part of the seasonal precipitation which is actually contributing to the surface runoff

For evapotranspiration, WetSpass proposes to convert seasonal evaporation value using the Penman equation, to a reference transpiration value based on a vegetation coefficient as

$T_{rv} = c\, E_0$ .... (Equation 2.10)

where T_{rv} is the reference transpiration of a vegetated surface (LT^{-1})

E_0 is the potential evaporation of open water (LT^{-1})

c is the vegetation coefficient

For vegetation in groundwater discharge areas, the actual transpiration (T_V) is equal to the reference transpiration, if soil water availability is infinity, resulting in Equation 2.11. But, where the groundwater table is below the soil zone, the actual transpiration for vegetated areas is calculated as Equation 2.12:

$T_V = T_{rv}$ if $(G_d - h_t) <= R_d$ .... (Equation 2.11)

$T_V = f(\theta)T_{rv}$ if $(G_d - h_t) > R_d$ .... (Equation 2.12)

where G_d is the groundwater depth (m)

h_t is the tension saturated height (m)

R_d is the rooting depth (m)

T_{rv} is the reference transpiration of a vegetated surface (LT^{-1})

T_V is the actual transpiration (LT^{-1})

$f(\theta)$ is a function of the water content.

Abovementioned, from the water balance equation, groundwater recharge can be calculated as a residual term:

$R_V = P - S_V - E_{TV} - E_s - I$ .... (Equation 2.13)

where
R_V is groundwater recharge (LT^{-1})
P is the average seasonal precipitation (LT^{-1})
S_V is runoff over land surface beneath vegetation (LT^{-1})
E_{TV} is the actual evapotranspiration (LT^{-1})
E_s is the evaporation from the bare soil between the vegetation (LT^{-1})
I is the interception by vegetation (LT^{-1})

Furthermore, the seasonal and annual water balance per raster cell and can be calculated in WetSpass, using the water balance components for vegetated, bare soil, open water and impervious parts of a raster cell, it can be described as

$ET_{raster} = a_V ET_V + a_s E_s + a_O E_O + a_i E_i$ .... (Equation 2.14)

$S_{raster} = a_V S_V + a_s S_s + a_O S_O + a_i S_i$ .... (Equation 2.15)

$R_{raster} = a_V R_V + a_s R_s + a_O R_O + a_i R_i$ .... (Equation 2.16)

Where ET_{raster}, S_{raster}, R_{raster} are the total evapotranspiration, surface runoff and recharge in a raster cell, respectively, and a_V, a_s, a_O and a_i are respectively the vegetated, bare soil, open water and impervious area fractions of a raster cell.

As mentioned before, the methodology described the estimation of spatially distributed recharge as surface function of vegetation, soil type, slope, groundwater depth, seasonal precipitation and other dynamic climate. The highlight of WetSpass was results in the relationship between groundwater recharge and discharge, and water balance components in the study area. In some areas, a thin unsaturated zone also presented both discharge areas and recharge areas. Furthermore, in summer season, recharge rates may have a zero value or negative values, especially in discharge zone because of the high rate of potential transpiration in the vegetation. However, in rainy season, recharge will compensate the negative recharge.

In addition, WetSpass can describe changed in groundwater storage on a seasonal basis in two ways. First, the difference between groundwater levels in the rainy and summer situations can be described. Second, it assumed that during rainy season, the plants allow soil moisture reservoir increase and that during summer these reservoirs can be decrease.

2.3.2 Groundwater flow modelling

A groundwater model is a computer-based representation of the necessary features of a natural hydrogeological system that uses the rules of science and mathematics [33]. The objectives of the models, were to represent framework for planning and organizing field data. Then, system dynamics in the study area were formulated by models and presentation in simply form. Furthermore, models can be used to study process in other environmental setting as geology, hydrogeology, hydrology, climatology etc. [34].

Kumar [33] described the details of groundwater modelling principle as two key components of the groundwater model which are a conceptual model and a mathematical model. In the first step, for understanding of the groundwater processes in the system, the conceptual model was used to represent the hydrogeological in the study area, and the details of the conceptual groundwater system should approximates that of the behavior of aquifers. Secondly, this essential concept is useful to help decide and determine the mathematical model types to use. In a small scale than encountered in the study area, an analytical model was used to simplify assumptions to enable solution of given problems. It is usually solved rapidly, and it can be used with both computer and analog. However, in large study areas, a numerical model was used to describe the physical processes and boundaries of a groundwater system using one or more solving formulas as varying over space and time. This enables are more complex, and more potentially realistic, representation of a groundwater system. Generally, numerical models are solved by a computer. Thus, the accuracy of a groundwater model to determine real situation depends on the input data and the parameters. As many parameters are complex in space, user is needed to expert at representative values. Determination of these requires reviewing study. Lastly, the model represents the groundwater system to a sufficient level of results, and provides a predictive tool to determine the impacts on the system of specified hydrological, pumping or irrigation stresses.

For flow simulation, a mathematical model is used to represent the groundwater flow through an aquifer which is composed of geological setting. From acquired data, a groundwater flow model simulates hydraulic heads, groundwater table and ground water flow rates in the boundaries of the system under the setting condition. In addition, it can estimate the groundwater balance and movement times along flow paths. The conceptual model of the aquifer was used to analyze groundwater and solute fluxes between the groundwater system under the boundary condition, such as source and sink features (surface water bodies, pumping bores, reservoirs etc.) are considered to connect the groundwater modelling for reality [33]. In a logical sequence, groundwater modeling is most efficiently developed. Kumar (2006) [35] described developing stages of process have in briefly reviewed as Figure 2.8.

2.3.2.1 Groundwater flow equation in modelling

In the first stage, a conceptual model for understanding the physical situation was designed. The next step was adjusting the physical situation into mathematical conception. The results were the groundwater flow equation. From Darcy’s flow equation, the flow equation for three-dimensional saturated flow is [35]:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)-Q=Ss\frac{\partial h}{\partial t} \quad \text{............ (Equation 2.17)}$$

where

Kxx, Kyy, Kzz is hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity;

h is piezometric head;

Q is volumetric flux per unit volume representing source/sink

Ss is specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

t is times

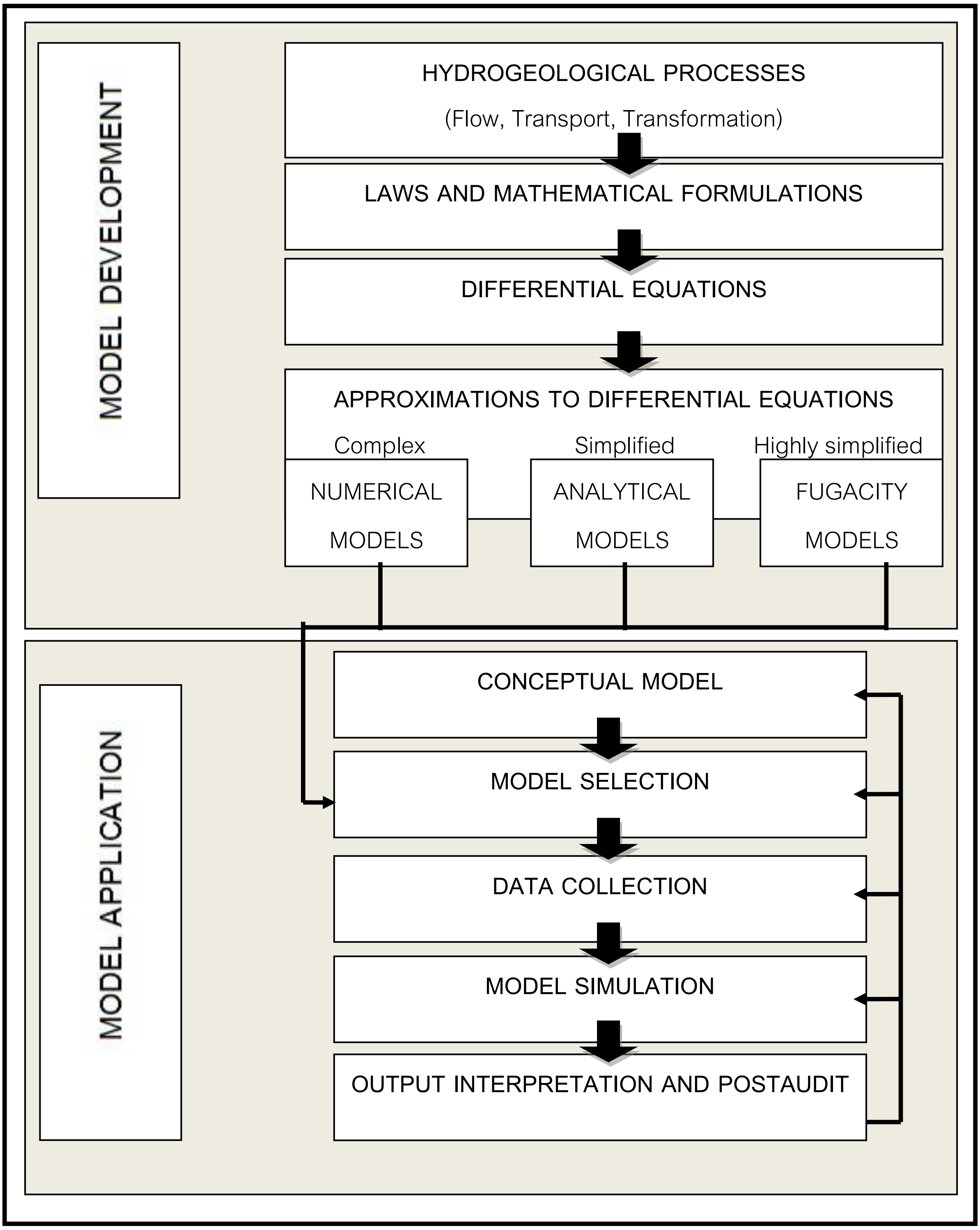

Figure 2. 8 Development process of a model [35].

In modelling, the flow region was subdivided into cells which were made from a grid. The medium properties and model layers are assumed to be uniform, but thickness was varying. In addition, a flow equation is written for each cell (Figure 2.9). Suitable solving method was provided to solve the resulting in matrix form, which the best solving method for the particular problem were depend on the user choosing. The results can be showed flow rate and quantity of water balances from each cell of inflow and outflow are computed for each stress period [33]. Thus, before solving a modelling problem, a coherence of suitable equations with the associated boundary and initial conditions was necessary. Most groundwater modelling studies were operated using numerical models for solving the problem, Finite Difference Method, Finite Element Method, and Analytical Element Method are three numerical techniques which can be distinguished. All techniques have their own advantages and disadvantages depending on availability, available data, expenditure, user suitability, applicability, and required expertise of the user [35].

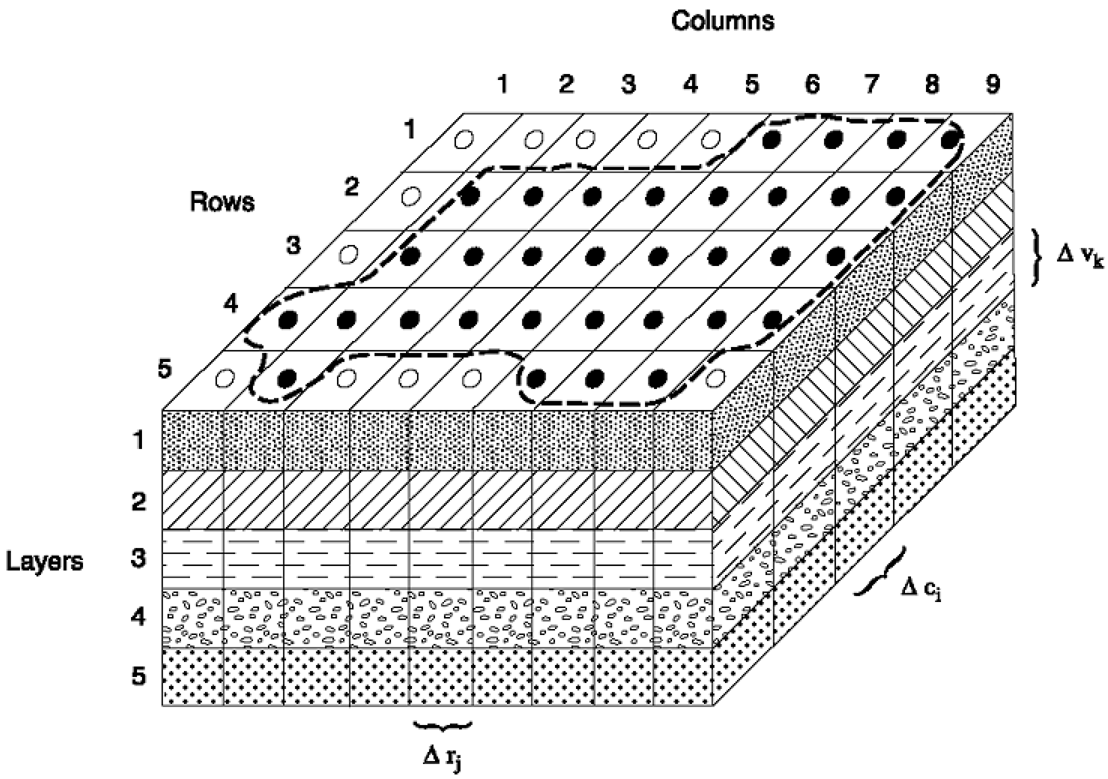

Figure 2. 9 Groundwater flow 3D grid [33].

2.3.2.2 Modular Three-Dimensional Finite-Difference Ground-Water Flow Model

The program which was widely used to establish numerical groundwater flow model was MODFLOW. MODFLOW is a three-dimensional model, originally developed by the U.S. Geological Survey [36]. The objectives in developing MODFLOW were to produce a mathematical program that can be simplified, readily modified and easily maintain. It can be operated on a variety brand and specification of software and hardware with minimal changes. Moreover, it has the ability to manage the large data sets when running equations for solving. MODFLOW can be simulate groundwater systems followed the objectives of research, such as groundwater flow, groundwater balance groundwater supply, groundwater contamination, including other application as containment remediation and mining wastering by using block-centered finite difference numerical techniques for saturated zone. However, the disadvantages of MODFLOW are surface runoff and unsaturated flows are not linked up this model. Hence, in case of transient state, if the flux at the groundwater table depending on the function is not known in detail, MODFLOW cannot be applied [35].

In MODFLOW, Layers can be generated as confined, unconfined, or a combination of both. In addition, other hydrogeological conditions such as flow to wells, recharge and discharge area, evapotranspiration, flow to drains, and flow through riverbeds can be generated in the finite-difference method. Generally, finite-different methods are only used on rectangular grids, but finite-element methods can readily be formulated on triangle grids. In grids, it has nodes which are the reference location of the finite-difference approximation for the derivative is written. In consideration of one-dimension (Figure 2.10), an approximation of second derivatives, especially found in the groundwater flow equations, will be the same regardless of whether the line is base or body centered. However, it is, $\Delta xi \neq \Delta xi+1$, when the body-centered line used variable web spacing. This is a conceptual advantage to the body-centered method. In consideration of in this regard (Figure 2.11) shows that the element of node ***i*** has the node in the center. Therefore, the two-dimension of the block-centered web was made up of boxes with the nodes in the middle. The mass balance was written at the edge of the boxes, and the fluxes at the side of the boxes are described by Darcy's law. Thus, it can be created the mass-balance equation for groundwater flow by approximating the fluxes in Darcy's law [37].

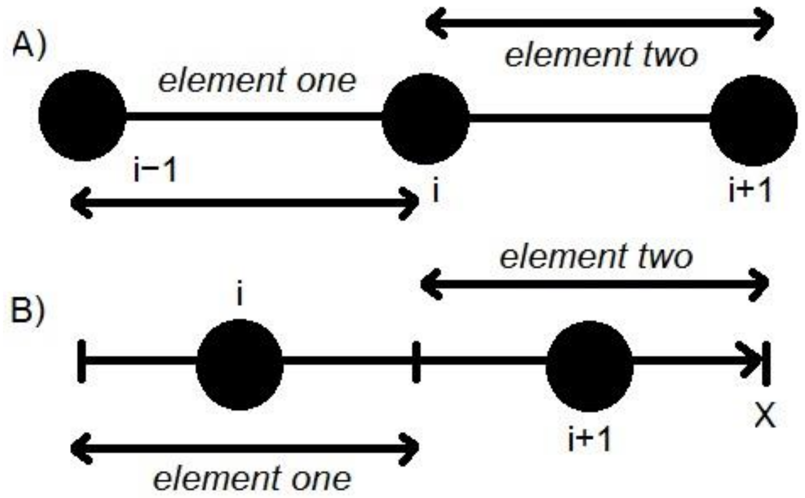

Figure 2. 10 Shows one-dimensional finite difference discretization as A) standard finite difference B) body-centered finite difference [37].

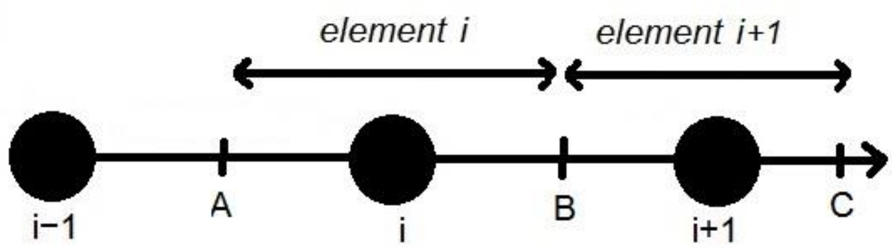

Figure 2. 11 Shows one-dimensional finite difference mesh with variable spacing [37].

In the modular structure of MODFLOW, it consists of a main Program called modules which are grouped in packages. Each package has a specific feature of the hydrologic system for solving problem. It can be simulated conditions with a specific method for describing the flow system. In the package selection, it depends on the user to examine specific features. The division of MODFLOW into modules permits the process independently. Furthermore, in model development, new packages can be added to the program easily. The input/output system of

MODFLOW is designed for suitable flexibility [33]. Most package of MODFLOW are shown in Table 2.2.

Table 2. 2 The following functionality that is documented in Harbaugh [38].

Packages	Descriptions
BAS	Basic Package
BCF	Block-Centered Flow Package
LPF	Layer-Property Flow Package
HFB	Horizontal Flow Barrier Package
CHD	Time-Variant Specified-Head Option
RIV	River Package
DRN	Drain Package
WEL	Well Package
GHB	General Head Boundary Package
RCH	Recharge Package
EVT	Evapotranspiration Package
SIP	Strongly Implicit Procedure Package
PCG	Preconditioned Conjugate Gradient
DE4	Direct solver

2.4 The previous investigations for groundwater flow, groundwater balance and groundwater recharge assessment

The previous investigations on groundwater balance assessment have been studied in many places of the world. Some important literatures have been briefly reviewed below in chronological order to be the background information.

Flugel and Michl [6] developed GIS technique for dynamic groundwater modeling in the alluvial aquifer of the River Sieg, Germany using “MODFLOW” and “IDISI”. Ten years databases (1984-1993) were prepared into spatial data, hydraulic conductivity was used to define recharge areas. Finally, steady-state and transient groundwater conditions were simulated, and these scenarios were calibrated using observations wells. The results showed that 30% of the precipitations in the area became groundwater recharge and 70% of the recharge came from the seepage from the river Sieg. The conditions simulation also showed that groundwater heads accordingly varied by seasonal, an effective and improved pre- and post-processing was obtained. In addition, the integrating with GIS and the numerical model were used to foundation for spatial groundwater modeling and hydrogeological study in the future.

Hassan and Bhutta [39] estimated the rate of the long term average seasonal groundwater recharge in Rechna doab, Pakistan using water balance model which developed in “FORTRAN 77”. Rainfall, evapotranspiration and runoff were used for water balance calculation, which was conducted on seasonal basis (6 months) for a period of 31 years (1960-1990). For comparison, recharge was also estimated by a specific yield method from 34 observation wells groundwater levels. The results showed that seasonal rates of groundwater recharge varied from 10 to 120 mm., the average value of net groundwater recharge during wet season (April-September) had a value 60 mm. However, in summer season (October-March), recharge did not occur, which influenced a depletion of the groundwater reservoir. The groundwater storage in the area was being decreased about 2.3 m fall over the 1960-1990 periods.

Smedt and Batelaan [40] evaluated changing in the groundwater systems which have been induced by human activities in the Dijle basin, Belgium using WetSpass. Based on remote data of 1995, 18 land use classes, they can be grouped into 4 major categories as agriculture areas (48.6%), forest areas (25.3%), urbanized areas (24.9%), and open water (1.2%) In addition, they were used to evaluation. However, the hydrological and hydrogeological settings were complex because the land use was strongly affected by urbanization, industrialization and agriculture. Finally, the results showed that the groundwater recharge rates which varied from 0-250 mm/y, with an average value of 166 mm/y or 22% of the total precipitation. In natural conditions, the groundwater recharge was an average value of 199 mm/y or 26% of the total precipitation. The results also showed that the effect of urbanization was the main cause of the significant reduction in groundwater recharge. All urban land-use classes yield lower recharge rates ranging from about 0-100 mm/y. The remaining 10% of recharge occurred in the center of urban area. However, it was difficult to determine the relationship between an effect of plant-cover area and groundwater recharge. Based on the results, the following study needs to be determined the interaction between an effect of plant-cover area and topographical feature which influences the groundwater recharge.

Portoghese, Uricchio and Vurro [41] evaluated hydrogeological water balance based on a mass-balance model in the southern Italy. The GIS tool was designed for analyze the groundwater resource planning during water shortage periods. The natural groundwater recharge was evaluated using a soil water balance equation, which was the difference between the inflows and the outflows. Conversely, the groundwater balance was calculated using a lumped water balance equation, which estimated together with inflows from other water bodies and coastal outflows. Finally, the interaction of surface and subsurface systems was discussed. The results showed that the averaged groundwater balance was in agreement with the piezometric head and chlorine concentration trends measured in selected 4 monitoring wells, the natural recharge ranges from 16.6% to 30.3% of the total precipitation, as a consequence of the geomorphologic features. In the study area, The Tavoliere hydeogeological unit had the highest flow rate which was about 28% of the total precipitation, but lowest of the recharge which was about 16.6%, that mean the geologic features is major controls of the recharge process in the study area.

Idrysy and Smedt [10] simulated groundwater flow condition in Trifa agricultural plain of north-eastern Morocco using “MODFLOW and WetSpass”, was contained with two main layers namely; the Quaternary deposit and the Secondary deposit. The model was calibrated and verified using groundwater head from 46 observation wells from 1995-1996. In addition, relevant parameters were assessed by WetSpass module; rates of recharge and groundwater pumping were estimated and filled in the MODFLOW for groundwater balance assessment. The results showed that the groundwater flow direction was from the highest levels in the south at about 200–280 m. asl, toward the center of the Trifa plain at about 80 m. asl, and decreased in different directions to the rivers in the west and the east at elevations of 50–20 m. asl. The results also showed that the water balance in the study area. The groundwater recharge, which occurs mainly in the wet season, varies from 150-200 mm. per year. The amount of groundwater used for irrigation was considered as the quantity of water needed to meet the potential evapotranspiration demand, which varied from 0-500 mm. per year. For these results, it showed the instability in the study. The outflow from the groundwater abstraction (about 83 Mm^3/y) was higher than the inflow from the recharge (about 68 Mm^3/y). Hence, imported water from outside the study area was necessary for irrigation. In addition, a reduction in groundwater abstraction by at least 25% may be necessary to achieve sustainable conditions.

Wang et al. [42] integrated MODFLOW with GIS for groundwater flow condition and groundwater balance in the North China Plain, which contained with three unconsolidated sediment aquifers. Parameters and hydrogeologic condition were set up on the basis of the conception model, recharge and discharge package was adopt to achieve the data input. Furthermore, various GIS techniques were used to study the groundwater condition such as computer languages, database management and Cato Web design etc. Finally, the simulation period was from 1 January 2002 to 31 December 2003, and the calibration was estimated value with observed value. The results showed that the groundwater flow directions were in accordance with the practical hydrogeologic conditions, and the water balance results showed that the shortage of the budget. The total recharge in the study area was 49,374x$10^6 m^3$, and the total discharge was 56,530X$10^6 m^3$, which the difference was 7,156x$10^6 m^3$. This verified the groundwater in the North China Plain P was over-exploited and the water crisis was serious.

Tilahun and Merkel [43] estimated the groundwater recharge in Dire Dawa, Ethiopia. WetSpass model was used to simulate the long-term average recharge using land-use, soil texture, topography, and hydrometeorological parameters. In addition, WetSpass is a physically based methodology for estimation of the water balance components, the long-term average spatial distribution of surface runoff and actual evapotranspiration were estimated for correlation of the groundwater recharge. The results showed that the long-term temporal and spatial average annual rainfall of 626 mm (100%) was distributed as: surface runoff of 126 mm (20%), evapotranspiration of 468 mm (75%), and recharge of 28 mm (5%), which the recharge rate of 817 l/s was less than the currently assumed recharge of 1,000 l/s. The future groundwater development and management in the area should take this into account.

Abu-Saleem et.al [44] estimated water balance components in the Hasa Basin, the long-term average spatial distribution of surface runoff, actual evapotranspiration and recharge were simulated using WetSpass Model. DEM, land use and soil data were prepared into 90 grid cell size spatial data, and the model was simulated base on quasi-steady state time. The results showed that the average annual groundwater recharge ranged from 0-12.83 mm, with an average value of 0.976 mm/yr, and the annual surface runoff showed that average value of 23.64 mm/yr. However, the average annual evapotranspiration ranged from 19-593 mm, with average values of 128.68 mm/yr which accounts for more than 80% of the total annual rainfall, this showed that evapotranspiration is the main process that water is lost in the basin.

For the international previous investigations, it is necessary to integrate the numerical groundwater model with the Geo-Informatics technology because the high ability function of GIS is useful to define the relationship between the actual spatial area and model simulation. And the groundwater recharge is also an important parameter in groundwater flow and transport models because groundwater potential is directly dependent on recharge. In Thailand, the literatures on groundwater flow and groundwater balance assessment and similar cases are also reviewed in chronological order as below.

Sont Chindasanguan [45] simulated groundwater flow condition in Kamphaeng Phet province using “MODFLOW and GMS”. According to geological, hydrological and geolophysical review, the hydrogeological conditions were set up into 3 layers, as unconfined aquifer is the first layer, and confined aquifer are the second and the third layers, which were formed with the slope from West to East. Data from the experimental wells of the year 1995 to 1997 were collected and used to calibrate parameters in order to obtain a suitable set of model parameters. The parameters resulting from the calibration were found to be as, the hydraulic conductivity is 70 m/day, the transmissivity of these aquifers is 560 m^2/day, the storage coefficient in first and second layers was 0.0034 and 0.0015 , and the percent of pumping rate is 50% and 20% of the overall groundwater demand. The results showed that an annual groundwater level decreasing with the rate of 1-2meters because of pumping for agriculture, especially in Ampour Muang, Ampour Lankrabue, Ampour Sringam and Ampour Thungsry. The suggestion in this study advised to control and reduce pumping rate for 5% per year for 3-4 years.

Panot Siriputtichaikul [12] simulated groundwater flow condition in the upper part of lower central plain, Thailand. Because of the constraint of limited observed well data and specific conditions in the study area. Parameters were estimated for groundwater modeling such as hydraulic conductivity and consumption groundwater use. The water situation in 1999 was used to calibrate the steady state, while the observed well data in 2000-2001 were used to calibrate for unsteady state. The results indicated that those periods (1989-1999), groundwater use in the area increased from 300 to 800 MCM. As a result of pumpage increasing, groundwater level tended to decrease to 2-10 m, especially in Singburi and Ang Thong Provinces. In addition, the model results were used to form an empirical relationship between groundwater level and significant factors, which found that the seasonal recharge and groundwater use in the study area have an effect on groundwater balance. High domestic use in dry period caused depletion of groundwater level. However, in wet period, groundwater level was filled because of high recharge and low domestic use.

Arun Lookjan [46] applied numerical model “MODFLOW” for groundwater flow, seawater intrusion and the study of water balance in the Hat Yai basin. This basin was contained with three main unconsolidated aquifers namely; Hat Yai aquifer, Kutao aquifer, and Korhong aquifer. The model was calibrated and verified using groundwater head and chloride concentration data from 47 monitoring wells from 2002-2008. In addition, the rate of groundwater recharge was assessed by water balance equation. Rainfall data, evaporation data, and runoff data were prepared and filled in the recharge module. The results showed that the groundwater flow direction was from the recharge areas in the east, the west and the south toward the center of the basin and to areas. The groundwater recharge had a value 134 MCM per year or 7.64 % of the total rainfall, total inflow and outflow were 115.00 Mm^3/yr, and groundwater safe yield of the Hat Yai basin evaluated using the developed model was 36 Mm^3/yr. The simulation results also indicated that for projected groundwater pumpage of 5 and 10% annual increment, a drawdrown of 5 meters at Hat Yai city was observed at Hat Yai City within 8 and 6 years, respectively. Futhermore, the results showed that seawater intrusion simulated from current pumpage, affected areas covered the distance of approximately 7.59 kilometers inland from the Songkhla Lake.

Furthermore, the literatures on background in the study area have been briefly reviewed as below.

Amares Boksuwan [7] characterized the drought condition in the Yom watershed which overlay with the Phrae aquifer and Chao Phraya aquifer, according to the drought detection index. The availability of water by rainfall and runoff was assessed and compared with water consumption in all activities in the Yom watershed. The results were found that many parts of the area, especially in

Sukhothai and Phrae provinces had the drought in early raining and summer season because of low amount of rainfall. In addition, it was found that there was a decreasing trend of annual rainfall about 1-14 mm. per year and the runoff in dry season had continuingly decreased due to increasing of water uses.

According to study of Wiroj Pitaksaithong [8] this study focused on a simple surface water balance in Yom watershed. Rainfall data and stream flow data were used to statistical analysis according to the hydrological principle. The water balance conditions were made in 3 scenarios, as the average year (2001-2002), the dry year and the wet year. The water balance component resulting from the studies were found to be as, the reference evapotranspiration which was calculated by the Modified Penman method with the average value 1,588 mm/yr, while the average annual rainfall was 1,119 mm/yr, the average crop water requirement was about 5,440 MCM per year, and the water consumption was about 5,478 MCM per year. Finally, the results showed that the total amount of water in the watershed was lost through evapotranspiration (41.5% - 45.6%). About 16.6 - 18.2 percent was consumptive use, 5.2 - 20.2 percent was infiltration and groundwater recharge, and 16.7 - 35.0 percent was runoff. Furthermore, the results showed that most of the watershed areas were shortage of water in the dry season and the beginning of wet season because the water requirement was higher than the available rainfall, especially in the middle and the lower watershed areas.

All of the above, the groundwater balance study to plan for the sustainable is necessary to be assessed in terms of spatial interaction between recharge and discharge. GIS and mathematical model as MODFLOW should be used to apply in storage, manipulating, and analyzing the digital data for better efficiency.

CHAPTER III
SITE DESCRIPTION

Literature reviews of previous works in the study area are necessary to understand clearly the physical features. From data preparation, thematic data mapping was used to discuss the relationship between existing parameter and physical feature in the study area. Meanwhile, the conceptual model determination for groundwater flow modelling is also reviewed. In addition, the detailed statistical analysis of maps of this study area was explained in the following chapter.

3.1 Location and Topography

Phrae province is a dominant feature of Northern Thailand. The Plateau has an area of approximately 6,483 km^2 or about 24 percentage of the total area of the Yom Watershed, which reaches a maximum elevation of 1,633 meters attitude sea level (a.s.l) in the northern part. The altitude gradually decreases in the southern part where it is 150 meters (a.s.l). The site lies between X UTM 1950000 – 2075000 N and between Y UTM 535000 - 662500 E. The Phi Pan Nam Mountain ranges from northern to southern in the west. It separates the west of the province from the Wang watershed. The Phu lueng Mountain ranges from northern to southern in the east. It separates the east of the province from the Nan watershed. The eastern part of the province is connect to Phayao province. In addition, a The Phi Pan Nam Mountain range divides the Phrae groundwater basin into three sub-basins: the Ngao Sub-basin (approximately 1,524.06 km^2), the Phayao Sub-basin (approximately 2,765.47 km^2) and the Phrae Sub-basin. The major fluvial system drains the Phrae Sub-basin is the Yom River, which originates in the northern Phi Pan Nam Mountain ranges of the Yom watershed. The river flows through Phrae and Sukhothai provinces before it joins the Nan River at Chum Saeng district, Nakhon Sawan Province [47]. In the center of the study area consists of gentle slopes that range between 0 to 5% whereas the mountainous surrounding area consists of steep slope that range between 15 to greater than 40%. For using topographic features data, and instead of using a topographic map, the contour data was converted into a color-coded continuous map (DEM), which represented the topographic characteristics in the area such as topography, topographic profile and slope as shown in Figure 3.1 and Figure 3.2.

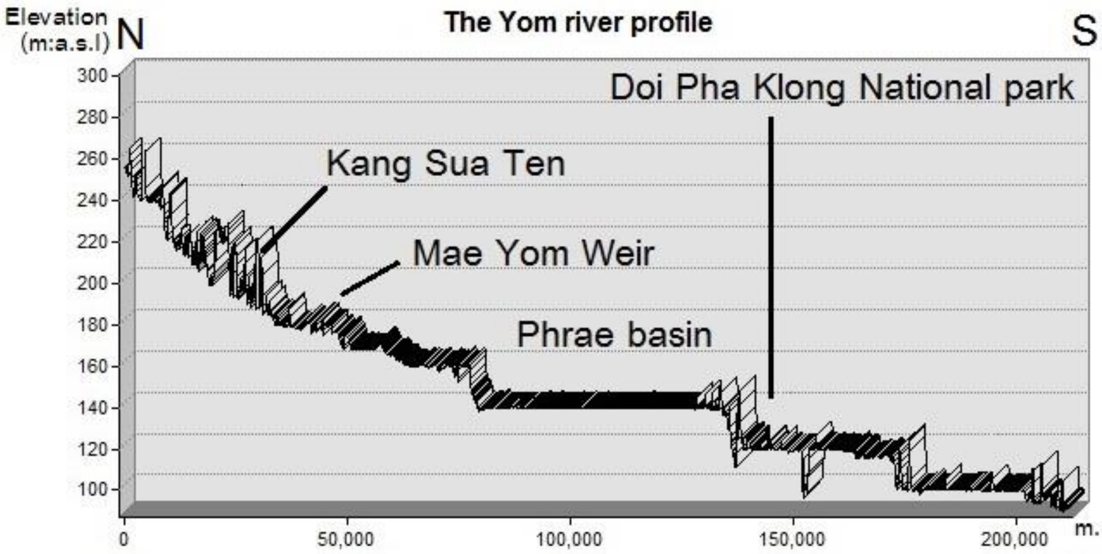

Figure 3. 1 Show the Yom river profile of the study area.

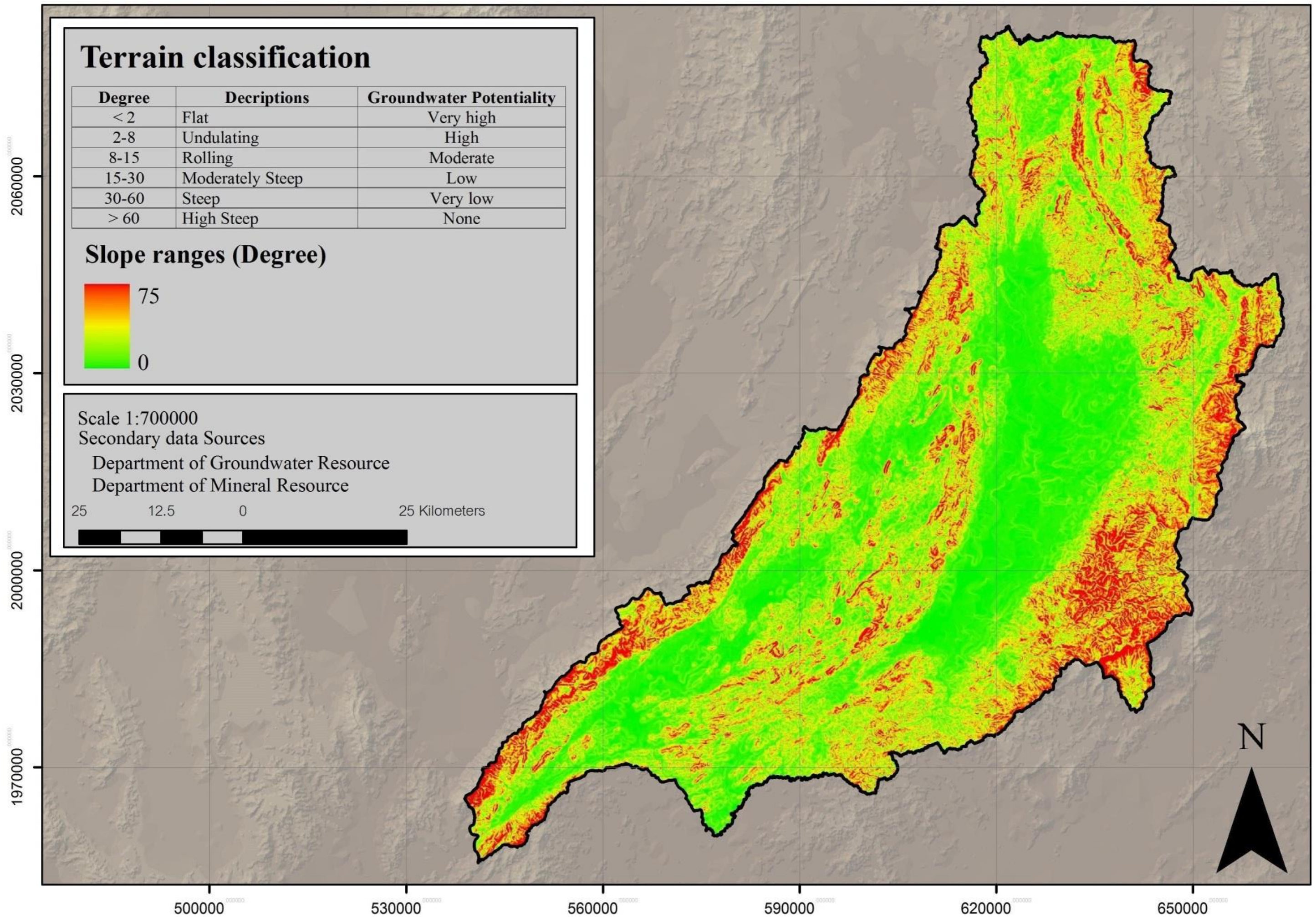

Figure 3. 2 Slope map of the study area, secondary data derived from the Land Development Department (2011).

3.2 Climate

According to the Royal Irrigation Department [47] , and the KÖppen climate classification, Phrae province has a tropical savanna climate (Aw), which has a longer dry season and a prominent but not extraordinary wet season. The climate is generally divided into three seasons:

The rainy season is influenced by the southwest monsoon from mid-May to mid-October, High rainfall in August to September during the retreat of the southwest monsoon. Furthermore, the abundant rainfall comes from tropical cyclones from August to October.

The winter season is influenced by the northeast monsoon from mid-November to mid-January. The amount of rainfall is less than during the rainy season.

The summer season is a transition period between the shifts from the northeast to the southwest monsoon and occurs between mid-February and mid-May. The hottest month of the year is usually April.

3.2.1 Precipitation

In 2012, the average annual rainfall over the whole area was 1,009.80 mm. The highest amount of rainfall was 401.10 mm. in August, and the lowest amount of rainfall was 0.00 mm. in February. The number of rainy day is 117 days.

3.2.2 Temperature

Thailand is located in the tropical zone and average annual temperatures are 27 °C., which a nearby the average annual temperature in Phrae province is 27.64°C. However, temperature varies according to topography and seasons in the different regions. Highly variable temperatures between day and night, and summer and winter occur in regions that are located in the valley, the highest temperatures during the summer season are about 37.00°C in the afternoon and in April, during December to January are the coldest months of the year, with temperatures are about 19.50°C in the mountainous areas.

Table 3. 1 Mean monthly climatic data for Phrae province, for the years 1980 – 2010, data from TMD and RID (2012).

Mon	Rainfall	Rainy day	Humidity	Temperature (°C)			Wind	Pressure
	mm.	*Days*	*%*	*Mean*	*Max*	*Min*	*(Knot)*	*Mil*
Jan	7.00	1	70.00	22.00	31.00	14.00	1	995
Feb	5.00	1	64.00	25.00	33.00	17.00	1	992
Mar	21.00	2	58.00	28.00	36.00	20.00	2	991
Apr	72.00	5	60.00	30.00	37.00	23.00	2	989
May	179.00	12	72.00	29.00	35.00	24.00	2	987
Jun	122.00	12	77.00	28.00	33.00	24.00	2	986
Jul	144.00	14	79.00	28.00	32.00	24.00	2	986
Aug	233.00	16	81.00	28.00	32.00	24.00	2	954
Sep	191.00	14	83.00	27.00	32.00	23.00	1	989
Oct	97.00	8	81.00	27.00	32.00	22.00	1	992
Nov	21.00	2	77.00	25.00	31.00	19.00	1	994
Dec	3.00	0	73.00	22.00	30.00	15.00	1	996
Total	**1095.00**	**87**	**875.00**	**-**	**-**	**-**	**-**	**-**
Dry	**129.00**	**11**	**402.00**	**25.33**	**33.00**	**18.00**	**1.34**	**992.84**
Rainy	**966.00**	**76**	**473.00**	**27.83**	**32.66**	**23.50**	**1.67**	**982.34**
Avg.	**91.25**	**-**	**72.91**	**26.58**	**32.83**	**20.75**	**1.50**	**987.58**

Table 3. 2 Statistic climatic data for Phrae Meteorological Station, in the years 1980 - 2010, data from TMD and RID (2012).

Statistic		Date
Temperature		
Highest max temperature	43.0 °C	May 2010
Lowest min temperature	5.0 °C	Dec 2009
Lowest humidity	13 %	Mar 2003
Max wind speed	48.05 Knot	-
Rainfall		
Max rainfall intensity	218.2 mm.	Aug 2000
Highest monthly rainfall	442.8 mm.	Aug 1974
Highest yearly rainfall	1,556.0 mm.	1970
Lowest yearly rainfall	635.9 mm.	1993
Average climatic data for the years 1980 - 2010		
Pressure	1009.14 Millibars	
Mean temperature	26.81 °C	
Max temperature	33.19 °C	
Min temperature	21.63 °C	
Rainfall	1,114.8 mm.	
Average rainy days	127.4 Days	
Humidity	75.16 %	

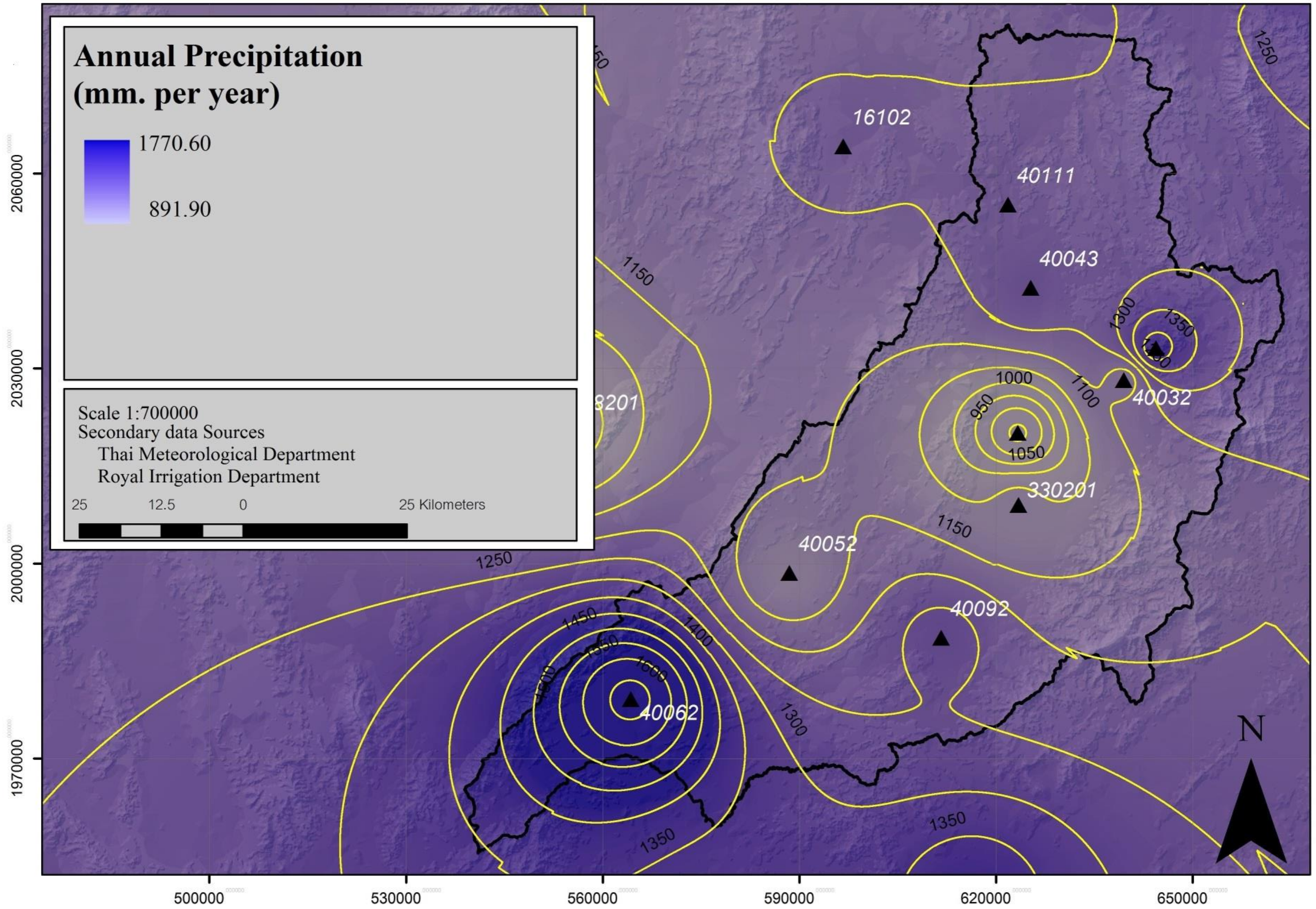

Figure 3. 3 Isohyets average rainfall map of the study area, secondary data derived from the Thai Meteorological Department (Data from 1980 - 2010).

3.3 Soil properties

For the Geo-Informatics database of the Land Development Department in 2005, soil group units of the area were classified into 29 groups of soil properties varied according to the origin and landforms. Most soil group is unit 62, which covered 50.59 percent of total area, located on mountainous area. This group of soils includes all steep lands with more than 35 percent slopes (SC: slope complex). Soil properties varied as geological setting of the areas, which were most is parent material. This group of soils should restrict their uses to woodland, watershed protection and wildlife conservation.

Soil Group Unit 47 of soil covered 22.56 percent of total area. This group of soils was well-drained, shallowly deep coarse-textured that developed from weathered rocks in dry areas. It was low fertility. Soil pH of this group unit varied from 6.0-7.5. Soil series in this unit consisted of *Li series (*Li), *Muak Lek Series (*Ml), *Nakhon Sawan series (*Ns), *Pong Nam Ron series (*Pon), *Sop Prap series (*So) and *Tha Li series (*Tl)

Soil Group Unit 15 of soil covered 6.70 percent of total area, located on alluvial floodplain. This group of soils, which was low fertility, was coarse-drained, highly deep sandy silt-textured that developed from stream sediment. Soil pH of this group unit varied from 5.0-8.0. Soil series in this unit were composed of *Lom Sak series* (La), *Mae Sai series* (Ms) and *Mae Tha series* (Mta) [48].

In other Soil Group Unit, it represents the soil group unit mapping in the area as shown in Figure 4.4 and Table 4.3. In addition, the summary of soil texture, soil permeability and soil properties were related to the land use in the study area, most area was slope complex, low fertility, and might have a problem of the soil erosion (As can be seen in Figure 4.5).

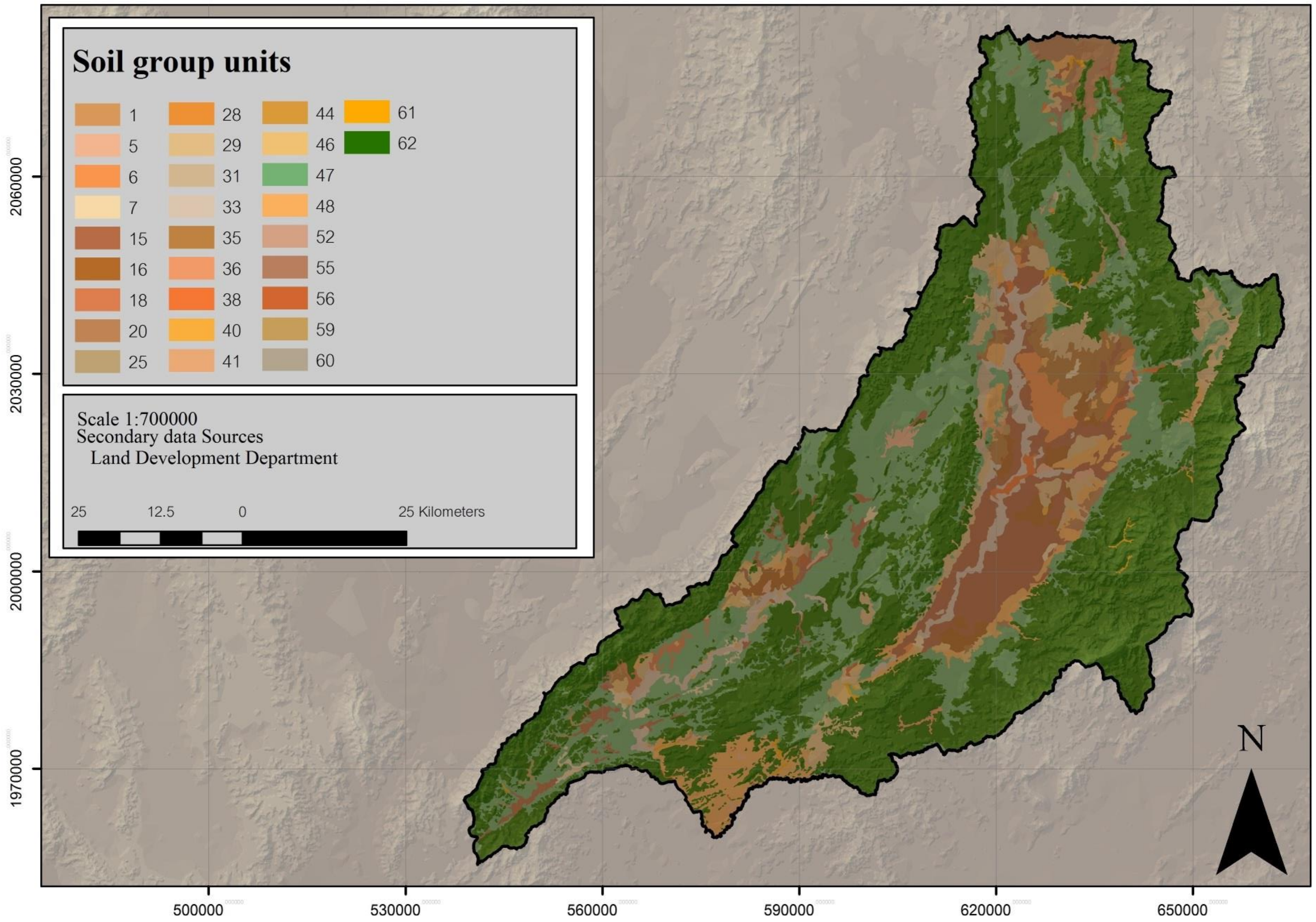

Figure 3. 4 Soil group unit map of the study area, secondary data derived from the Land Development Department (2011).

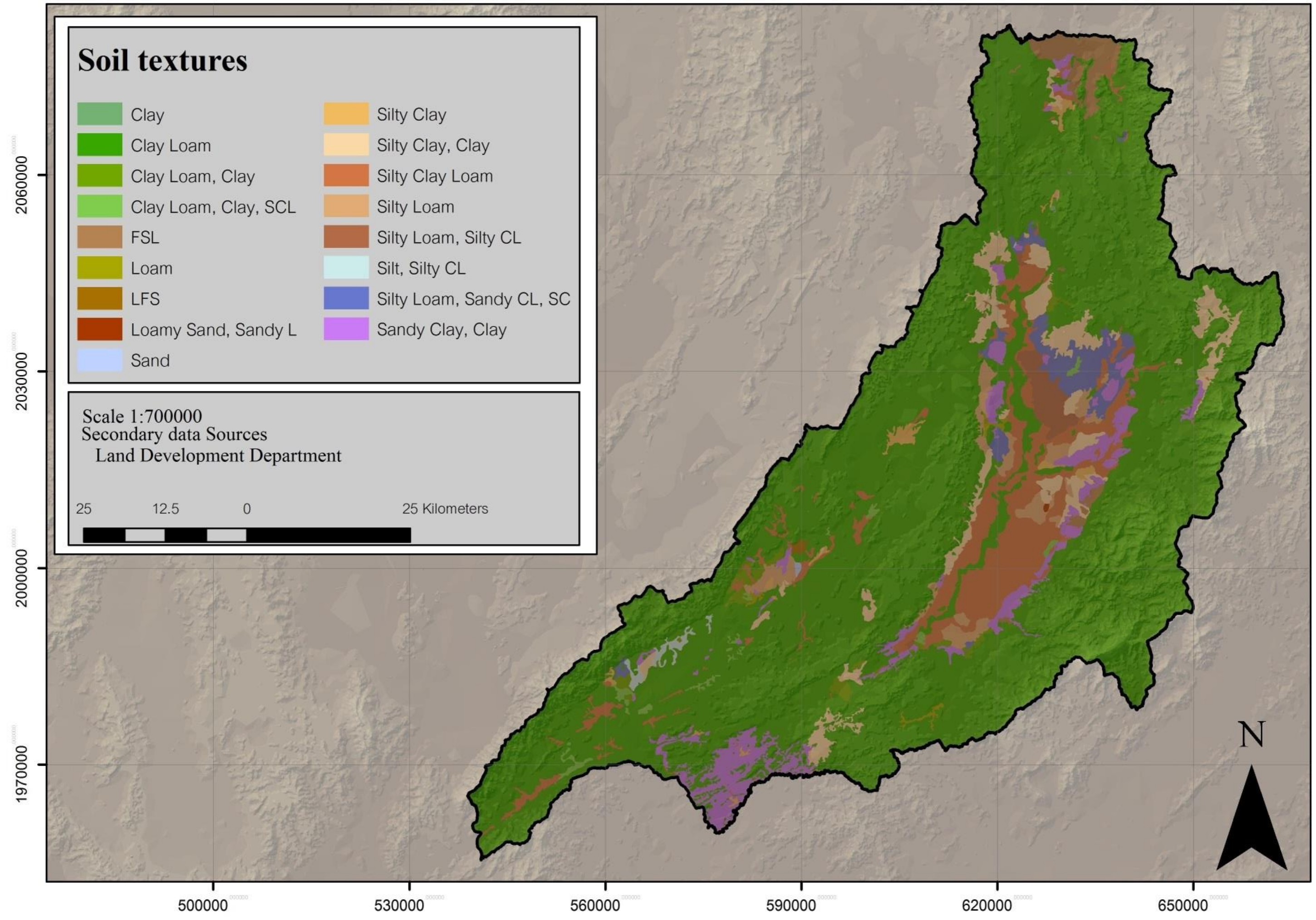

Figure 3. 5 Soil texture map of the study area, secondary data derived from the Land Development Department (2011).

Table 3. 3 Percentage of the soil group unit area.

Soil Group Units	Area (Square meters)	Percentage
5	25724817.71	0.40
6	59215517.56	0.91
7	29028567.30	0.45
15	434568977.50	6.70
16	83892029.31	1.29
18	17753220.44	0.27
20	92426877.32	1.43
25	2419585.96	0.04
29	255518841.40	3.94
31	25227305.92	0.39
33	171164847.50	2.64
35	116455267.20	1.80
36	10009338.90	0.15
38	19823592.59	0.31
40	936969.34	0.01
41	3819212.63	0.06
44	1662249.72	0.03
46	50011214.79	0.77
47	1462929935.00	22.56
48	273337703.40	4.22
55	8683887.67	0.13
56	3647257.19	0.05
59	26855521.42	0.41
60	11534934.02	0.18
61	15797306.50	0.24
62	3279707379.00	50.59
Total area	6483057952.00	100.00

*The total area of Soil group units 1, 5, 28 and 52 are lower than 0.00 percent.

3.4 Land use

For the Geo-Informatics database of the Land Development Department in 2009, Visual image interpretation based on Google image 2012, and Field investigation, land use units of the area classified into 4 types of land cover was varied with respect to the landforms and human activity, as shown in Figure 3.6, Table 3.4.

3.4.1 Agriculture area

In the study area, the agriculture area covered 1,377.86 sq. kilometers or 21.45 percent of total area. Commonly this area was paddy field (588.76 sq. kilometers) and field crop in the floodplain landforms (336.06 sq. kilometers). However, there was an abandoned area spreading over a wide area, and shifting cultivation was found in the northern part of the area which was steep land and slope complex. That was wrong land use utilization.

3.4.2 Forest area

The forest area was the highest proportion of land cover type of the study area, which covered 72.11 percent of total area. This forest area was approximately 4,632.72 sq. kilometers. It consisted of approximately 3,978.28 sq. kilometers and 526.60 sq. kilometers of deciduous forest and the evergreen forest in the mountainous landforms, respectively. In addition, the old clearing was found over a wide area owing to the shifting cultivation for field crop planting which was commonly found in the north part of the area.

3.4.3 Water body

The water bodies were only 0.7 percent of total area, because this area did not have a large reservoir. Populations in the Phrae province used water from the Yom River for agriculture, which cause a problem in dry season because the water resource did not have enough water for supplying domestic use and agricultural in the area.

Table 3. 4 Percentage of land use unit area.

W			F			M			U			A		
Typ	Area	%	Typ	Area	%	Typ	Area	%	Typ	Area	%	Typ	Area	%
W	47,379,972	0.7	F1	526,597,379	8.2	M1	168,504,817	2.6	U1	31,668,564	0.5	A1	588,557,947	9.2
			F2	3,978,284,861	62	M2	3,086,030	0.1	U2	119,428,486	1.9	A2	363,036,972	5.7
			F5	127,840,921	2.0	Etc.	10,202,340	0.2	U5	5,960,600	0.1	A3	130,327,888	2.0
									Etc.	27,470,924	0.4	A4	192,287,645	3.0
												A5	477,474	0.0
												Etc.	102,972,225	1.6
Sum	**47,379,972**	**0.7**	Sum	**4,632,723,162**	**72**	Sum	**181,793,189**	**2.8**	Sum	**184,528,576**	**2.9**	Sum	**1,377,660,154**	**21.4**

W is Water body
F1 is Evergreen forest
F2 is Deciduous forest
F5 is Old clearing
M1 is Range land
M2 is Wetland
U1 is Urban and built-up land
U2 is Villages
U5 is Industrial land
A1 is Paddy field
A2 is Field crops
A3 is Perennial crops
A4 is Orchards
A5 is Horticultural

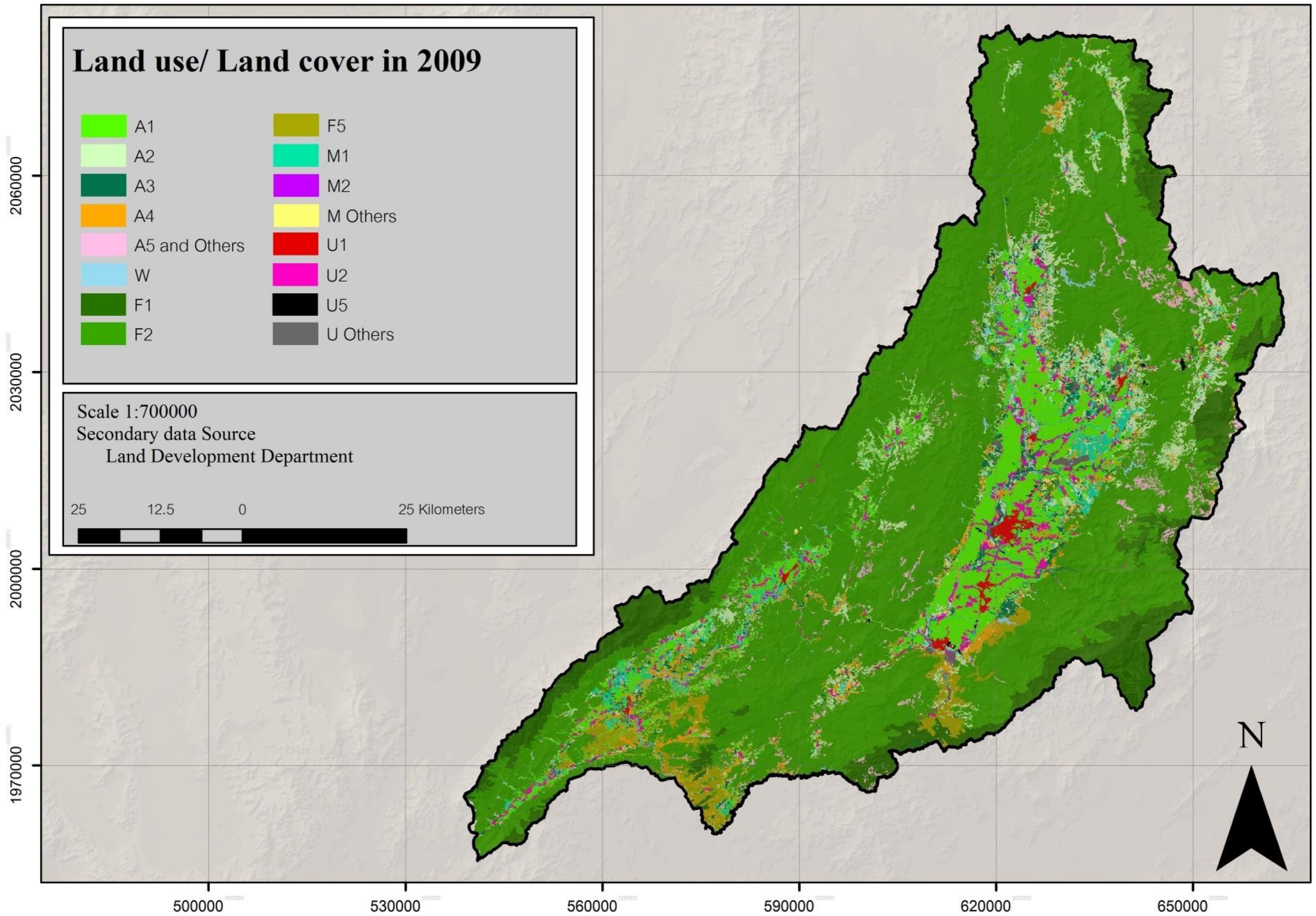

Figure 3. 6 Land use map in the study area, secondary data derived from the Land Development Department (2011).

3.4.4 Building-up and Miscellaneous area

The information from field investigation was used for land use interpretation, which found that building-up and miscellaneous area situated surrounding the study area, were generally in floodplain landforms. Most industrial activities in Phrae province were household size. Hence, water use in this area was a domestic use.

3.5 Geology and Structure

3.5.1 Lithology

Phrae province is located on the subcontinent Shan – Thailand. The units of rock in this area are Carboniferous (360 million years) to Quaternary (Recent) age. Geological features are associated with the landforms in the study area, for example, the high mountainous area on the eastern and western sides of the basin are characterized as Permian and Triassic rock units, which are composed of conglomerate, sandstone, siltstone, shale and mudstone. Some of rock units in the western part of the basin are also dominated by volcanic rocks [49]. In the details, based on literature reviews and geologic GIS data at scales of 1:250,000 from the Department of Mineral Resources of Thailand [50] , the National Research Council of Thailand [51] and the literature reviews of Ratri [52], it can be described that type of rock in the study area arranges from geochronology in the following (Table 4.5 and Figure 4.7).

3.5.1.1 Lithostratigraphy

1.) Carboniferous Period

In the Carboniferous Period of northern Thailand, The rocks mostly are clastic sediments (sandstone, conglomeratic arkoses and shale) with some chemical sedimentary rocks as limestones or chert intercalations, which had average thickness ranging from 300 to 400 meters in the end of the Lower Carboniferous. In the Upper Carboniferous It shows both marine and continental facies. Marine sediments consist of chert, limestone, shale, and conglomerate, and non-marine sediments consist of a thick red conglomerate, shale, sandstone and chert. The thickness of Upper

Carboniferous sequence is up to 200 meters. Moreover, the Uppermost Carboniferous formation is composed of mafic volcanic.

In Phrae province, these period rock units consists of conglomerates, conglomerate limestones, sandstones, shales, slates and cherts, which are found along in the eastern of Amphoe Rong Kwang, Phrae province to Nan province.

2.) Permian Period

In the central part of the northern Thailand, especially in Changwat Phrae, the most complete succession of Permian rocks is exposed. The Permian rocks in the region are crystalline limestone with subordinate clastic and volcaniclastic sediments [52]. The average thickness of the Permian limestone is ranging from 100-150 meters. According to spatial geology data from the Department of Mineral Resource in 2009, these period rock units spread around the northern as The Ngao group. In this area, they can be divided into three rock formation as:

Kio Lom Formation (Png1, Pkl): This formation was widely found surrounding in the norther part of Amphoe Song and Amphoe Rong Kwang, as well as the southern part of Amphoe Sung Men, Amphoe Den Chai, and Amphoe Wang Chin, Phrae province. It consisted of volcanic sandstones, sandstones, greenish gray and gray shales. In addition, Permian limestones were found on the top layer of stratigraphy.

Pha Huat Formation (Png2, Pph): This formation was found in the eastern part of Phrae province, in Amphoe Muang, Amphoe Rong Kwang, and the some parts of Amphoe Song. It is composed of highly thick black limestones, which shales and sandstones are intercalated in the limestone thickness.

Huai Tak Formation (Png3, Pht): This formation was found in the western part of Phrae province, in Amphoe Song, Amphoe Long, and the eastern site of Amphoe Rong Kwang. This formation was composed of shales, siltstones, limestones and dark gray mudstones.

3.) Permian-Triassic Period (PTr)

The Permo-Triassic rocks are mostly rhyolitic and andesitic which distributed in almost northeastern-southwestern direction from Changwat Chiang Rai to Changwat Lampang. In Changwat Phrae, it found along the eastern part of Amphoe Rong Kwang to Nan province. It is composed of sandstones, volcanic sandstones, limestones, semi-metamorphic rhyolitic tuffs, shales and cherts.

4.) Triassic Period (Lampang Group)

In the Mesozoic Period of northern Thailand, the rocks are characterised by two principal facies as marine sequence in the west and central parts of the region, and continental strata in the northeastern part of the region. In the Triassic Period of Changwat Phrae generally originated from marine sediments was found in the northern part of Thailand and surrounding area as '*the Lampang Group*'. These rocks rest unconformably on the Permian rocks and overlay on the Permo-Triassic volcanic rocks in the central and eastern regions. The Triassic period rocks consisted of shale and limestone with the facies change into a sandstone-shale sequence [53]. In detail, it can be divided into five rock formation as:

Phra That Formation (Trpt): The formation is 100-400 m. thick, red and coarse grained, and made up of siltstones, sandstones and red conglomerates.

Pha Kan Formation (Trpk): The formation is a limestone unit which conformably overlies the Phra That Formation, which is 80-500 m. thick and found in the Doi Pha Lak Muan. It was predominantly composed of grey limestones with minor grey to green shales and sandstone beds.

Pha Dang Formation (Trpd): It can be found around the study area which found in the top unit of the Lampang Group. It consists of shallow marine red to grey sandstones, shales and red conglomerates up to 600 m thick.

Kang pla Formation (Trkp): This unit is derived in Amphoe Long, where conformably overlies the Pha Dang Formation. The formation comprises thin to massive, grey to greyish black limestones whose thickness ranges from 100-500 m.

The Wang Chin Formation (Trwc): This formation can be found around the study area. This formation is consists of grey to greyish green mudstones interbedded with sandstones. Thickness ranges from 600 to 1000 m and overlies Kang Pla Formation conformably. In addition, it lies directly on the Pha Dang Formation.

5.) Triassic to Jurassic Period (TrJ)

This formation can be found some part in the northern part of the study area, in Amphoe Song. It consists of conglomerates, red brown sandstones, shales and mudstones.

6.) Jurassic Period (J)

This formation found in the northern part of the study area, in Amphoe Song and Amphoe Rong Kwang is composed of reddish conglomerates, sandstones, shales and mudstone.

7.) Jurassic Period (Jk/ JKl)

This formation was found in some western and eastern parts of Phrae province. In the western part, the rock consisted of mudstones, limestones, shales and siltstones. In the eastern part, the rock consisted of arkoses, mudstones, and reddish siltstones. In addition, gastropods and bivalves were found in bottom of the interbedded.

8.) Jurassic to Cretaceous Period (JK)

This unit consists of arkoses-sandstones, conglomerates and shale. It was found in the northern part of the area, in Amphoe Song, such as Doi Pha Tai, Doi Luang.

According to Ratri [52] , the Mesozoic rocks during the Late Triassic periods to Cretaceous periods had a relation of continental clastic sedimentary rocks in northern Thailand, which rocks of the continental environment appeared in form of Jurassic periods. The continental sedimentary sequence consists of red sandstone, mudstone, shale and mafic-intermediate volcanic rock. They are mainly exposed in the south of Changwat Phrae.

3.5.1.2 The Quaternary units (Q)

The Quaternary units in the center part of The Phrae sub-basin are found along the alluvial plains of Phrae province, which thus mainly of fluvial origin but have experienced pile up throughout the Pleistocene. Soe et al. [49] described following the study of Sinsakul (1987) which may classified the Quaternary units into four distinctive units: high-terrace, stream-valley, low-terrace (including old alluvial plain), and active alluvial deposits. According to Regional scale of the Department of Mineral Resource in 2009, the Quaternary stratigraphy of the basin can be classified into two distinctive units from oldest unit and the most recent unit.

1.) Terrace deposits (Qt)

The oldest unit occurs near the mountains in flat plain area along Amphoe Muang, Amphoe Sung Men, Amphoe Rong Kwang, Amphoe Song, Amphoe Long and Amphoe Wang Chin. It can separate to two types of terrace deposits sub-units: *Quaternary High Terrace* (Qth) and *Quaternary Low Terrace* (Qtl). In the Quaternary High Terrace (Qth), it consisted of alluvium, conglomerate (pebbles of sandstone, volcanic fragments, shale and limestone), siltstone, clays, lateritic soils and laterite. Similarly, the Quaternary Low Terrace (Qtl) was formed as dunes surround the basin boundary. It consisted of sands, silts, clays, gravels and lateritic soils [52].

In conclusion, the Terrace deposits (Qt) consisted of bedrock fragments mixing with alluvial deposits as sand, silt, clay and laterites.

2.) Alluvial deposits (Qa)

The youngest unit, covering along the Yom River of this basin and is composed of fluvial sediment such as sand or silt mixing with clay layer overlay sandy clay and gravelly sand layers, which were found in Amphoe Muang, Amphoe Sung Men, Amphoe Nong Muang Kai, Amphoe Song and Amphoe Long.

Table 3. 5 Mesozoic stratigraphy of the Lampang-Phrae Basin in Northern Thailand [54].

Age			Basin	
			Lampang sub-basin	**Phrae sub-basin**
Jurassic	Early			Phu Kradung Formation
Triassic	Late	Rhaetian		Nam Phong Formation
		Norian		Wang Chin Formation
		Carnian		Kang Pla Formation
			Pha Daeng Formation	Pha Daeng Formation
	Middle	Ladinian	Doi Long Formation	
		Anisian	Hong Hoi Formation	
	Early	Olen.	Phra Khan Formation	
		Ind.	Phra That Formation	

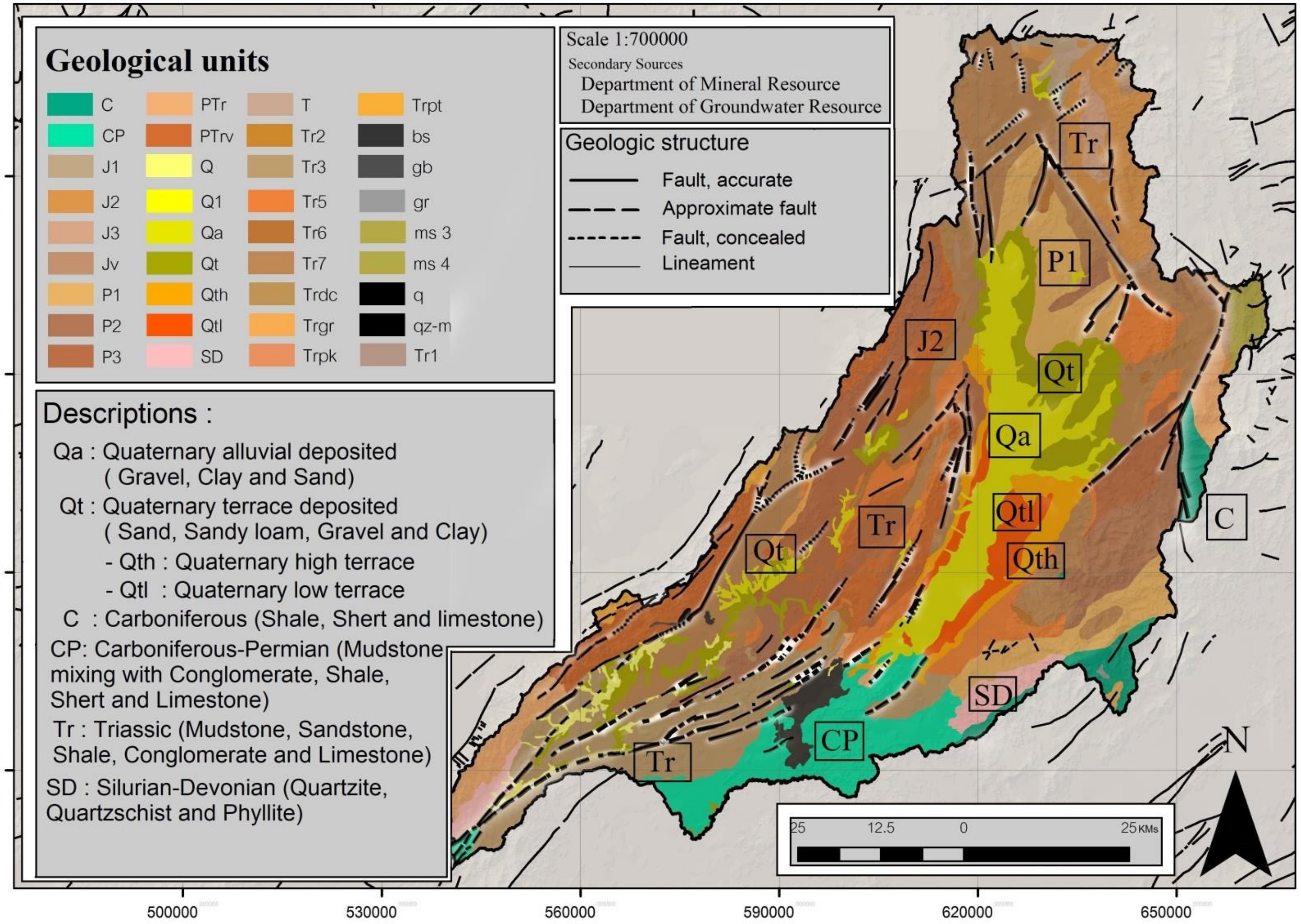

Figure 3. 7 Geology map in the study area, secondary data derived from the Department of Mineral Resource in 2011

3.5.1.3 Igneous Rock

In northern Thailand, Paleozoic formation rocks (Carboniferous-Permian) have been affected by high-grade regional metamorphism and granitization. Plutonic activities produced intrusive rocks in several areas. Furthermore, the tectonic activity started in the early Upper Carboniferous age after widespread deposition of felsic to intermediate volcanism. According to the category of volcanic belts, the age of volcanics in northern Thailand extend from Late Permain to Early Triassic which had relation with the collision of the Shan -Thai with the Indochina cratons [52]. The igneous rock in the Phrae sub-basin can be classified into two distinctive units in terms of modes of occurrence. Igneous rocks can be either intrusive (plutonic) or extrusive (volcanic), which were arranged from oldest to the most recent.

1.) Triassic intrusive igneous rock (Trgr)

Most landform in the western part of the basin in Amphoe Long is high mountainous was composed of Biotite granite, Tourmaline granite, Granodiorite, Biotite-Muscovite granite, Muscovite-Tourmaline granite, and Biotite-Tourmaline granite.

2.) Permian-Triassic volcanic rock (PTrv)

It was found along the ranges of western part in the study area, in Amphoe Song, Amphoe Long, some parts of Amphoe Sung Men and Amphoe Muang. In addition, it can be found in the western part of the study area, in Amphoe Den Chai and Amphoe Wang Chin. Compositions of the rock unit are generally Rhyolites and Andesites, Volcanic Breccia, Rhyolitic and Andesitic-Tuffs.

3.) Quaternary Volcanic rock (Qbs)

It was found in the southern part of the study area, in Amphoe Den Chai, and some part in Amphoe Long and Amphoe Wang Chin. Compositions of the rock unit are Alkali-olivine basalts, Nephelinite, Basanite. In addition, the basalts in the northern part of Changwat Phrae are probably of the same age as the Lampang basalt in the Pleistocene period.

3.5.2 Geologic structure

The Phrae Basin is a Tertiary fault-bend basin covering approximately 1,100 sq. kilometers that formed during the Late Oligocene-Early Miocene. Sinistral strike-slip movement of the Phrae-Thoen Fault was a major control on the creation of accommodation space in the Phrae Basin. The Phrae and Rong Kwang sub-basins are separated by a basement high which may be a part of a transfer zone or may be created by right overstep of the controlling left lateral Phrae-Thoen Fault. The Song sub-basin is separated from the Rong Kwang sub-basin by the Long Fault. The regional controls on the evolution of the Phrae Basin are extension associated with subduction of the Indian Oceanic Plate beneath the Sunda Shelf and strike-slip displacement on major regional strike-slip faults. Inversion is associated with the interaction of the Philippine and Australian Plates [55]. Presently, Phrae Fault Zone is still active. Its movement rates range from 0.02-0.07 mm. per year [50].

3.6 Hydrogeology

In general, the hydrogeology data was a relation with geology data. However, in detail of the aquifers identifying or the hydrogeologic unit classification, it was quite different from Geologic unit classification. According to the Department of Groundwater Resource [56], hydrogeologic factors were used to identify aquifers such as:

- Distribution of aquifers, which consist of aquifer boundary, thickness, and depth of aquifer. The lithologic well-log and geologic cross-section were used to determine the boundary of aquifers, both vertical scale and horizontal scale.
- Hydraulic properties of aquifers by using pumping test data and groundwater recovery method in different geologic unit. Then, the different of Hydraulic conductivity (K), Transmissivity (T) and Storativity (S) were used to determine the aquifers properties.
- Groundwater flow system, presenting in Piezometric level and Direction of groundwater flow map.
- Distribution of recharge and discharge areas, which was useful to determine aquifers system in basin scale.

- Groundwater potentiality, both in term of quality and quantity by using hydraulic properties and hydrogeochemical of aquifers to determine the maximum yield, groundwater safe yield and groundwater quality standard of aquifers.
- Groundwater quality of aquifer by using groundwater quality data from different of aquifers. Generally, Total Dissolved Solids (TDS), (Hardness), Iron (Fe) and Chloride (Cl) were used to identify the hydrogeochemical of aquifers.

However, according to Scott [57] who recommended on a hydrogeologic unit classification. Basin scales of groundwater systems are complex and interaction between surface water and groundwater have not been reported in the context of a groundwater classification system. Hence, the factors of land use, ecosystem conservation, and watershed management should be considered in determining aquifer system in the future.

The Phrae basin is an intermontane basins located in the central part of Changwat Phrae. The basin covers approximately 1,000 square kilometers which the length of the basin is approximately 60 kilometers and 15 kilometers wide, with the northern end of the basin bifurcated. Following the literature review of Vaji and Somchai [58], The Phrae groundwater basin had the specific storage of 160 million cubic meters (MCM), and specific yield in the basin was 32 MCM per year, or 87,000 cubic meters per day. The most potential aquifers generally are sediments in Quaternary period, which the highest proportion of geologic cover type of the Phrae basin is the Quaternary Terrace deposits, and the Quaternary alluvial deposits located in the central part of the Phrae basin. Meanwhile, in regional scale, Changwat Phrae was composed of unconsolidated deposited aquifers and consolidated aquifers. The details are as follows (Figure 3.8).

3.6.1 Unconsolidated aquifers

Unconsolidated deposited consisted of four main aquifers as:

3.6.1.1 The Quaternary floodplain deposited (Qa/ Qfd)

The youngest units, which were found in the depth of 0 to 15 meters, occurred along the Yom River by fluvial process in the central part of Changwat Phrae. The yield of the aquifer was 3-8 cm^2/ hr. It composed of gravel layers, sand or silt layers overlay with clay layers was found in Amphoe Muang, Amphoe Sung Men, Amphoe Nong Muang Kai, Amphoe Song and Amphoe Long.

3.6.1.2 The Quaternary Younger Terrace deposited (Qyt)

It was found in the depth of 25 to 40 meters, and the average thickness was 25 meters. It occurred along the foothills by weathering and erosion process. The Younger Terrace deposited was mostly composed of gravel mixing with clay layers, which lap over with clay or sandy clay layers. That can be called multi-aquifers. The groundwater was stored in the gravel beds. The yield of the aquifer was 3-5 cm^2/ hr. It was found in Amphoe Muang, Amphoe Sung Men, Amphoe Nong Muang Kai, Amphoe Song and Amphoe Long.

3.6.1.3 The Quaternary Old Terrace deposited (Qot)

The depth of Old Terrace deposited was higher than 40 meters and the highest thickness was deeper than 100 meters under the Younger Terrace deposited which that was multi-aquifers. The groundwater was stored in the gravel beds. The composition of the aquifer was gravel mixing with clay layers. The uppermost of the aquifer, which the depth is not higher than 100 meters, was a poor source of groundwater because of large size of the gravel beds, coarse grains of sand and clay. The yield of the layer was 5-10 cm^2/ hr. Meanwhile, the Quaternary terrace sub-layers which were found in the depth of 100 to 300 meters were a good source of groundwater. Three sand layers mixing with gravel which thicknesses of these layers approx. 10 to 15 meters, had the yield of layers as 10-50 cm^2/ hr. The Quaternary Old Terrace aquifer was found in Amphoe Muang, Amphoe Sung Men, Amphoe Nong Muang Kai, Amphoe Song, Amphoe Long and Amphoe Wang Chin.

3.6.2 Consolidated aquifers

In Hard rock aquifers, it was consisted of main consolidated-confined aquifers such as *Permian-Carboniferous Metasediments aquifers* (PCms), *Permian-Carbonates aquifers* (Pc), *Triassic-Carbonates aquifers* (TRc), *Triassic Lampang group aquifers* (TRlp) and *Triassic Lower Korat group aquifers* (TRJlk). The details are as follows

3.6.2.1 Permian-Carbonates aquifers (Pc)

It was composed of dark-grey and highly thick limestone beds, which was stuffed with thin shale, tuff-sandstone and chert. The groundwater was received from fracture and fault of the aquifers. The depth of aquifers ranged from 30-150 meters, Good quantity, and yield of the aquifer were 2-20 cm^2/ hr.

3.6.2.2 Permian-Carboniferous Metasediments aquifers (PCms)

It was composed of volcanic conglomerate, volcanic sandstone, slate, shale, limestone and chert. The groundwater was received from fracture and fault of the aquifers. In addition, the depth of aquifers ranged from 30-150 meters, and good quantity. The yield of the aquifer was 5 cm^2/ hr.

3.6.2.3 Triassic Lampang group aquifers (TRlp)

The Triassic marine sedimentary rock aquifers were composed of four rock formation as *Pha Dang Formation*, *Hong Hoi Formation*, *Pha Kan Formation* and *Phra That Formation*. Generally, they were sandstone, shale and limestone. The groundwater was stored in the rock fracture of shale and sandstone. The water quality was good, but its quantity was low. The yield ranged from 1-5 cm^2/ hr.

3.6.2.4 Triassic Lower Korat group aquifers (TRJlk)

It was composed of brown shale, siltstone, sandstone and conglomerate. The groundwater was received from fracture and fault of the aquifers. Its quantity was good for domestic use, and its yield of the aquifer was 4-18 cm^2/ hr.

3.6.2.5 Volcanic aquifers (Vc)

It mostly consisted of fine grains Basalt, Rhyolite and Andesite. The groundwater was stored in rock fracture. The depth of aquifers varied from 20 to 60 meters, and groundwater yield ranged from 1-5 cm^2/hr. It was found along the ranges of the western part in the study area, in Amphoe Song, Amphoe Long, some parts of Amphoe Sung Men and Amphoe Muang. In addition, it can be found in the western area of the study area, in Amphoe Den Chai and Amphoe Wang Chin.

For groundwater exploration, The Quaternary Old Terrace and Triassic Lower Korat group aquifers were the most important aquifers for usage and management. According to observation wells data which was both unconsolidated and hard rock aquifers from the Department of Groundwater Resource, it showed that Phrae groundwater basin was varied in groundwater table depending on topographic features and hydraulic characteristic. In addition, the dynamic of seasonal groundwater table was more significant to groundwater storage changes than the yearly dynamic. Following the literature review of Vaji and Somchai [58] , who studying the groundwater potential in Thailand, which found that the average rate of groundwater recharge from precipitation was 10 percent per the total of annual rainfall (mm. / year). In detail, the average rate of groundwater recharge from precipitation to unconsolidated aquifers was 5 percent per the total of annual rainfall (mm. / year), and the average rate of groundwater recharge from precipitation to hard rock aquifers was 2-3 percent per the total of annual rainfall (mm. / year). In groundwater development of the Phrae basin, the depth of groundwater well should be higher than 300 meters for extreme rates of groundwater quantity. Moreover, the rates of safe yield in this basin should be higher than 20 percent of specific storage.

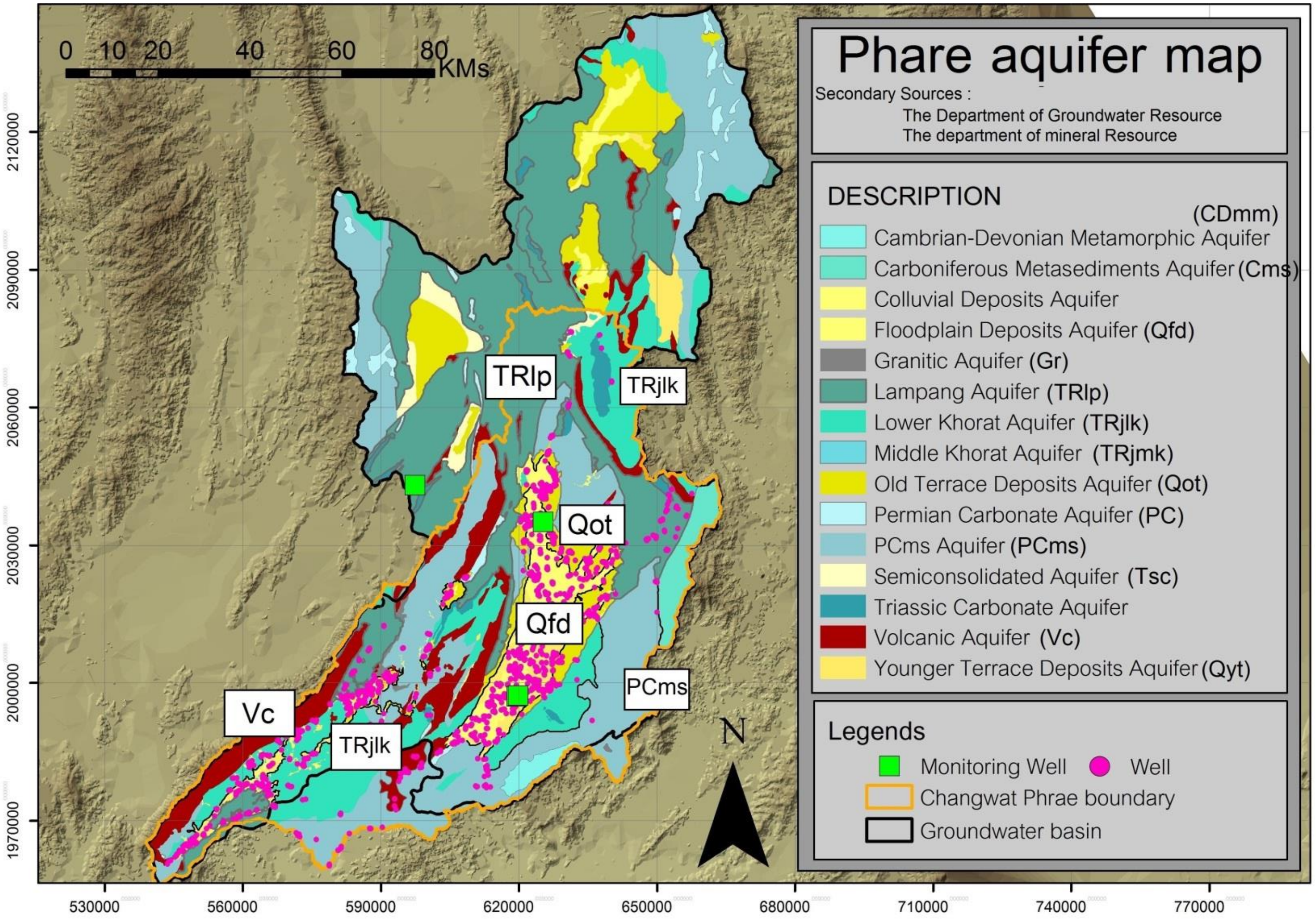

Figure 3. 8 Hydrogeological map in the study area, secondary data derived from the Department of Groundwater Resource in 2011.

CHAPTER IV

METHODOLOGY AND MODELLING

This chapter, all methods and sources of data were shown in each step. The thematic data used in this research are prepared and processed below. Modelling part is separated into two parts as groundwater recharge simulation using WetSpass, and groundwater flow and groundwater balance simulation using MODFLOW. Furthermore, field investigation for surveying and groundwater table depth collecting are also show on period 2012-2013.

4.1 Phases of data collecting and field investigation

4.1.1 Data collection step

Collection of existing data from government, private sector and field investigated, include an information interviews from relevant sector as showed in Table 4.1 and Table 4.2.

Table 4. 1 Lists of relevant sector.

Acronym	Government Sector
DGR	Department of Groundwater Resources
DPOA	Department of Provincial Administration
DWR	Department of Water Resources
LDD	Land Development Department
MOI	Ministry of Interior
MOAC	Ministry of Agriculture and Cooperatives
RID	Royal Irrigation Department
TMD	Thai Meteorological Department

Table 4. 2 Lists of data collection.

No.	Data type	Source	Acquisition year	Remark
1	**General data**			
	Groundwater basin Boundary	DGR	2011	Shape file (.shp)
	Village location	DPOA	2011	Shape file (.shp)
2	**Topology data**			
	DEM	LDD	2011	Grid file
	Land use patterns	LDD	2012	Shape file (.shp)
	Soil group properties	LDD	2011	Shape file (.shp)
3	**Meteorology data**			
	Monthly temperature	TMD	1981-2011	Statistical (.xls)
	Monthly potential evaporation	TMD	1981-2011	Statistical (.xls)
	Monthly precipitation	TMD	1981-2011	Statistical (.xls)
	Weather station	TMD	2011	Shape file (.shp)
4	**Hydrology data**			
	Stream line	DWR	2011	Shape file (.shp)
	Runoff data	RID	1981-2011	Statistical (.xls)
5	**Geology data**			
	Lithology	DMR	2011	Shape file (.shp)
6	**Hydrogeology data**			
	Groundwater wells location	DGR	2011	Shape file (.shp)
	Depth of groundwater table	DGR, FI	2012-2013	Statistical (.xls)
	Aquifer unit	DGR	2011	Shape file (.shp)
	Aquifer properties	DGR	2011	Statistical (.xls)
	Groundwater usages	DGR, MOI, MOAC	2011	Statistical (.xls)

4.1.2 Field investigation step

For groundwater model calibration and validation, observation wells data are necessary and critical steps in model development. Groundwater wells selection for field investigation is depending on database from the Department of Groundwater Resource, topography and geological setting. Furthermore, the aim of field investigation is to confirm as many of the land use pattern, topology and geology as possible in Phrae province. Field investigation surroundings of the study area based on the L7018 series 1:50000 maps had four times as year period.

Topography map at scale 1:50,000 in L7018 series, the required map sheet as 5046 II, 5046 III, 5045I, 5045 II, 5045 III, 5045 IV, 5044 I, 5044 IV, 4945 II, 4944 I and 4944 IV prepared and published by the Royal Thai Survey Department, were used to identified site of requirement groundwater wells which are difference in aquifers condition (Figure 4.1). In addition, for clearly understanding in study area situation, Google Earth and ArcGIS version 9.3 programs were used to analyze target sites and routing mapping. It is accomplished through interpretation of satellite images from visualize image interpretation, and data preparation from GIS application.

The example of the best possible way to target sites using true color composite bands 3-2-1 (RGB) in Google Earth was shown as Figure 4.2. And field investigation maps, which were received from the overlay technique with the outlines and labels of the draft vectors supplied by main roads, rural tracks, river and villages, were shown in *Appendix A*.

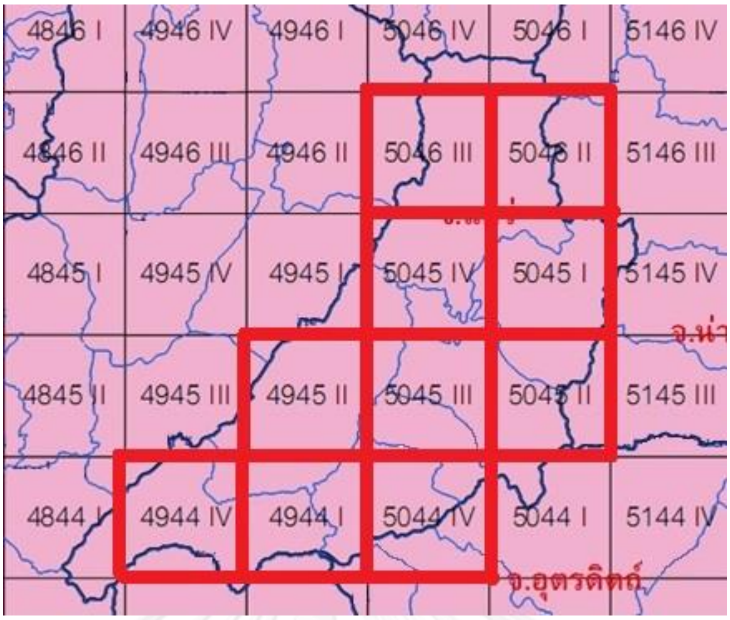

Figure 4. 1 Show 1:50000 L7018 index maps.

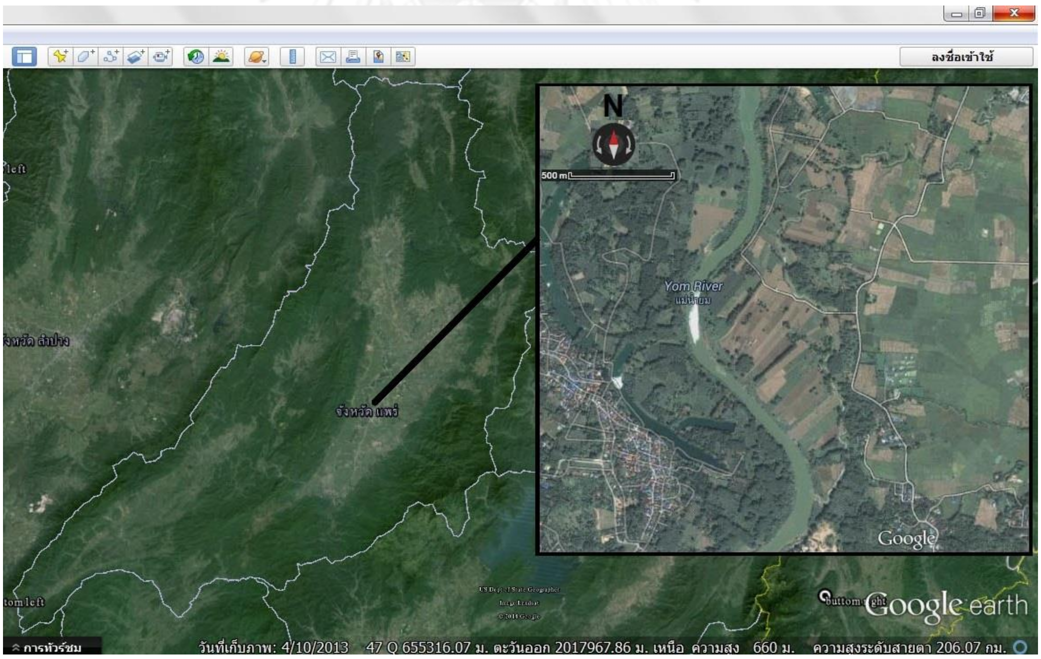

Figure 4. 2 The example of true color composite bands 3-2-1 (RGB) in Google Earth application.

In the field, GPS can be used to detect groundwater wells in the study area. Meanwhile, GPS were also used to identify groundwater wells of unknown and add it into GIS database. The first surveyed in August, 2012, to understanding the study area and to find a suitable route from where to access the observation wells. Meanwhile, Information from interviewed about groundwater usage and water supply problem were received in this step. Routing mapping and problem information are show in Figure 4.3 and Table 4.3 The surveying for groundwater measuring was separated into two periods, dry season (November-April) and rainy season (May-October) However, in rainy season on June 2012, only a few observation wells were founded and measured because of the weather conditions. Hence, the second groundwater measuring in rainy season was surveyed in July 2013. Meanwhile, the groundwater measuring in dry season was surveyed in January 2013.

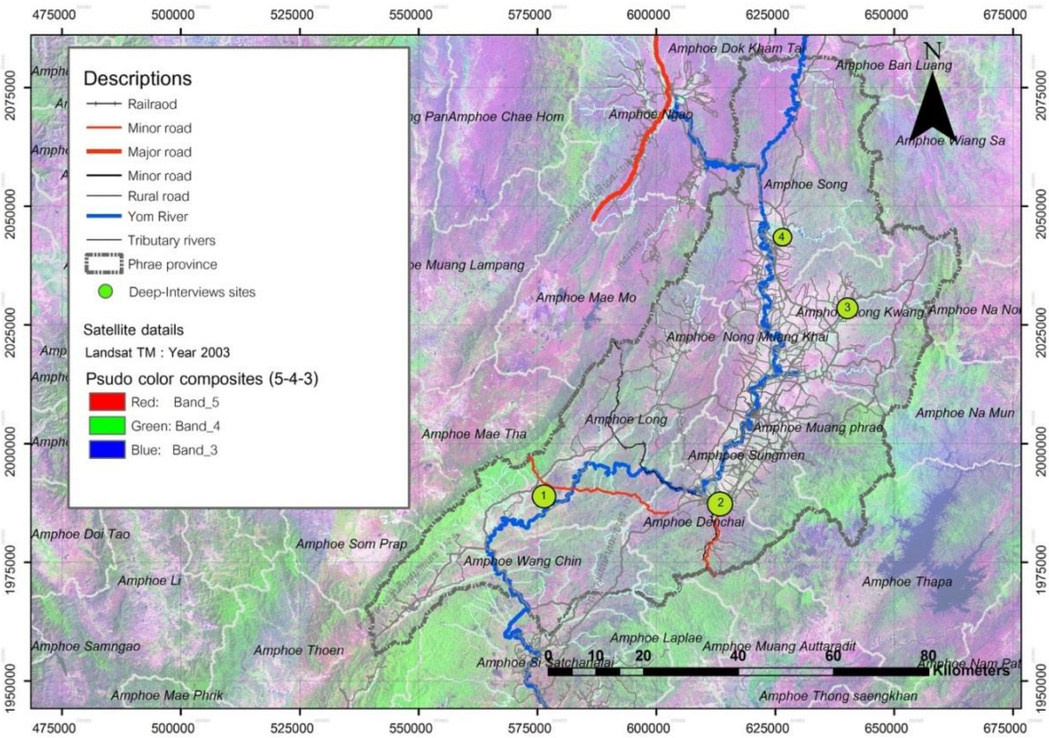

Figure 4. 3 Pseudo color composite bands 5-4-3 (RGB) in Routing map.

Table 4. 3 Lists of state of problem in the study area

Location	Descriptions
1	Tambon Mae Chua, Amphoe Den Chai, Phrae province
	Mostly is paddy field in irrigation area, about 10,000 Rai, irrigated water from the Mae Chua Reservoir is use to two periods agricultural. The outside irrigated area is the teak tree. Began experiencing drought in the year 2007, during the dry season, due to mudslides flew into the reservoir cause the capacity reducing.
2	Tambon Hua Tung, Amphoe Long, Phrae province
	This site is the non-irrigation area, water use for agriculture, mostly from precipitation and Pong river, the major river of the site. In dry season, all villages in this area still face a lack of water, especially in the drought season. Meanwhile, in rainy season, flash flood still occurs every year.
3	Tambon Rong Kwang, Amphoe Rong Kwang, Phrae province
	Agriculture area mostly is paddy field, soy bean and tobacco. In highland, mostly is cabbage. States of problem in the area are found, both in quantity and quality. High levels of fertilizer and pesticides cause contaminate in surface water and groundwater. In the drought season, these areas still face a lack of water, both in surface water and groundwater. Meanwhile, in rainy season, flash flood still occurs every year.
4	Tambon Tao Pun, Amphoe Song, Phrae province
	This area, water use for agriculture is from Mae Song reservoir. In addition, shallow groundwater wells are also used for agricultural. Generally, paddy field are cultivate two periods per year. Unless the drought occurs, mostly from deficit of precipitation in dry season and beginning of rainy season.

The intensity of sampling in field investigation varied between map sheets depending on accessibility, and the nature of the study area [59]. Traverse line method along minor road was used to field investigation, that was done by travelling in a vehicle for this reason a set of intensive 74 measuring point was organized during

1st-7th January 2013, and 64 measuring point was organized during 18th-23th June 2013, that are wells spread over the study area. All values were calculated and interpolated for estimating of the groundwater heads and groundwater flow schematic, groundwater investigate map is show in Figure 4.4

For groundwater measuring, the electric-tape method was used (Figure 4.5). The electric-tape method consists of an ammeter, which is connected across a pair of insulated wires. Exposed ends are split by an air gap in an electrode and containing. Alkaline batteries are a source of power. In the circuit, when the electrode touches the groundwater surface, current flows through the system circuit and is indicated by a deflection of the needle in an ammeter. The insulated wires are marked at 1-m intervals. On the insulated wires, the nail of the index finger is placed, at the measuring point when the ammeter indicates that the circuit is closed. A carpenter's rule is used to measure the distance from the indication point to the next highest mark. This distance is subtracted from the value of the mark to identify the depth of groundwater. In the difference between the electric-tape method and the wetted-tape method, the subtraction involves the length of the submerged tape in the wetted-tape method, whereas the subtraction involves the distance between the measuring point and the next highest mark in the electric-tape method [11].

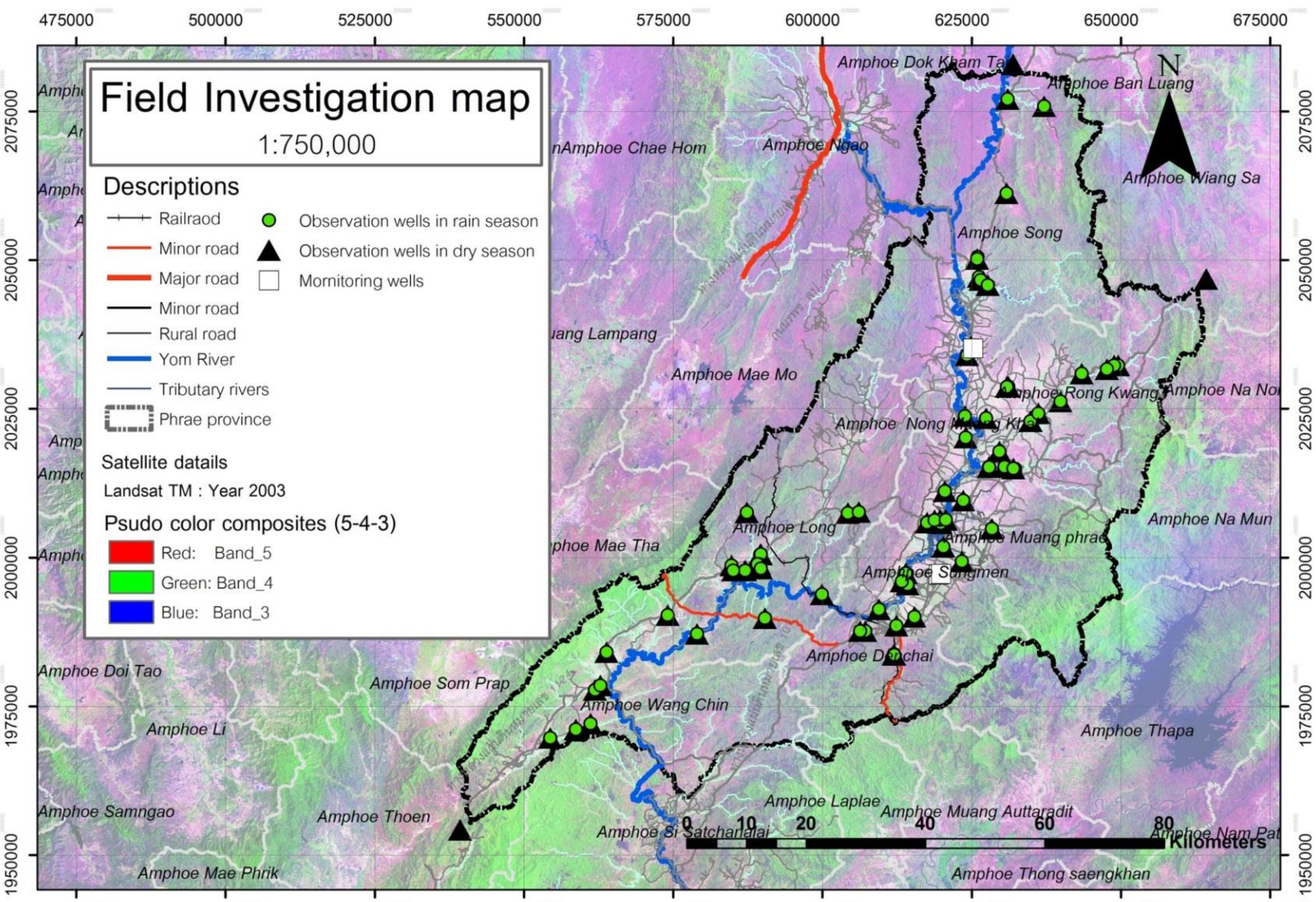

Figure 4. 4 Pseudo color composite bands 5-4-3 (RGB) in Field investigation map.

Figure 4. 5 Shows A) The electric-tape measuring B) A sample of observation wells C) The electric-tape method for measuring D) A sample of monitoring wells.

4.2 Phases of data preparation and map construction

Following phases of data collecting and field investigation, GIS technique and database were used to construct spatial thematic maps of the study area and are applied in developing, manipulating, and analyzing in groundwater modelling. The map construction procedure was done as outlined below:

4.2.1 Database design step

In primary statistical data, such as meteorology data and depth of groundwater table data, it is necessary to verification, extraction and adjustment, for accuracy and reliability. Hence, attribute data which were stored, was converted into GIS database and relate information using location as the key index variable, which are recorded as x and y coordinates system. Finally, it was representing in point station around the study area [60]. Hence, the database design and definition of the way in which the data will be collected and stored [27].

4.2.2 Data verification step

For using secondary data, it is necessary to verify the data for accuracy and reliability, especially groundwater basin boundary, landuse pattern, soil group properties, lithology and topographic feature. Landsat ETM+ band 5-4-3 in the year 2008 and Digital Elevation Measurement (DEM) were used to verify the topographic pattern, Phrae groundwater basin and stream line were adjusted by geometric technique. In addition, the landuse/ land cover data during year 2009 from Land Development Department (LDD) was compared with true color composite bands 3-2-1 (RGB) of the Google Map satellite images in National Research Council of Thailand [51]. Furthermore, the field investigation database which is reported by Supattra Kitichuchairit [61] was also used to compare with the landuse/ land cover data from LDD for validation which is shows in Figure 4.6.

Generally, a principle of image interpretation involves several basic characteristics of features, which were shown on an image as tone, color, size, shape, texture, pattern, site, height and association (as shown in Table 4.4). These are routinely used when interpreting a satellite images [62].

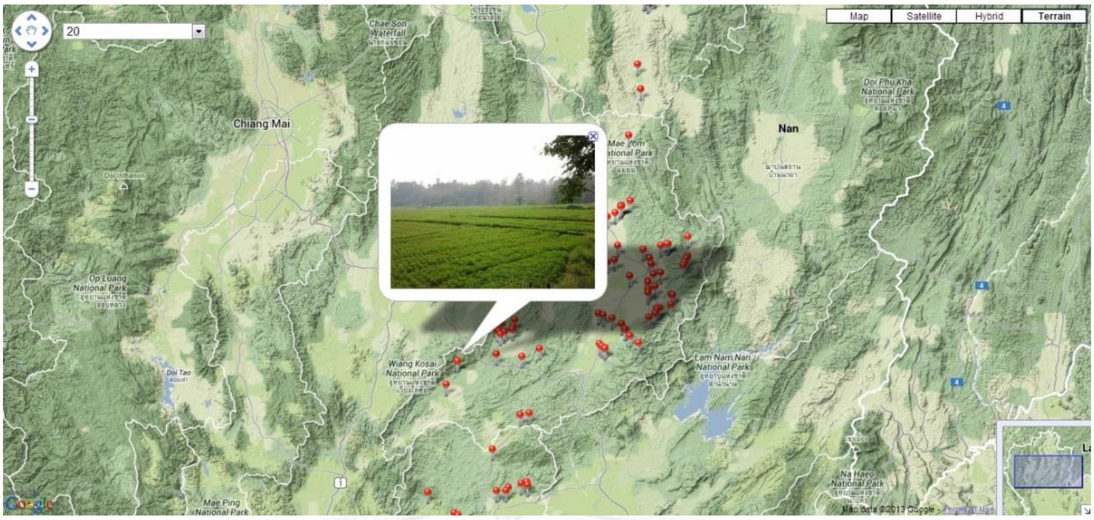

Figure 4. 6 Show field investigation sampling points, based on google catoweb [51].

Table 4. 4 Elements of Image Interpretation [62].

No.	Elements	Characteristics description
1	tone/ color	Relative brightness of black and white image and hue for colored pictures
2	Size	Relative dimension of different objects
3	Shape	Form also height of an object (in 3D)
4	Texture	Relates to the frequency of tonal change and is expressed as coarse, fine, smooth or rough, even or uneven, etc
5	Pattern	Spatial arrangement of objects and implies characteristic repetition of certain forms or relationship. It can be described as concentric, radial, check board, etc
6	Site	Occurrence of an object to a particular easily identifiable feature
7	Height	z-elevation, slop, aspect, volume
8	Association	Close relationship/links of different or combination of objects.

4.2.3 Data preparation step

GIS techniques were used to prepare the spatial database into groundwater flow model. The data used in this study consists of several spatial data categories from the available resources, being digitized from available thematic maps and prepared from image interpretation, and from field investigation data. These input data will be further used to analyze the groundwater balance and groundwater flow by the numerical analysis in the Chapter 5. The brief techniques of the input data produced in this study such as soil properties, landuse, precipitation, potential evapotranspiration, topographic features (slope and DEM) and depth of groundwater are consequently presented as below (Figure 4.7).

Average seasonal rainfalls were calculated in the period 1980–2010 (30 years), from different 12 stations, average seasonal rainfalls were interpolated to obtain distributed maps of seasonal rainfall using the Inverse Distance Weighted (IDW) methods. The monthly rainfalls were divided to dry and rainy season following from monsoon season standard of the Thai Meteorological Department, where dry season is assumed from November to April and rainy season from May to October, and this thesis got the seasonal trends of mean precipitation and represented them at the grid scale of 90 m x 90 m. However, it just only one meteorological station which have completely data of the potential evapotranspiration (PET). Hence, average seasonal potential evapotranspiration were calculated from meteorology data using modified penman equation in agricultural model CROPWAT 8.0 [63] (Figure 4.8), the equation for evaporation given by Penman equation is show in Equation 4.1, Then, average seasonal potential evapotranspiration were interpolated to obtain distributed maps of seasonal PET (Figure 4.9). Furthermore, the 30 years temperature data in Phrae province meteorology station was also used to represent the seasonal mean temperature in the study area by converted into a grid file.

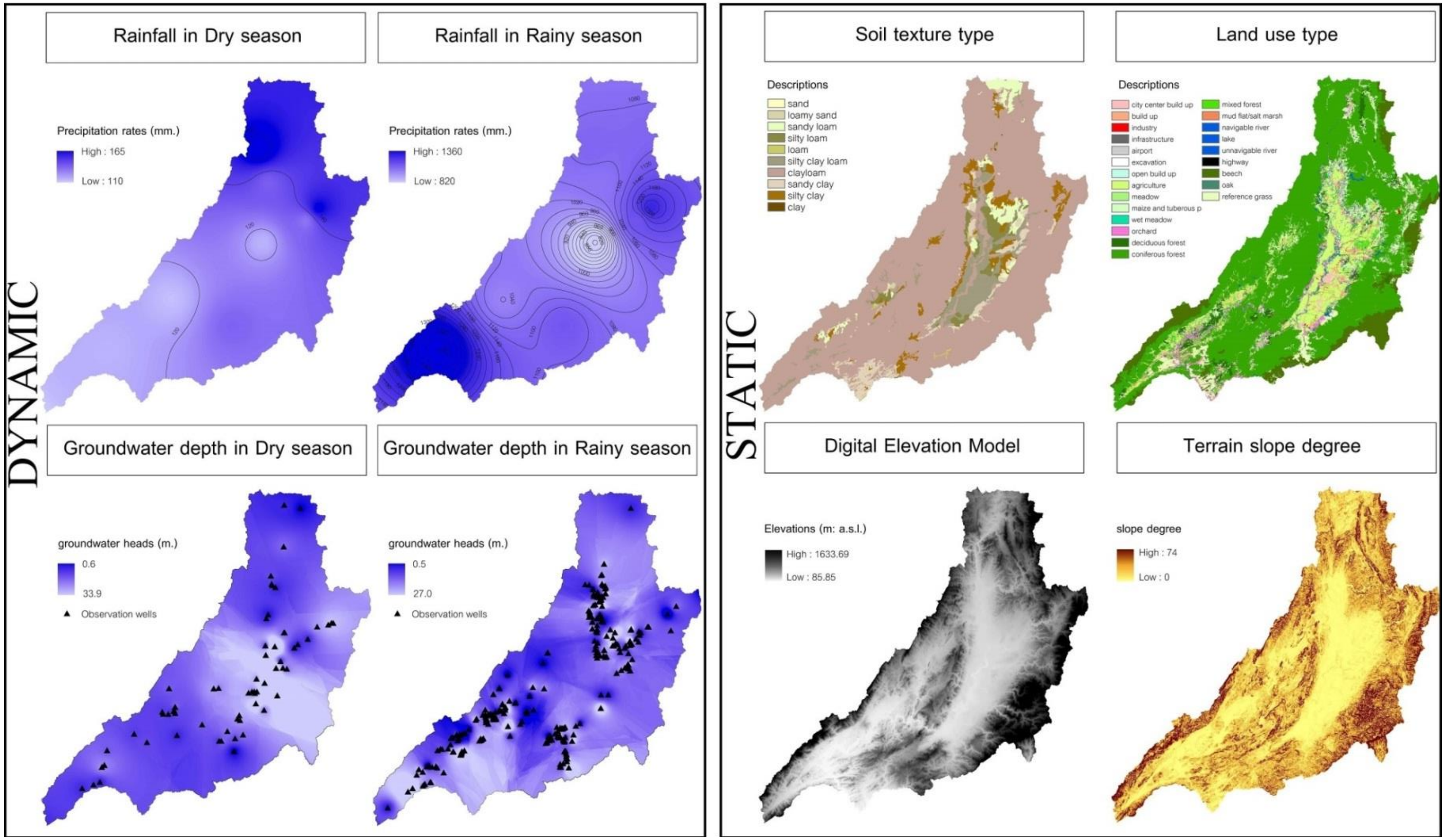

Figure 4. 7 Spatial data of the parameters used in WetSpass module and MODFLOW, generated from secondary data in GIS.

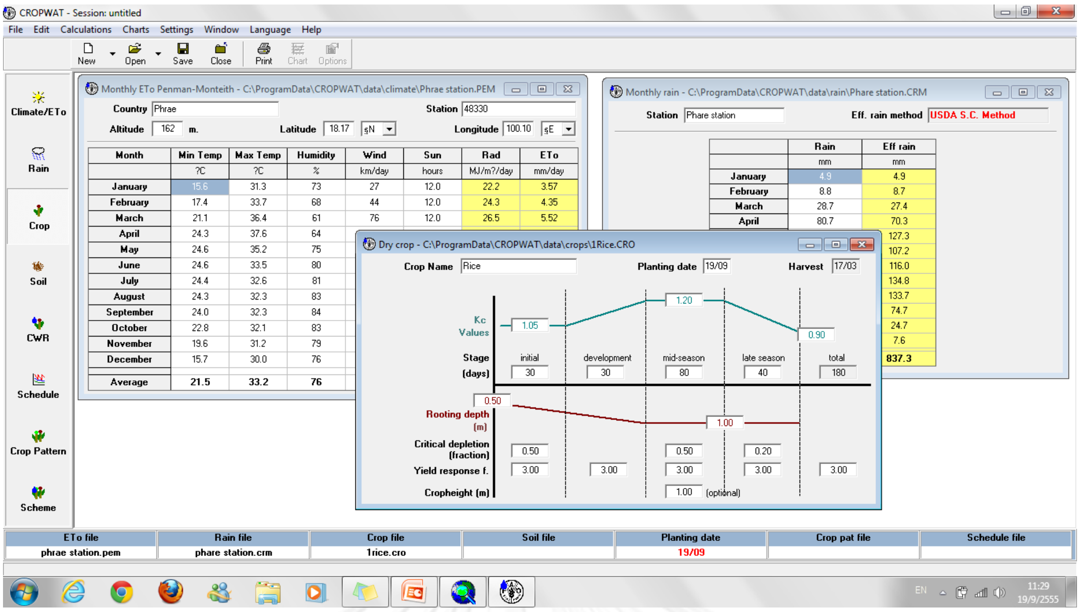

Figure 4. 8 Shows an interface of CROPWAT 8.0

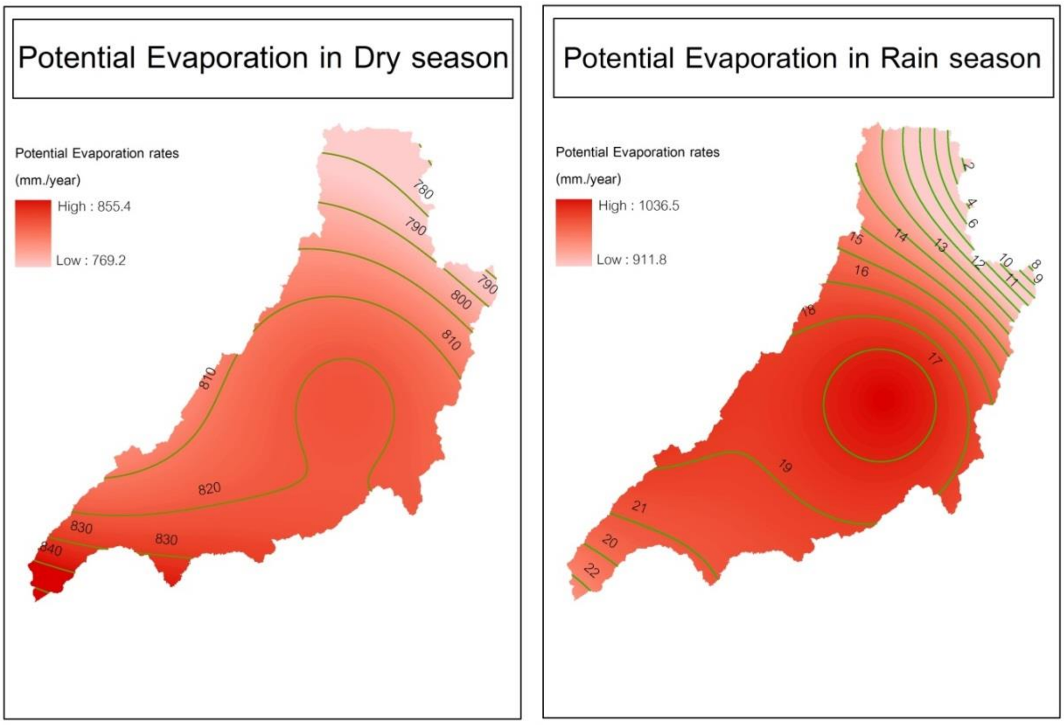

Figure 4. 9 Seasonal Potential Evaporation features from CROPWAT 8.0 generating.

$$E_{mass} = \frac{mR_n + \rho_a c_p(\delta e) g_a}{\lambda_v (m+y)}$$ .... (Equation 4.1)

where

m = Slope of the saturation vapor pressure curve (Pa/ K^{-1})
R_n = Net irradiance (W/ m^{-2})
ρ_a = density of air (kg/ m^{-3})
c_p = heat capacity of air (J kg^{-1} K^{-1})
g_a = momentum surface aerodynamic conductance (m/ s^{-1})
δe = vapor pressure deficit (Pa)
λ_v = latent heat of vaporization (J/ kg^{-1})
γ = psychometric constant (Pa/ K^{-1})

For modeling, the elevation raster data of the study area is necessary. Thus, Digital Elevation Models (DEM) was generated from topographic features (elevation contour, stream, spot elevation and model boundary) which were obtained from Land Development Department. Then, the elevation data was converted into a color-draped relief continuous map. In addition, DEM is also used to generate a slope, aspect and landform topographic features. The slope is a measurement of surface steepness and is calculated in degrees of inclination, slope’s range are vary between 0 degree and 90 degrees, 0 degree representing the flat lying areas and 90 degrees as the vertical ones. Any other value indicates the steepness areas. Furthermore, slope is also significantly effect to groundwater flow and recharge area.

The soil properties and land use data were collected in a form of soil group and land use/ land cover unit maps of the study area prepared by compiling data from the spatial data of Land Development Department, which were transformed into digital image, via digitizing and edit using GIS software. These parameters are connected to the model as databases of the land use and soil raster maps, which parameters of the classification are based on the U.S. Department of Agriculture classification, resample to a 90 by 90 m resolution.

For soil properties database, the original base were stored in form of soil series group, which established by the National Cooperative Soil Survey of the United

States Department of Agriculture (USDA), which are levels of classification in the USDA Soil Taxonomy classification system hierarchy. Soil series consist of soil individual that are grouped together which consider from similarity in soil horizons of soil evolution (topography, mother material), soil chemistry (soil pH, consistence, mineral and chemical composition) and physical properties (soil color, soil texture, soil structure). These result in soils which perform similarly for land use planning in 2005. Thus, soil series group database in the study were reclassified to soil texture database. Twelve soil textures were represented into spatial data, and also stored into attribute database for groundwater recharge modeling (As shown in Table 4.5).

Same as land use, the land use classification system presented in this study includes the more generalized second and third levels. This study used land use spatial database in the years 2009 representing, the three major attributes of the classification level process as outlined by Land Development Department in conjunction with USDA were reclassified into 25 land use patterns (As shown in Table 4.6). Moreover, all parameters for groundwater recharge modelling were showed in *Appendix B*.

Table 4. 5 Soil series group database for modelling.

ID Code	Soil texture	Soil group unit
1	Sand	44
2	Loamy sand	40
3	Sandy loam	18, 35, 48
4	Silty loam	6, 16, 31
5	Loam	25, 36
6	Silt	-
7	Sandy clay loam	-
8	Silty clay loam	15, 38
9	Clay loam	7, 33, 46, 47, 52, 59, 60, 61, 62
10	Sandy clay	-
11	Silty clay	5, 29, 55, 56
12	Clay	1, 28

Table 4. 6 Land use and land cover database modelling.

ID	WetSPASS code	Runoff	LU/ LC (L I)	LU/ LC (L II)
1	City center	Grass	Built-up land	City, Town commercial
2	Build up	Grass	Built-up land	Urban and built-up land
4	Infrastructure	Grass	Built-up land	Transportation and Utilities
6	Airport	Grass	Built-up land	Transportation and Utilities
3	Industry	Grass	Built-up land	Industrial land
10	Open-build up	Grass	Built-up land	Villages
201	Highway	Grass	Built-up land	Transportation and Utilities
202	District road	Grass	Built-up land	Transportation and Utilities
11	Paddy field	Grass	Agriculture	Paddy field
21	Agriculture	Crop	Agriculture	Agricultural land
27	Maize	Crop	Agriculture	Field crops
29	Orchard	Forest	Agriculture	Orchards
303	Beech	Forest	Miscellaneous	Perennial crops
305	Oak	Forest	Miscellaneous	Perennial crops
31	Deciduous forest	Forest	Forest land	Deciduous forest
32	Coniferous forest	Forest	Forest land	Evergreen forest
33	Mixed forest	Forest	Forest land	Forest plantation
51	Navigable river	open water	Water Bodies	Water Bodies
55	Unnavigable river	open water	Water Bodies	Water Bodies
52	Lake	open water	Water Bodies	Water Bodies
7	Excavation	bare soil	Miscellaneous	Miscellaneous land
23	Meadow	Grass	Miscellaneous	Range land
28	Wet meadow	Grass	Miscellaneous	Wetland
36	Shrub	Grass	Miscellaneous	Bush and shrub
307	Reference grass	Grass	Miscellaneous	Grass land

4.2.4 Map construction and Present output maps step

Finally, following phases of data preparation, various thematic maps of the study area was constructed using GIS technique and were showed in Chapter 3. In addition, attribute database from spatial data were also used to apply in developing for recharge and groundwater modelling.

4.3 Phases of groundwater recharge modeling

Following phases of data preparation, the methodology consists of these steps were shown in Figure 4.10 In the first step, spatial data were prepared for modelling. These inventory data consists of topographical data, meteorological data, soil data and land use data. The GIS software was applied in storage, manipulating, and analyzing the digital data. These data were adjusted and prepared to raster grid cell which resolution is 90 by 90 m, which is mainly based on the acquiescence that with this resolution can be modelled and reasonable for the study area [64]. Then, the groundwater recharge modelling procedure was done as outlined below:

4.3.1 Groundwater recharges assessment step

The raster data were used in the WetSpass module to simulate the annual and seasonal recharge rates maps in the study area. The spatial overlay technique was merged with water balance equation to calculation. Then, the results were shown as temporal groundwater recharge and various water balance components.

4.3.2 Map construction and Present output maps step

Finally, the results are correlated with water balance components and physical features, which are significant for groundwater recharge, such as seasonal surface runoff, seasonal precipitation, topographic feature and landuse data. Furthermore, the depth of groundwater and groundwater discharge was also discussed in this step.

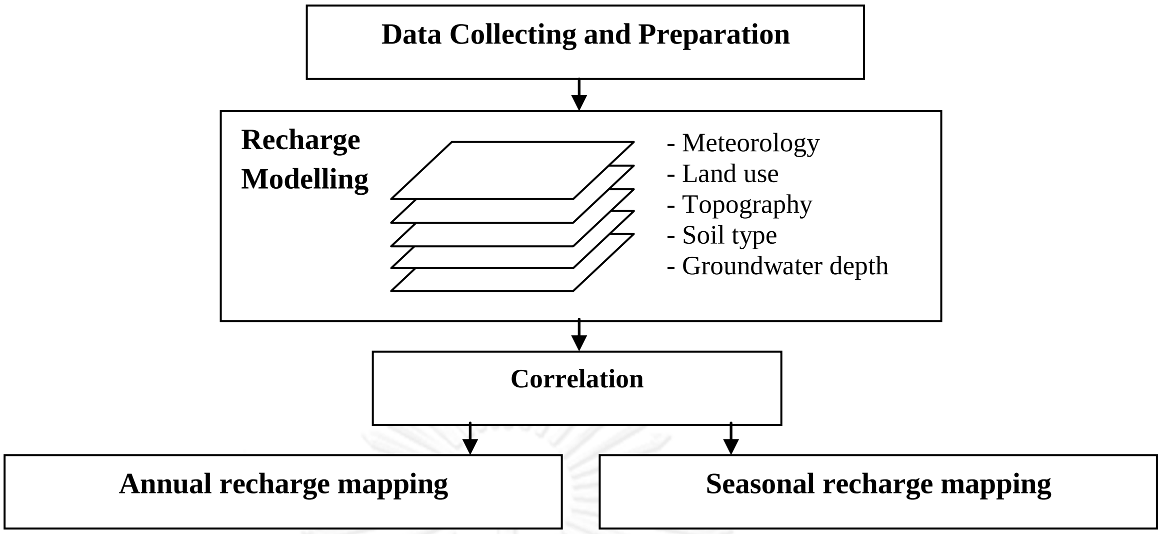

Figure 4. 10 Schematic of the processing.

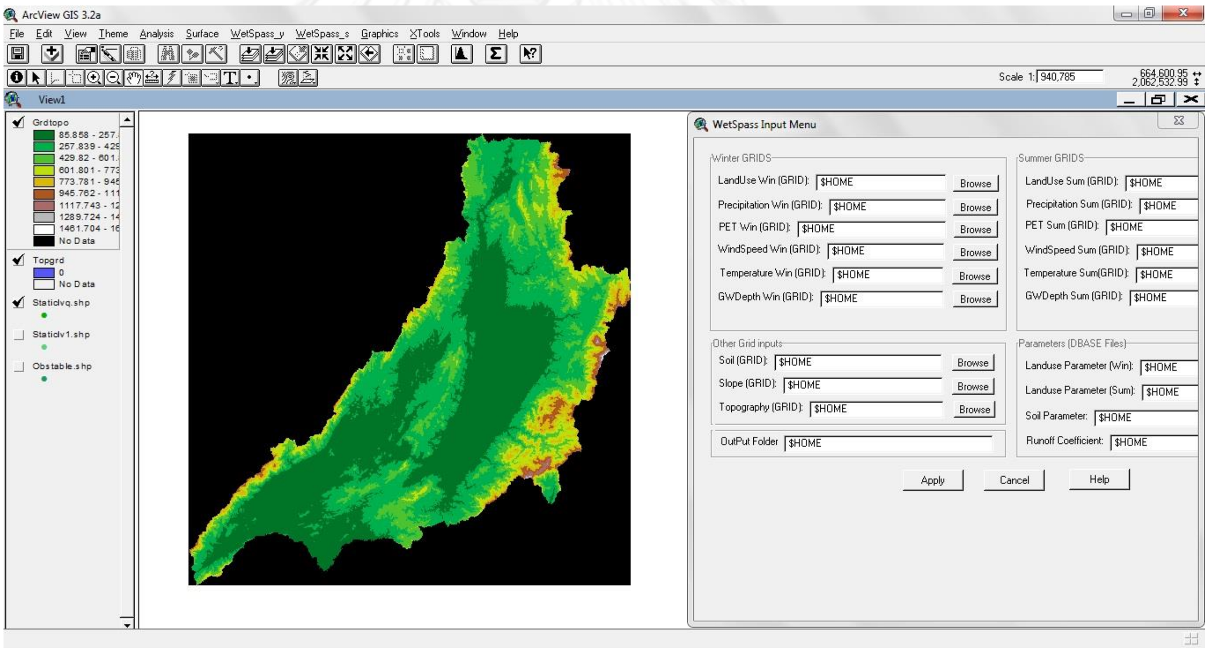

Figure 4. 11 Shows an interface of WetSPASS module in Arcview3.3 program.

4.4 Phases of groundwater flow and groundwater balance modeling

4.4.1 Model Conceptualization step

A groundwater flow conceptual model is a physical framework upon which data related to hydrogeology can be considered. A conceptual model consists of the basic components such as the sources of water into the area and sinks of the outflow, the topography and/or physical boundaries of the area, and the distribution of hydrogeologic properties. The information of a conceptual model is essential to the development of a more quantitative representation of the mathematical groundwater flow model. Thus, before a model construct, specific knowledge or data gaps in the study area must be filled into the conceptual model. In addition, the simplest groundwater model is a groundwater basin mass balance.

In hydrologic setting, water is added to the system in general as precipitation, and also be added to the system as subsurface flow. Then, Water is lost from the system as runoff, subsurface flow, evapotranspiration, and human activity. In the unconfined aquifers, the change of groundwater storage can be determined as same as changing of the groundwater table elevation through time. But in the complex groundwater aquifers, it depends on the movement of water within the domain and hydraulic properties. Hence, the mathematical groundwater flow model is use to determine the change of groundwater storage. The spatial distributions of water inflow and outflow were requires a steady state groundwater flow model as well as the hydraulic properties be defined throughout the area. These models can be used to characterize the movement of groundwater and changing of the groundwater table elevation through time [65].

Phrae groundwater basin locates in the upper part and middle part of Yom watershed, high mountainous surrounding the area was represented is groundwater basin divide. The south part of the study area, hill ridges range across from east to west was represented is topographical boundary between Phrae groundwater basin and Upper Chao Phraya groundwater basin. The Yom River runs across the basin from north to south. The geologic cross-section data from the Department of Groundwater Resource and the National Research Council of Thailand [51] was used to determine the conceptual design, which shows the geologic cross-section lines in Figure 4.12. And the cross-section data, there were shown in Appendix C.

From the cross-section lines, which were ranges from north to south, it can be determine the hydrogeological in the study area, mostly is consolidated confined aquifer. But, in the alluvial floodplain and terrace areas of the basin, unconsolidated deposited were separated into three layers, consist of the Quaternary floodplain deposited (Qfd) in the depth from 0 to 50 meters, the Quaternary Young Terrace (Qyt) in the depth from 50 to 150 meters, and the Quaternary Old Terrace (Qot) in the depth higher than 150 meters, approximately. Mainly groundwater movement, flows from the highest elevation in drainage divide to the Yom River, and flow through the area from north to south. Source of recharge in the area mostly is precipitation. On the contrary, Source of discharge in the area mostly is groundwater outflow into Upper Chao Phraya groundwater basin and groundwater pumping, which as show in Figure 4.13. In addition, pumping test secondary data from the Department of Groundwater Resource in 2012 and the National Research Council of Thailand [51] were also used to determine hydraulic characteristic of aquifers.

The results of three constant rate pumping test from the National Research Council of Thailand [51], as two Quaternary Young Terrace aquifers in Amphoe Long and Amphoe Song, and Permian Carbonated aquifers in Amphoe Long, which found that in the Quaternary Young Terrace aquifers has a hydraulic conductivity is about 1-2 meters per day, rates of transmissivity ranges from 8 to 11 sq. m. per day, the specific storage in these aquifers is 2.54×10^{-4}, the depth of groundwater table was ranges from 0.5-6 meter from elevation surface and can be drawdown ranges from 11-17 meters, which has product the rate of groundwater yield is 3-8 cubic meters per hour. In the Permian Carbonated aquifers, it has a hydraulic conductivity is about 18 meters per day, rates of transmissivity ranges from 110 sq. m. per day, the depth of groundwater table was ranges from 4.8 meter from elevation surface and can be drawdown ranges from 16.6 meters, which has product the rate of groundwater yield is 13 cubic meters per hour.

The results of three constant rate pumping test from the Department of Groundwater Resource, which found that in the Quaternary Young Terrace aquifers in Amphoe Muang has a hydraulic conductivity is about 40 meters per day, rates of transmissivity ranges from 480 sq. m. per day, the specific storage in these aquifers is 0.17. The Quaternary Old Terrace aquifers in Amphoe Muang has a hydraulic conductivity is about 0.35 meters per day, rates of transmissivity ranges from 6.9 sq. m. per day, the specific storage in these aquifers is 0.02.

In Hard rock aquifers, the Permian Carbonates aquifers has a hydraulic conductivity is about 0.015 meters per day, rates of transmissivity ranges from 0.09 sq. m. per day, the specific storage in these aquifers is 0.05. The depth of groundwater table was ranges from 5.36—9.1 meters from elevation surface. And the Lampang aquifers has a hydraulic conductivity is about 1.3 meters per day, rates of transmissivity ranges from 10.3 sq. m. per day.

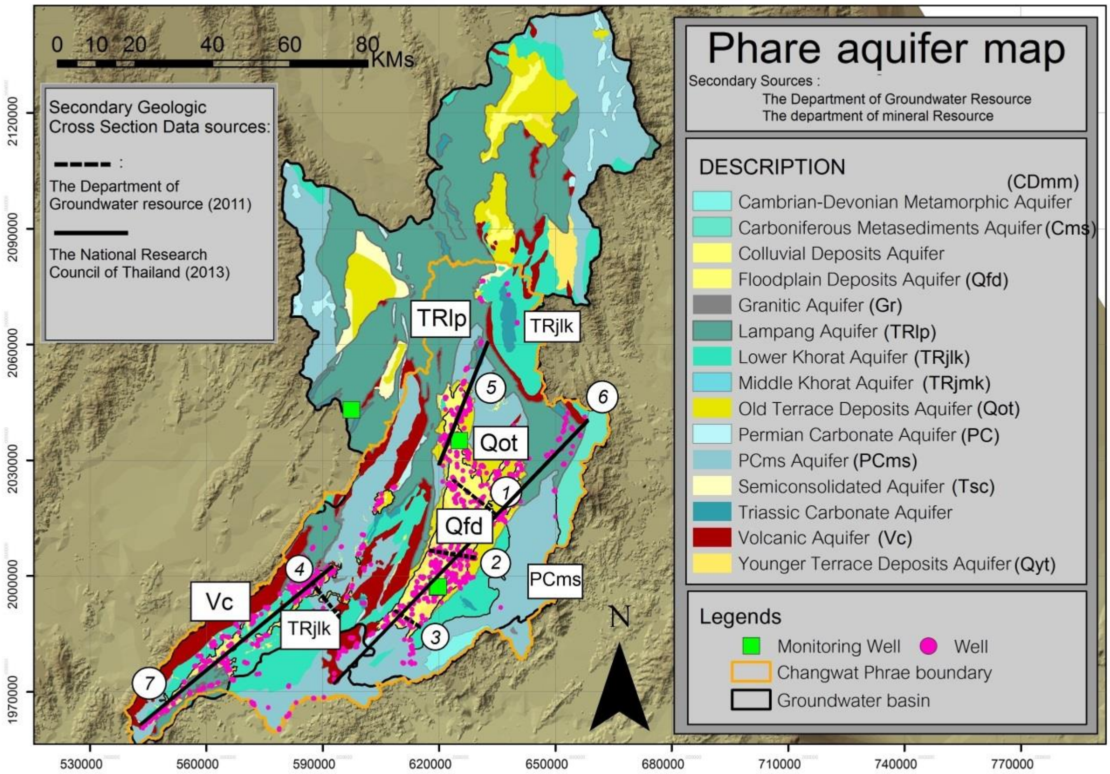

Figure 4. 12 Lithological Cross Section map of the study area (Secondary geologic cross-sections were showed in *Appendix C*).

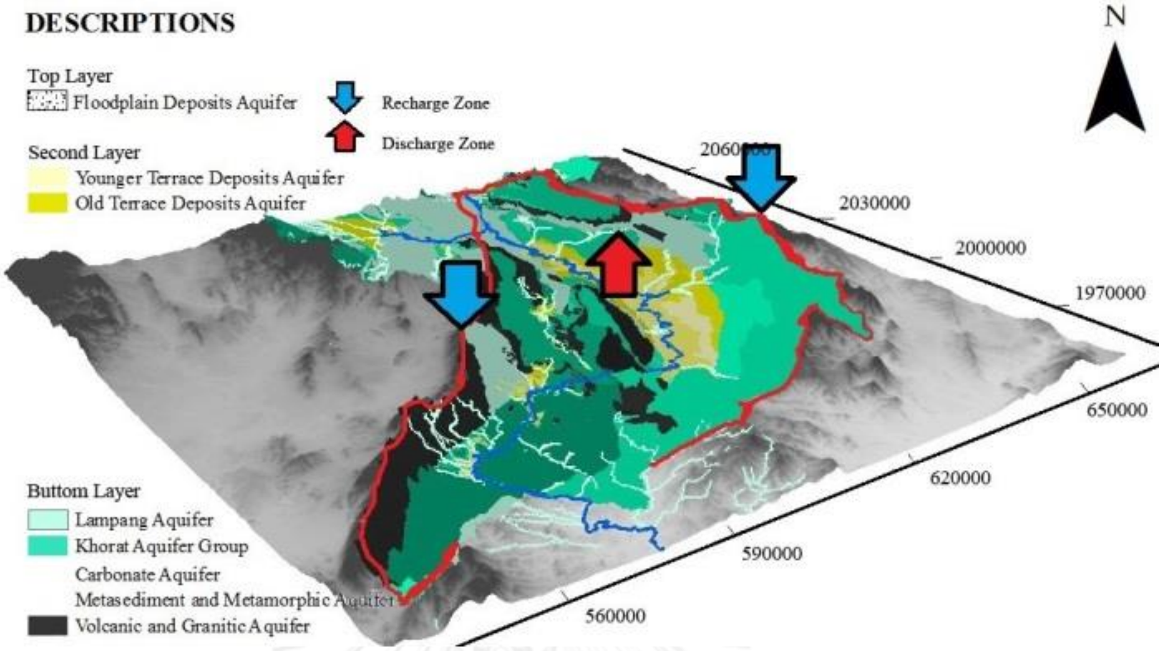

Figure 4. 13 The conceptual model of the study area shows recharge zones (blue arrows) on watershed divides areas, and discharge zones (red arrows) on fluvial floodplain areas.

4.4.2 Boundary setting step

For boundary setting, the y coordinates approximately are 1955441 - 2082881 N from south to north (710 kilometers), and x coordinates approximately are 538937 – 663857 E from west to east (420 kilometers). The total area of approximately is about 6,424 square kilometers. Grid cell size for modelling were stipulate into 90 x 90 square meters, and also separated into three layers, where each layers had a different grid cells bottom number. The first layer had 789 rows and 467 columns. The number of grid cells in the first layer was 368,463 cells. The second layer has 789 rows and 467 columns. The number of grid cells in the second layer was 368,463 cells. The third layer had 1416 rows and 1388 columns. The number of grid cells in the third layer was 2,007,048 cells (Figure 4.14). Hence, in GMS, for reasonable with raster grid cell, active cells of three layers were set on 200x200.

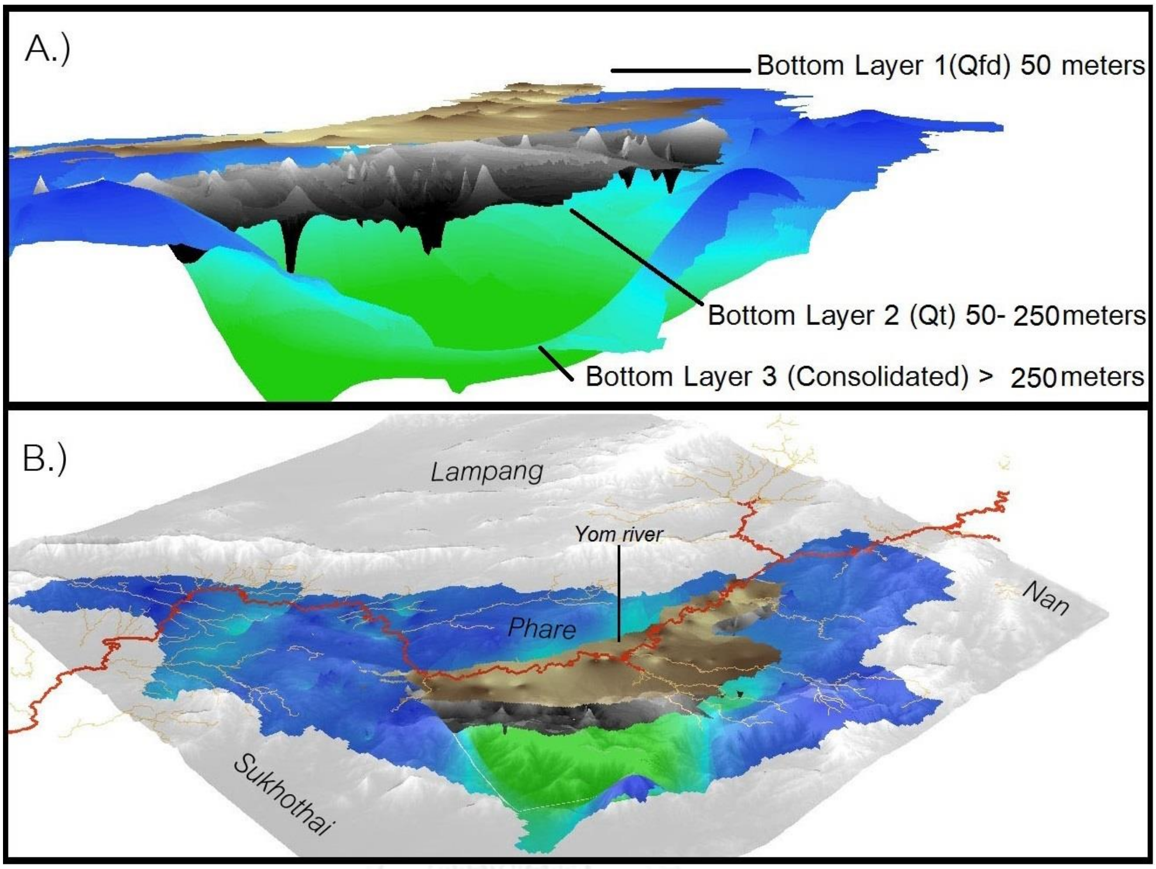

Figure 4. 14 Shows A) The side view and B) The oblique view of boundary conditions, construct from conceptual modelling design.

Furthermore, the Phrae boundary condition was specified using existing data such as lithology, hydrology, hydrogeology and topographic features. Each condition was specified as outlined below:

- The top layer grid cells is specified in active condition of the groundwater head, it depends on the hydrologic characteristic in the study area such as groundwater recharge, groundwater discharge, evapotranspiration, groundwater usage and surface runoff.

- Each of bottom layer grid cells were estimated using lithological well-log and conceptual model information. The interpolation technique was used to generate three bottom layers. Following ***4.4.1 Model Conceptualization step***, the topic is determining the bottom condition in the study area as based on geologic setting. Main layers were separated into three layers, consist of the Floodplain

Quaternary deposited aquifers (Qfd), the Terrace Quaternary deposited aquifers (Qt) and Consolidated confined aquifer. The first bottom layer (Qfd) has the depth of the layer varies from 0 to 50 meters. The second bottom layer (Qt) has the depth of the layer varies from 51 to 250 meters. The third bottom layer (Consolidated) is the deepest layer. It is deeper than 250 meters.

- In GMS MODFLOW package, Block-center flow package was used to solve the boundary condition. The different between Block-center flow package (BCF) and Layer Properties flow package is a boundary setting method, parameters for solving and application of hydraulic properties [38]. Because the study area is an intermontane basin, almost 80 percent of the area covered by consolidated rock units, and 20 percent of the area was alluvial floodplain area. Hence, Block-center flow package was used to for corresponding with areal geological boundary in the Quaternary aquifer of layer2, which showed in Figure 4.15. However, from the secondary data of Groundwater Resource in 2011, the study area had only 3 monitoring wells surrounding the region. It influenced to determination of the aquifer boundary in Block-center flow package. Hence, geologic setting data were used to carry the boundary condition. The Quaternary Terrace deposits (Qyt and Qot) were represented in the layer 2 for reduced problems of the Block-center flow solving. In addition, hydraulic properties secondary data which received from the 3 monitoring wells observation of the Department of Groundwater Resource were used to represent the hydrogeologic characteristic in the study area.

- The hydraulic head in the study area depend on topographic setting. In the groundwater basin divide or watershed divide, the specified condition was determined as no flow boundary. In the other word, the outside the study area was set up as inactive cells. Some parts of the region, especially as the foothill of the Phare groundwater basin divide, Borderland with others groundwater sub-basin such as Ngao sub-basin and Chao Phraya groundwater basin, and the range of hill that separated Amphoe Song and Amphoe Muang, The constant head boundary was represented. The Last, a head-dependent flux boundary is specified as stream line (Figure 4.16).

4.4.3 Time discretization

The time discretization is based on stress periods. Each stress period has a length that defines the temporal in model units. The starting date of the model is 1/5/2012, and the time steps are days. The measurement of groundwater levels were observed in two periods, on January and August 2013. Thus, simulation time is divided into three stress periods varies by seasonal and the end of the stress periods are based on 365 days. In addition, the groundwater balance analysis is simulated into three steady-states, such as an annual period, a dry period and a rainy period.

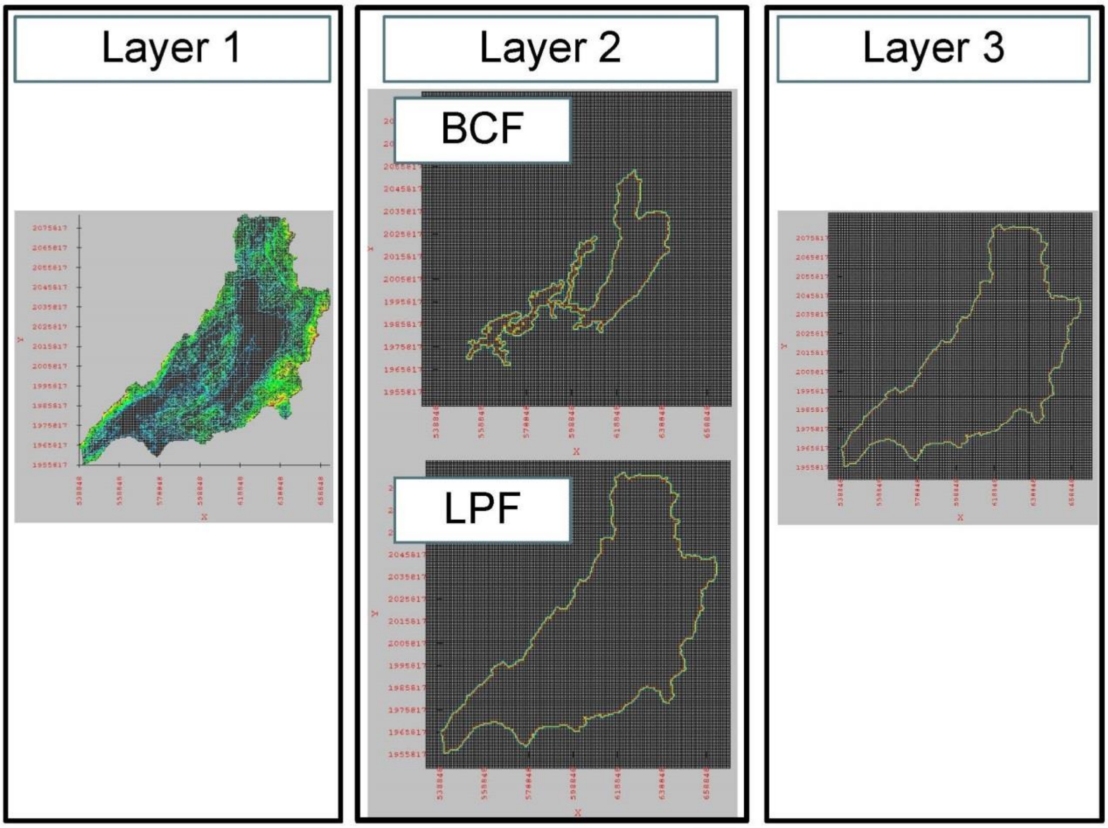

Figure 4. 15 The different of boundary solving between Block-center flow package and Layer properties flow package.

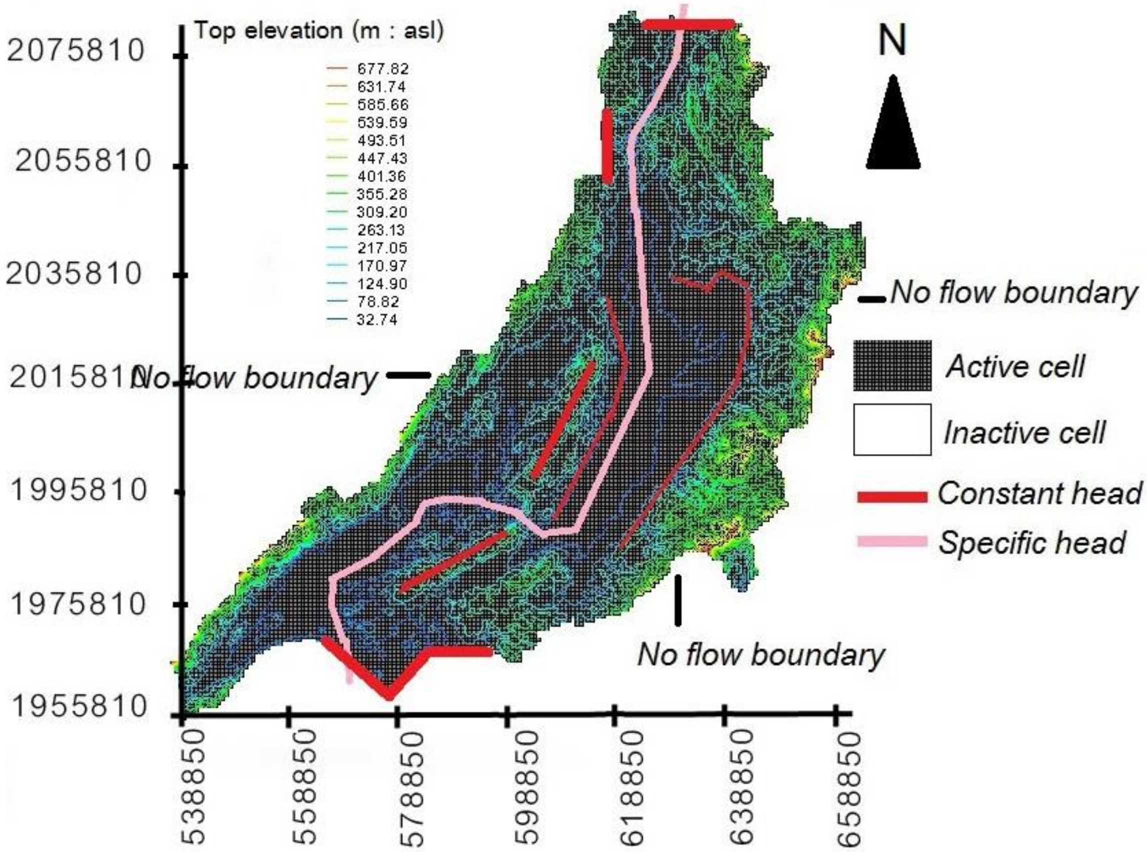

Figure 4. 16 Numerical boundary conditions of the study area in GMS MODFLOW, constructed from conceptual modelling design.

4.4.4 Model Design step (Parameters Input)

4.4.4.1 Aquifer Type

Aquifer type identifier is essential to determine the hydraulic characteristic in the aquifer. According to ***4.4.2 Boundary setting step***, Following hydrogeologic secondary data and the conceptual model, Unconfined Aquifer condition was specified in the top layer (Qfd). The second (Qt) and the bottom layers (Hard rock aquifer) were confined aquifers, approximately.

4.4.4.2 Porosity

The ratio of openings (voids) to the total volume of a soil or rock as show in Table 4.7 [11]. Generally, in solute-transport modelling, effective porosity and total porosity were used in MODPATH and MT3D module for determine temporal average linear groundwater velocities per path line. But, in groundwater flow simulation, the porosity was specified as 0.30, which is default value for each aquifer (as shown in Figure 4.17 and Equation 4.2).

$$n = Vv / Vt = 0.3\ m^3 / 1.0\ m^3 = 0.30 \quad \text{(Equation 4.2)}$$

where n is porosity (Percentage)

Vv is Volume of Voids (m^3)

Vt is Total Volume (m^3)

Table 4. 7 Selected values of porosity (Values in percent by volume) [11].

Material	Primary openings	Secondary openings
Equal-size spheres (marbles) :		
Loosest packing	48	-
Tightest packing	26	-
Soil	55	-
Clay	50	-
Sand	25	-
Gravel	20	-
Limestone	10	10
Sandstone (semi-consolidated)	10	1
Granite	-	0.1
Basalt (young)	10	1

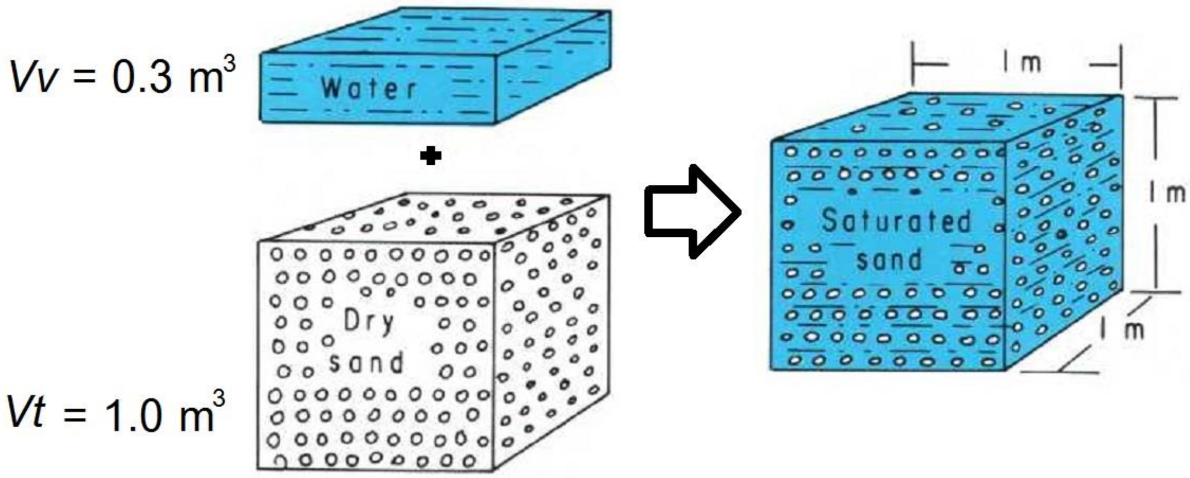

Figure 4. 17 The ratio of openings (voids) to the total volume of a soil [11].

4.4.4.3 Hydraulic Conductivity and Transmissivity

The hydraulic conductivity and Transmissivity value are the most important parameter for groundwater simulation. The units of hydraulic conductivity are those of velocity (or distance divided by time), and the rate of groundwater flows horizontally through an aquifer is the units of transmissivity (m^2/day). In a semi-confined aquifer or unconfined aquifer, the transmissivity has a small effect because the transmissivity corresponds to the distance of the groundwater table to the bottom of the layer which may change from place to place or from time to time, so that the transmissivity may vary accordingly. But, in a confined aquifer, the transmissivity is a quite stable [51]. Following related data of the Department of groundwater resource and the constant rate pumping test data of NRCT [51], the hydraulic conductivity and transmissivity were represented as parameters input, as shown in Table 4.8. and Table 4.10, and Figure 4.18

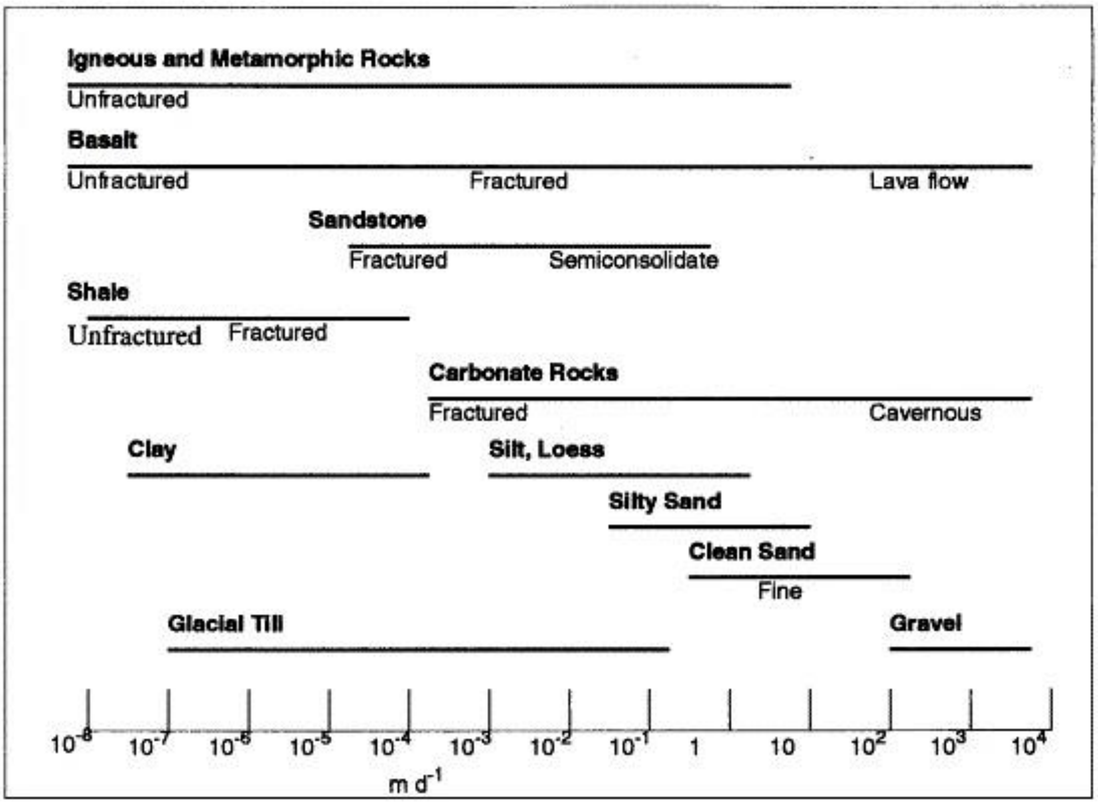

Figure 4. 18 Hydraulic conductivity of select rock [11].

Table 4. 8 Classification of Transmissivity Magnitude [66].

Transmissivity Coefficient (m^3/ d)	Class		Groundwater supply potential
1000	I	Very high	Withdrawals of great regional importance
100	II	High	Withdrawals of lesser regional importance
10	III	Intermediate	Withdrawals for local water supply
1	IV	Low	Smaller Withdrawals for local water supply
0.1	V	Very low	Withdrawals for local water supply with limited consumption
0.1	VI	Imperceptible	Sources for local water supply are difficult

4.4.4.4 Specific Storage

In transient calibration, the specific storage is an important parameter which is receives from a division of storage coefficient with a thickness of the aquifer. In addition, the physical factors that control specific storage are the same factor involved in the thickness and moisture content of the capillary fringe. Storage coefficient value from pumping test data of NTRC [51] and the thickness of the aquifers from conceptual model design were used to define the specific storage. However, this parameter is necessary to adjustment for accuracy using literature research because the results of pumping test showed the large ranging of the storage coefficient value. The National Research Council of Thailand define that the specific storage range in confine aquifer is 5.0×10^{-5} to 5.0×10^{-3}. For all soil unit groups, the specific storage range is 5.0×10^{-5} to 5.0×10^{-3}., as shown in Table 4.9 and Table 4.10

Table 4. 9 Values of porosity, specific yield and specific retention (percentage by volume).

Material	Porosity	Specific Yield	Specific retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone	11	6	5
Granite	0.1	0.09	0.01
Basalt	11	8	3

Table 4. 10 Hydraulic properties input for MODFLOW modelling [51].

Aquifer type	Quaternary deposited	Hard rock aquifer
Hydraulic Conductivity (K)	1.99 – 17.47 (9.68)	2.02 – 18.18 (8.53)
Transmissivity (T)	6.9-480 (m^2/day)	100 - 110 (m^2/day)
Specific Storage (Ss)	5.17×10^{-4} – 4.00×10^{-1} (7.90×10^{-2})	6.28×10^{-4} – 4.33×10^{-2} (8.39×10^{-2})

4.4.4.5 Initial Head

Observation wells in 2009 from Department of Groundwater Resources (DGR) were represented as Initial head input in each layer. In addition, observation wells from field investigations were used to model calibration. Furthermore, the groundwater simulation in steady-state condition is also used to represent as initial head parameter for transient condition. In addition, lists of groundwater well source was showed in Table 4.11

4.4.4.6 Recharge and Discharge Rates

Groundwater recharge and discharge are necessary for determine the groundwater flow and groundwater balance simulation. For groundwater recharge rate, it was calculated using the distributed hydrological model WetSpass. And groundwater discharge rate, schematic model and field investigation are used to groundwater discharge assessment. Generally, in natural condition, the most important factor of groundwater discharge is sub-surface outflows to river. But, in the case of human activity, 299 groundwater wells data from Department of Groundwater Resource were used to specify the groundwater usage. Parameters were consisted of well location, depth of well, groundwater yield per time unit. Furthermore, for accuracy, interviewed information from field investigation was used to determine groundwater use behaviors in the model. After field investigation, this study was specified the groundwater usage mostly is domestic use, especially in rural area. Thus, domestic use rate is calculated using the standard of domestic usage Provincial Waterworks Authority [4] which as shown in Table 4.12, per population in rural. The groundwater wells location and water usage mapping is show in Figure 4.19, and the groundwater recharge input is shown in Figure 4.20.

Table 4. 11 lists of groundwater well sources.

Groundwater wells Source	Number of wells	Applications
Field investigation in dry period	74	Groundwater calibration in GMS MODFLOW (dry period)
Field investigation in rainy period	64	Groundwater calibration in GMS MODFLOW (rainy period)
Secondary data with well screen, well bottom and depth of water table data from DGR (2009)	103	Groundwater starting heads in GMS MODFLOW
Secondary data with well screen, and groundwater usage from DGR (2009)	310	Groundwater usage in GMS MODFLOW

Table 4. 12 Show domestic use rates (L/ People/ Day) [4].

Urban type	Rates (L/ People / Day)
1. Rural area	50
2. Municipal and Build-up area (people)[1]	
3,000 – 10,000	120
10,001 – 20,000	170
20,001 – 30,000	200
30,001 – 50,000	250
> 50,000	300

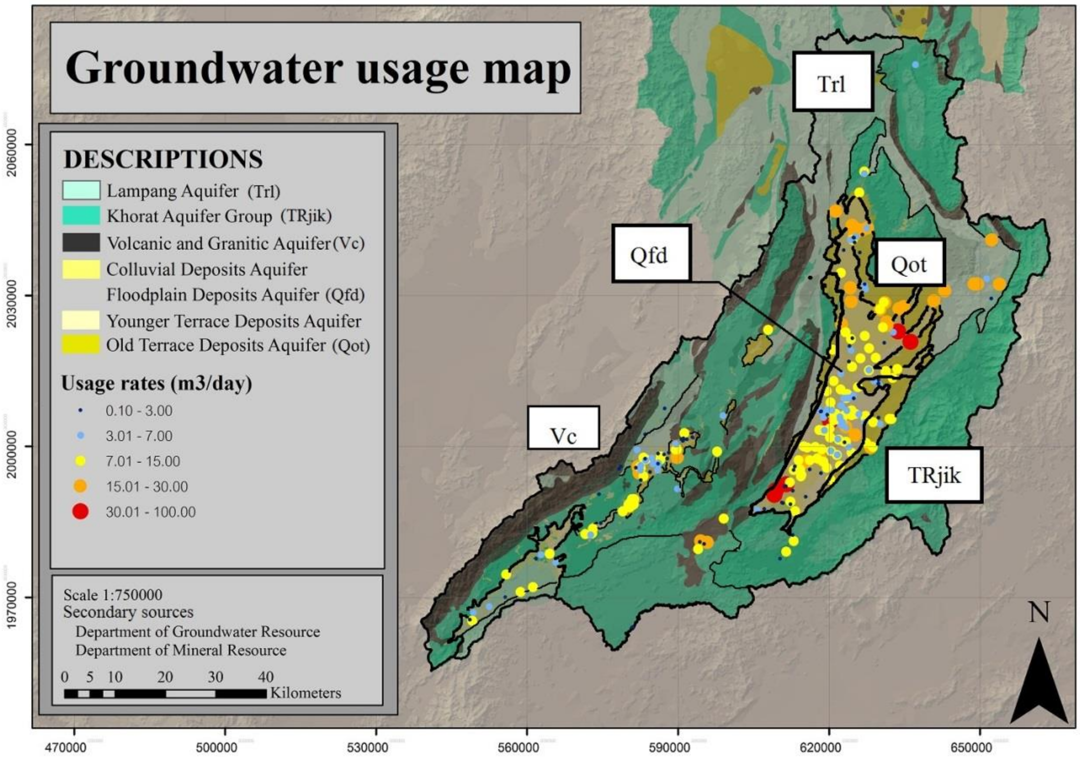

Figure 4. 19 The rates of groundwater usage per day, which shows the Quaternary floodplain (Qfd) and the Terrace deposited (Qt) have high rates of groundwater usage.

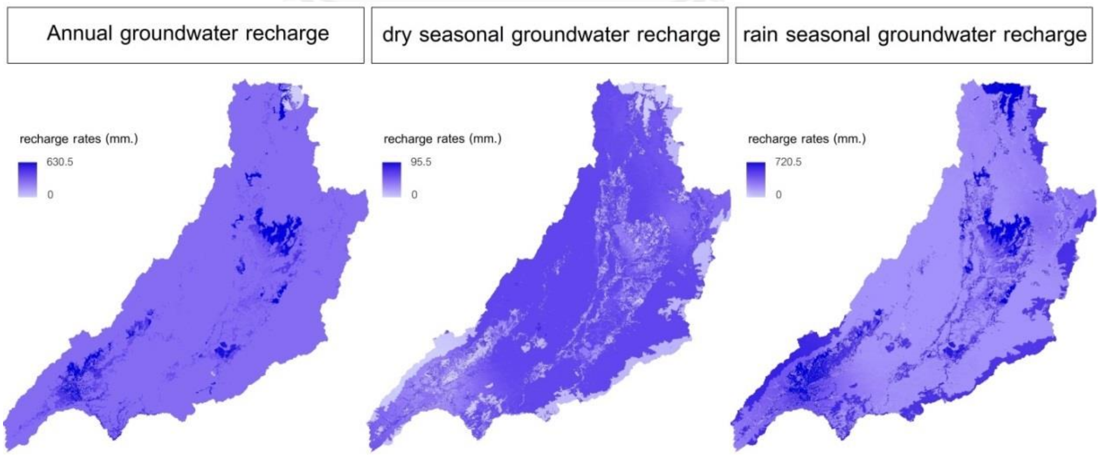

Figure 4. 20 The rates of groundwater recharge per day from WetSPASS.

4.4.4.7 River

Hydrological data in this study was obtained from Department of Water Resources (DWR), which represented as cross-sections of the Yom river channels and monthly runoff data. In groundwater flow simulation, river package (RIV) is used to specify head-dependent flux boundaries. The parameter consists of Stream gaging stations, Runoff volume, Channel depth, Channel width, Channel length, vertical hydraulic conductivity (Kz), and river bedding. Following the results of NTRC [51], the vertical hydraulic conductivity was set on default as 0.5-3.5 m/day, and assuming of the river bedding has a thickness as 1 meter along the river.

4.4.5 Model Calibration and Vilification

This study, the model calibration was separated in two steps, as the steady-state condition and transient-state condition. 40 groundwater wells data from field investigation were used to Steady-State calibration, the time discretization was set to start on 1/5/2012. In addition, an objective of this calibration is scrutinisation the model schematic and sensitive analyst. Major parameters were calibrated in this step such as Transmissivity (T), Hydraulic Conductivity (K), Recharge rate and Boundary condition accuracy. In Transient Condition, stress periods in 2012-2013 were used to calibrated, major parameters were calibrated in this step such as Hydraulic Conductivity (K), Specific Storage (Ss), Recharge rates and Boundary condition accuracy. Trial and Error method were used to calibrate the model.

CHAPTER V
RESULTS

In this chapter, the results of groundwater flow and groundwater balance assessment are shown, which includes analysis of the groundwater recharge, examination of significant factors in water balance and topographic feature, as well as groundwater flow modelling development by using relevant variables in GIS and MODFLOW model. The results can be divided into three parts. The first section describes results of variability of groundwater level in terms of spatial and temporal dimensions, derived from collecting secondary data and field study by using GIS. The second section shows relationship of relevant variables in groundwater recharge estimation. At last, incorporated with groundwater recharge from section 2, the groundwater flow was then calibrated and validated using GMS MODFLOW both steady state and transient states. The results of groundwater flow and groundwater balance were presented in form of spatial mapping technique.

5.1 Seasonal Changes of groundwater table and schematic groundwater flow direction

According to field investigation, 62 observation wells shown in Table 5.1 were used to develop the schematic groundwater flow both in summer and rainy season in the study area.

5.1.1 Schematic groundwater flow

Data of the water table, ascertained from the fieldwork, was compared with the mean sea level (a.s.l). The results of the groundwater flow in three aquifers are shown in Figure 5.1, Figure 5.2 and Figure 5.3. In addition, Table 5.2 also shows the hydraulic gradient in three aquifers.

Table 5. 1 List of Observation wells.

Well No.	X	Y	Depth	Elevation	Accuracy	Aquifer	Depth of water (M.)		Water table (M:asl.)		Change
							Dry	Rain	Rain	Dry	
NEW7	632001	2014926	-	186	3	Qfd	7.02	9.80	176.20	178.98	-2.78
NEW14	620641	2006323	-	158	3	Qfd	13.71	4.50	153.50	144.29	9.21
MR292	619671	2006296	27	147	4	Qfd	7.87	8.16	138.84	139.13	-0.29
unknow2	617501	2005859	-	161	2	Qfd	11.59	10.25	150.75	149.41	1.34
unknow4	613963	1997324	-	77	2	Qfd	11.07	3.75	73.25	65.93	7.32
PW15954	627880	2015185	30	167	2	Qfd	20.17	22.47	144.53	146.83	-2.30
PW346	627913	2015162	26	173	3	Qfd	15.41	16.55	156.45	157.59	-1.14
unknow7	624010	2020122	-	172	4	Qfd	10.66	3.47	168.53	161.34	7.19
MR54	620501	2011138	33	160	6	Qfd	8.91	2.75	157.25	151.09	6.16
DCD15937	623889	2023725	-	168	3	Qfd	5.10	6.25	161.75	162.90	-1.15
MR0507	626225	2047140	-	204	3	Qfd	4.80	5.90	198.10	199.20	-1.10
NEW12	619834	2005748	-	152	3	Qt	8.57	10.68	141.32	143.43	-2.11
NEW8	634835	2022883	140	199	2	Qt	2.68	3.51	195.49	196.32	-0.83
ก1642	634883	2022887	-	196	6	Qt	2.53	2.06	193.94	193.47	0.47
PR140	574097	1990310	92	146	3	Qt	4.26	4.38	141.62	141.74	-0.12
ก1270	587047	1997779	-	141	5	Qt	3.49	2.46	138.54	137.51	1.03
MR573	590390	1989807	24	148	5	Qt	2.94	2.98	145.02	145.06	-0.04
NEW13	618764	2006245	-	155	3	Qt	7.21	7.55	147.45	147.79	-0.34
unknow6	623374	1999326	-	170	4	Qt	7.78	6.22	163.78	162.22	1.56

Table 5. 1 (Continue) List of Observation wells.

Well No.	X	Y	Depth	Elevation	Accuracy	Aquifer	Depth of water (M.)		Water table (M:asl.)		Change
							Dry	Rain	Rain	Dry	
MR580	627694	2045770	114	195	6	Qt	2.10	2.15	192.85	192.90	-0.05
PW4824	630919	2028669	21	200	2	Qt	5.29	6.55	193.45	194.71	-1.26
MR465	563854	1984063	26	132	5	Qt	5.87	4.93	127.07	126.13	0.94
MR444	585048	1997802	144	242	3	Qt	5.40	4.47	237.53	236.6	0.93
NEW11	636165	2024208	-	195	3	Qt	2.34	2.94	192.06	192.66	-0.60
DCD15827	589579	2000451	-	148	5	Qt	0.52	0.45	147.55	147.48	0.07
New4	589664	2000524	-	158	4	Qt	13.22	14.08	143.92	144.78	-0.86
NEW1	562800	1978442	-	120	3	Qt	8.10	6.41	113.59	111.90	1.69
NEW2	562831	1978485	-	121	3	Qt	7.69	6.50	114.50	113.31	1.19
DCD1570	631132	2028698	-	203	7	Qt	8.09	8.84	194.16	194.91	-0.75
NT54/1-2	624901	2035497	90	186	3	Qt	1.68	-6.50	192.50	184.32	8.18
MR612	623596	2009575	114	161	4	Qt	26.51	13.90	147.10	134.49	12.61
MR278	615382	1990009	186	167	4	Qt	7.03	6.50	160.50	159.97	0.53
DOH11990	629625	2017806	-	171	4	Qt	2.20	2.88	168.12	168.80	-0.68
MR190	589080	1998871	24	126	6	Qt	2.20	1.06	124.94	123.80	1.14
DCD16633	589410	1998871	-	133	2	Qt	2.47	1.70	131.30	130.53	0.77
MB24	614274	1995457	60	120	3	Qt	9.26	9.42	110.58	110.74	-0.16
MR433	630484	2015248	51	185	2	Qt	8.24	8.04	176.96	176.76	0.20
MR666	612357	1988553	63	154	4	Qt	5.13	4.63	149.37	148.87	0.50

Table 5. 1 (Continue) List of Observation wells.

Well No.	X	Y	Depth	Elevation	Accuracy	Aquifer	Depth of water (M.)		Water table (M:asl.)		Change
							Dry	Rain	Rain	Dry	
DOH2007	628358	2004832	-	187	5	Qt	24.31	21.90	165.10	162.69	2.41
MR458	609447	1991291	48	145	4	Qt	7.71	8.10	136.90	137.29	-0.39
MR40	620244	2001812	72	158	6	Qt	17.88	18.80	139.20	140.12	-0.92
ก2824	578985	1987136	-	132	3	Qt	4.89	2.70	129.30	127.11	2.19
A4	606109	2007633	-	270	7	Trjik	8.05	7.40	262.60	261.95	0.65
MR475	648857	2032293	50	264	4	Trjik	11.95	11.05	252.95	252.05	0.90
MR577	643444	2030867	54	233	5	Trjik	9.34	9.14	223.86	223.66	0.20
MH375	647654	2031638	-	254	4	Trjik	10.64	11.05	242.95	243.36	-0.41
MR673	637159	2075840	45	386	3	Trjik	1.25	1.31	384.69	384.75	-0.06
TNB166	558710	1971114	112	117	3	Trjik	4.00	6.20	110.80	113.00	-2.20
MR127	561127	1972060	21	109	4	Trjik	2.69	2.93	106.07	106.31	-0.24
unknow1	630817	2061189	-	340	3	Trjik	6.52	4.90	335.10	333.48	1.62
Q382	631016	2077029	18	279	3	Trjik	2.99	3.45	275.55	276.01	-0.46
MR523	612024	1983631	63	178	3	Trjik	1.58	1.89	176.11	176.42	-0.31
MR78	587352	2007556	30	232	5	Trjik	6.17	16.63	215.37	225.83	-10.46
MR638	611992	1983731	57	181	4	Trjik	0.49	4.81	176.19	180.51	-4.32
ก2826	561892	1977729	-	117	3	Trjik	9.01	9.50	107.50	107.99	-0.49
MR628	554404	1969678	45	136	3	Trjik	3.14	2.80	133.20	132.86	0.34
MR24	649543	2032285	-	263	4	Trjik	10.61	11.08	251.92	252.39	-0.47

Table 5. 1 (Continue) List of Observation wells.

Well No.	X	Y	Depth	Elevation	Accuracy	Aquifer	Depth of water (M.)		Water table (M:asl.)		Change
							Dry	Rain	Rain	Dry	
DCD15775	604272	2007447	-	307	3	Trjik	10.00	12.75	294.25	297.00	-2.75
PW20033	604264	2007446	30	308	3	Trjik	8.98	5.55	302.45	299.02	3.43
A8	606325	1987625	-	170	6	Trjik	2.90	2.33	167.67	167.10	0.57
MR669	607153	1987634	81	176	5	Trjik	8.10	8.76	167.24	167.90	-0.66

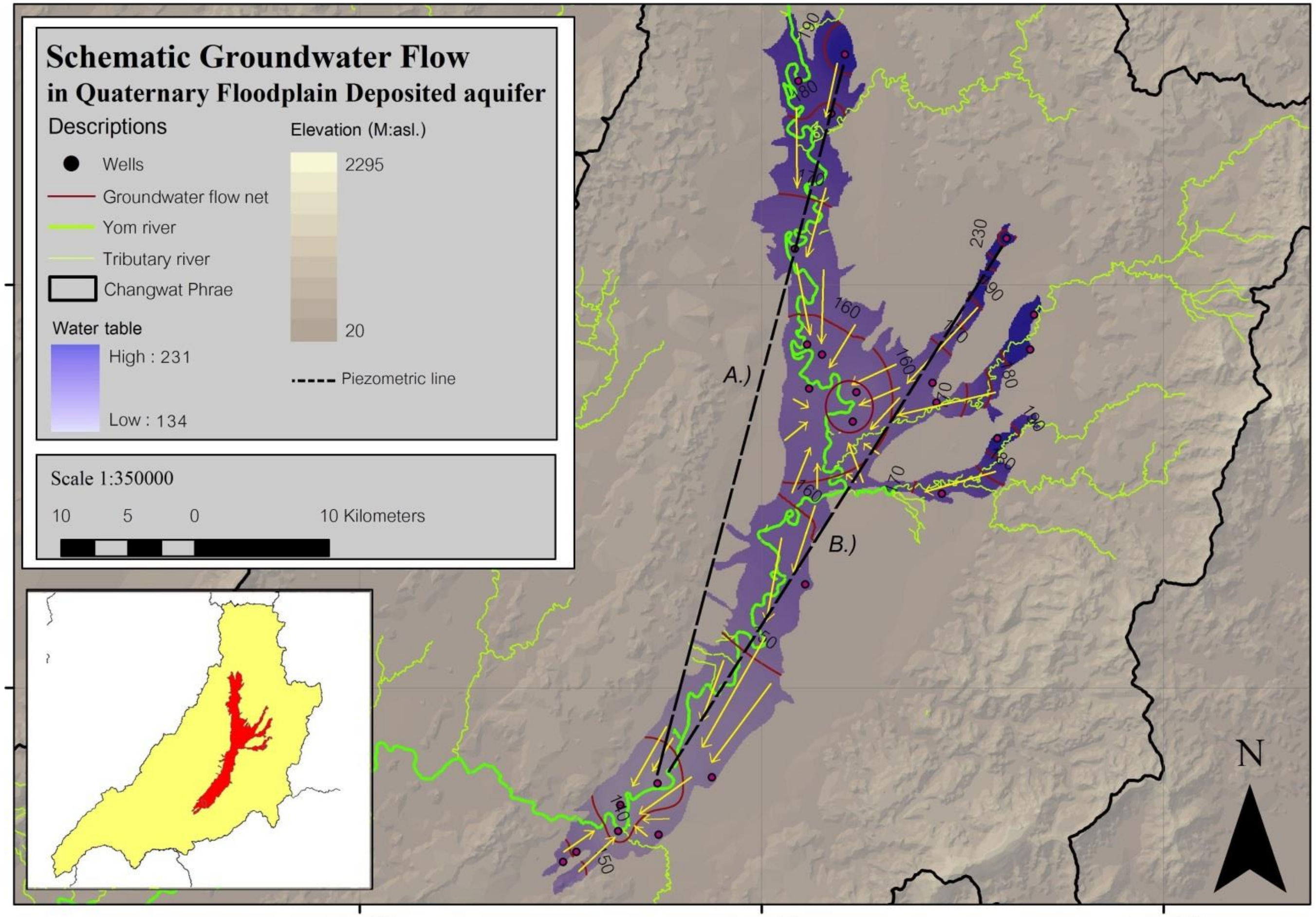

Figure 5. 1 Schematic groundwater flow in Quaternary Floodplain Deposited aquifer (Qfd).

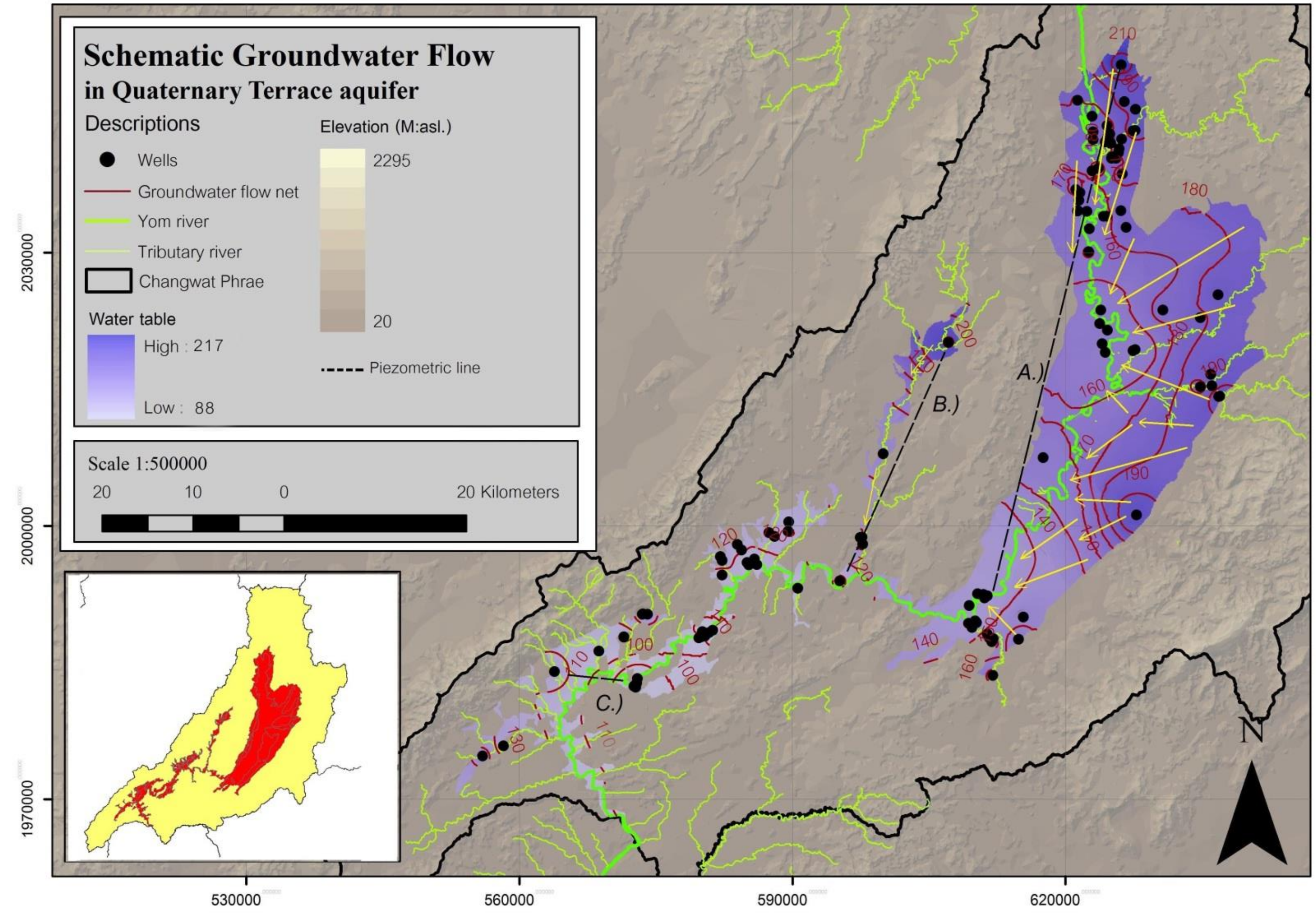

Figure 5. 2 Schematic groundwater flow in Quaternary Terrace Deposited aquifer (Qyt and Qot).

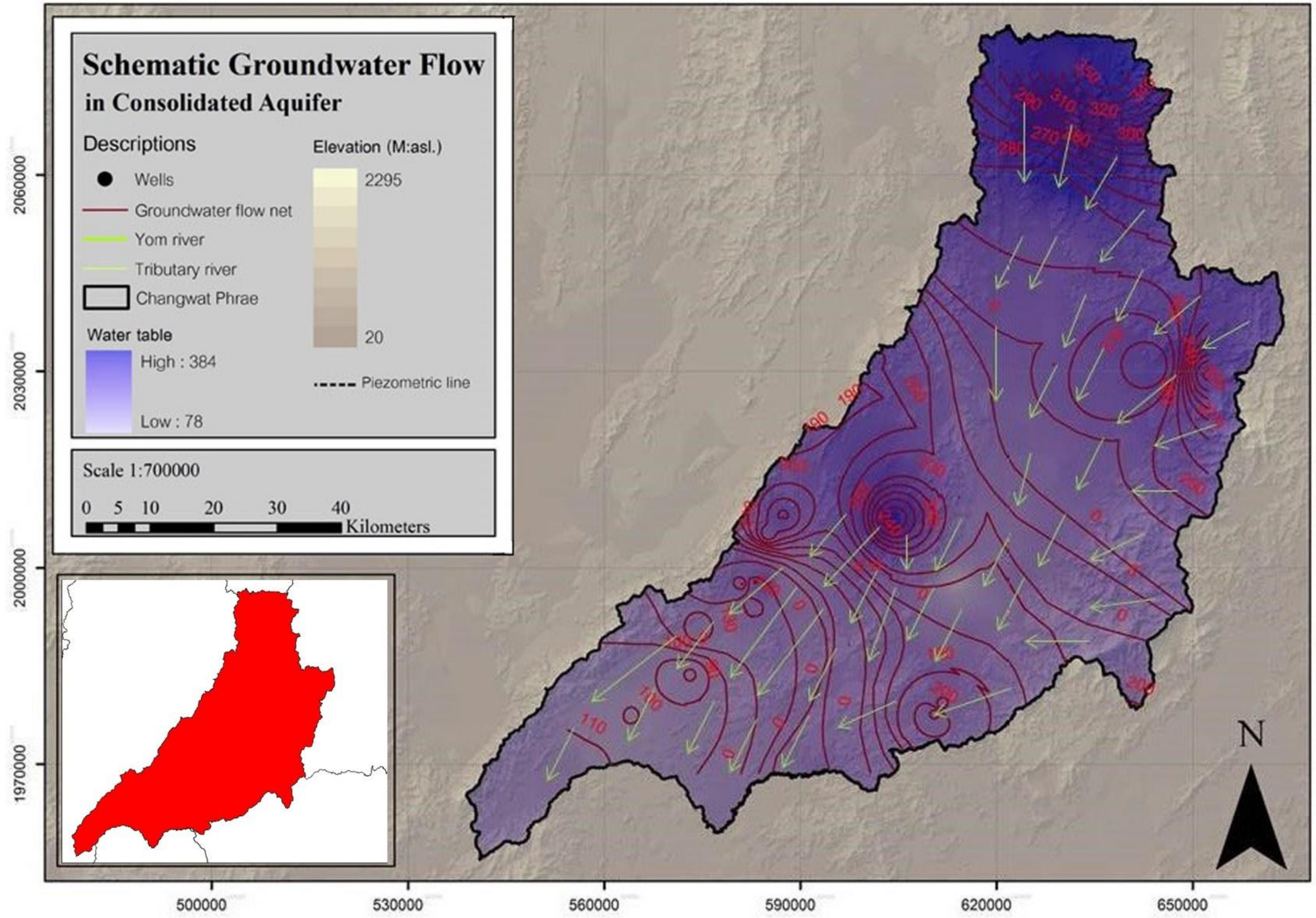

Figure 5. 3 Schematic groundwater flow in consolidated aquifer (Trjik, Pc and PCms).

Table 5. 2 The hydraulic gradient in three aquifers.

Aquifer	Line	h1 (m:asl.)	h2 (m:asl.)	Distance (M.)	*i*
Quaternary floodplain Deposited	A	204	139	56,000	0.0011
	B	231	139	48,000	0.0019
Quaternary Terrace Deposited	A	217	133	60,300	0.0013
	B	200	119	28,700	0.0018
	C	124	99	9,000	0.0027
Consolidated Aquifer	A	276	106	128,400	0.0013

In Quaternary Floodplain Deposited aquifer (Qfd), the groundwater flow flows from the north to the south and drain to the central part of the region. A mean hydraulic gradient is approximately 0.0015. In addition, some regions clearly show cones of depression. In regional consideration, the land surface of the floodplains behave as recharge zones, it depend on land use pattern. Meanwhile, Yom River in the floodplain areas behaves as a discharge zone.

In Quaternary Terrace Deposited aquifer (Qt), the groundwater flows from the north to the south with a mean hydraulic gradient of approximately 0.0015, as measured from the compiled piezometric map. In hydrogeological conceptual model, the aquifer is defined as the confine aquifer and the recharge is derived from vertical hydraulic conductivity of the Quaternary Floodplain Deposited aquifer. As described above, the foothill areas behave as recharge zones and the floodplain area behaves as a discharge zone.

Similarly, the groundwater direction of the consolidated aquifers flow from the north to the south with a mean hydraulic gradient of approximately 0.0013, as measured from the compiled piezometric map. In hydrogeological conceptual model, the mountainous areas behave as recharge zones and the floodplain behaves as a discharge zone. In addition, the outflow of all aquifers flows into the Upper Chao Phraya aquifer.

5.1.2 Change in groundwater table levels

Data of the groundwater head, ascertained from the fieldwork, was compared with the mean sea level (a.s.l). The results of the seasonal groundwater head and the differential groundwater head in three aquifers are shown in Figure 5.4 to Figure 5.10. In general, groundwater head in rainy season should be higher than that in dry season. However, some observation wells showed that groundwater head in dry season were higher than groundwater head in rainy season, especially wells along the Yom River in central part of the area. The groundwater heads are relatively high in rainy season due to water logging. The further details were described as follows:

In Quaternary Floodplain Deposited aquifer (Qfd), most of groundwater levels in dry season were lower than those in rainy season. The difference of groundwater levels varies between -2.78 to 9.21 meters. The highest of water table is 2.75 meters below ground surface elevation in rainy season, and the lowest of water table is 22.47 meters below surface elevation in rainy season. In the regions where groundwater levels in rainy season was lower than the water those in dry season, mostly are located at high land where it is far from Yom River.

In Quaternary Terrace Deposited aquifer (Qt), groundwater levels in dry season mostly were lower than those in rainy season. The difference of groundwater levels varies between -2.11 to 12.61 meters. The highest of groundwater levels is 6.50 meters above ground surface elevation in rainy season, and the lowest of groundwater levels is 26.51 meters below ground surface elevation in dry season. In areas where groundwater levels in rainy season was lower than those in dry season, mostly are located at high land where it is far from Yom River.

In contrary, groundwater levels in Consoilidated aquifer dry season mostly were higher than those in rainy season. The difference of water table varies between -10.46 to 3.43 meters. The highest of groundwater levels is 0.49 meters below surface elevation in dry season, and the lowest of water table is 16.63 meters below ground surface elevation in rainy season. However, the consolidated aquifer shows a little difference of seasonal groundwater table.

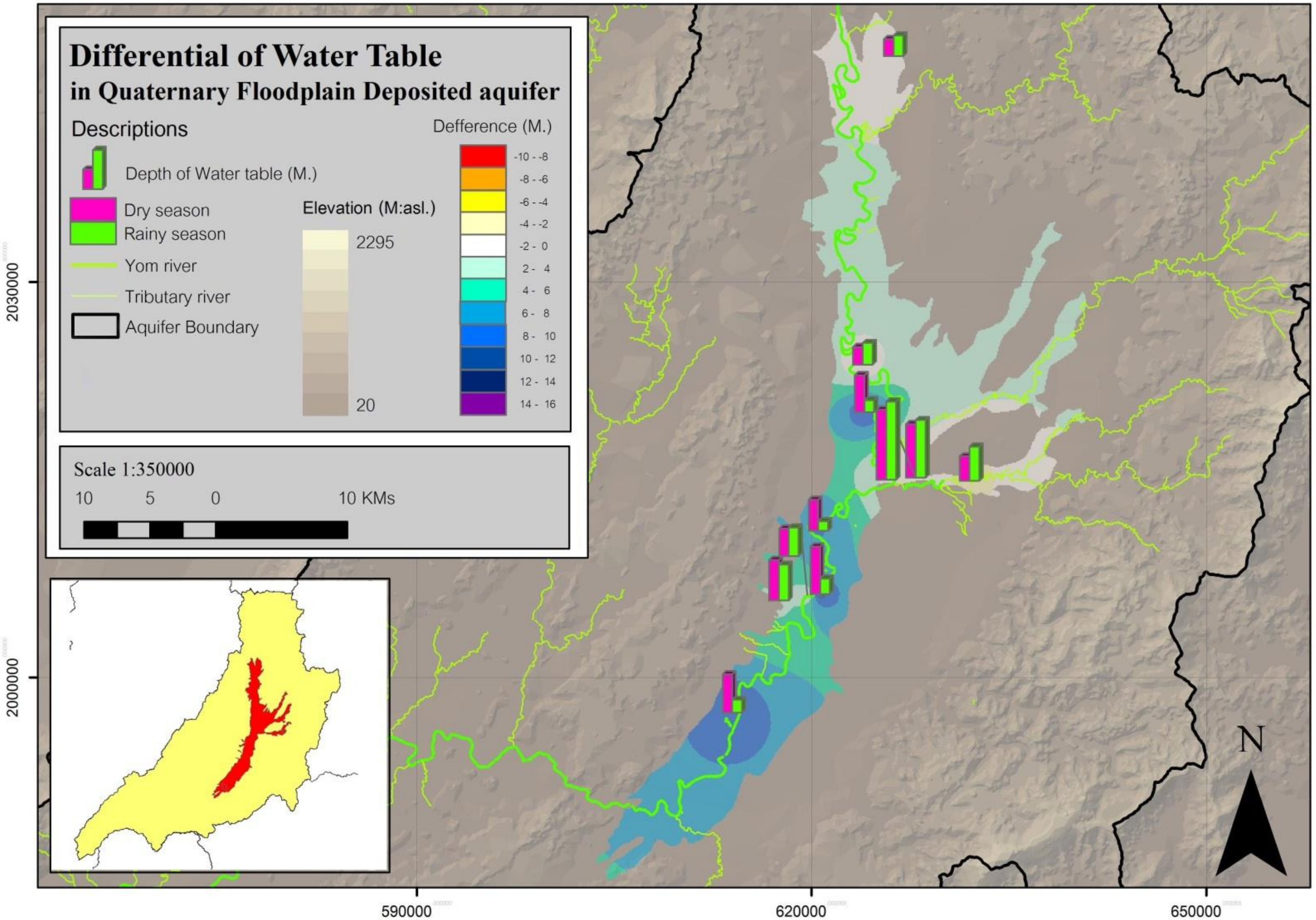

Figure 5. 4 Differential of groundwater level in Quaternary Floodplain Deposited aquifer (Qfd).

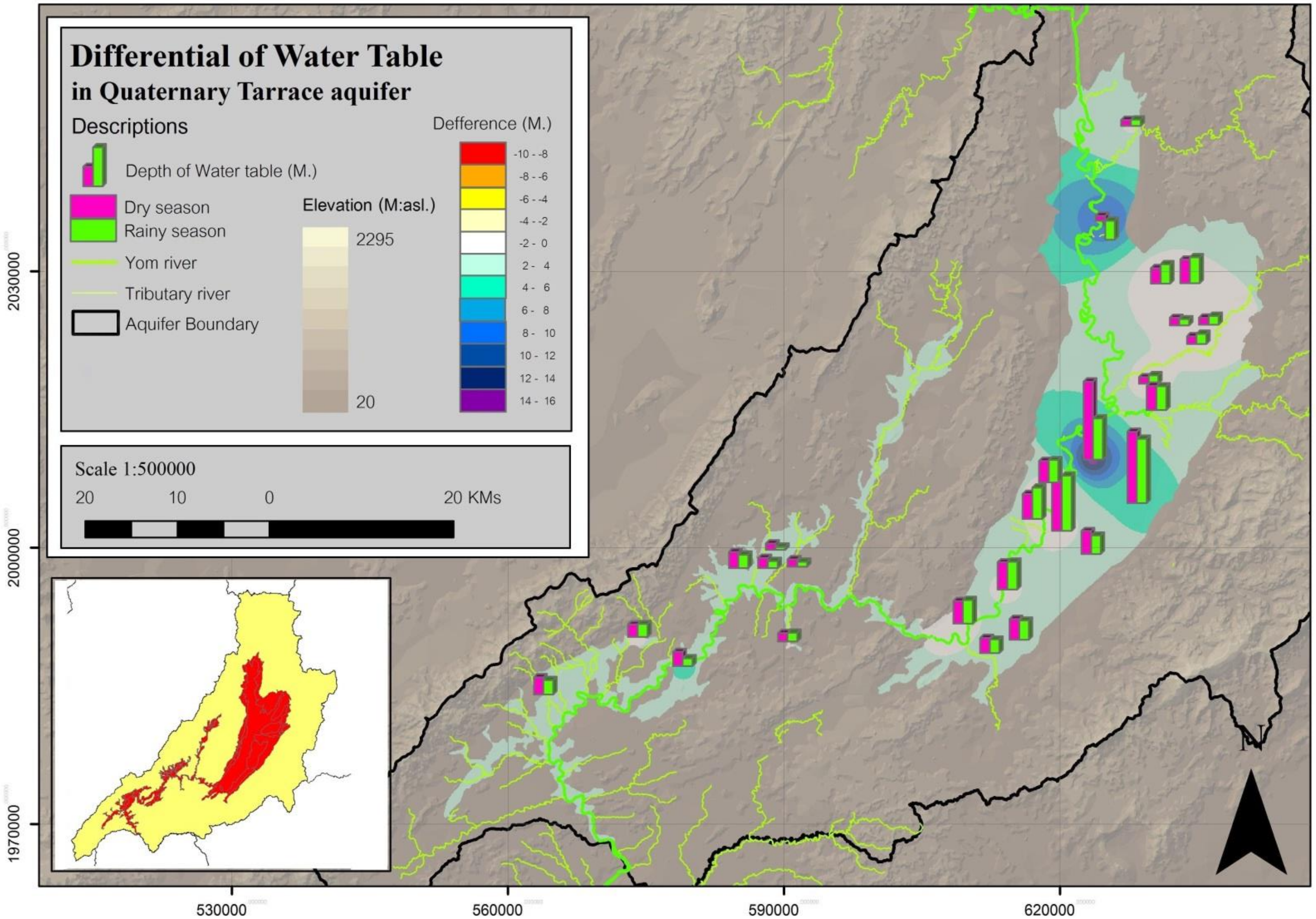

Figure 5. 5 Differential of groundwater level in Quaternary Terrace aquifer (Qyt and Qot).

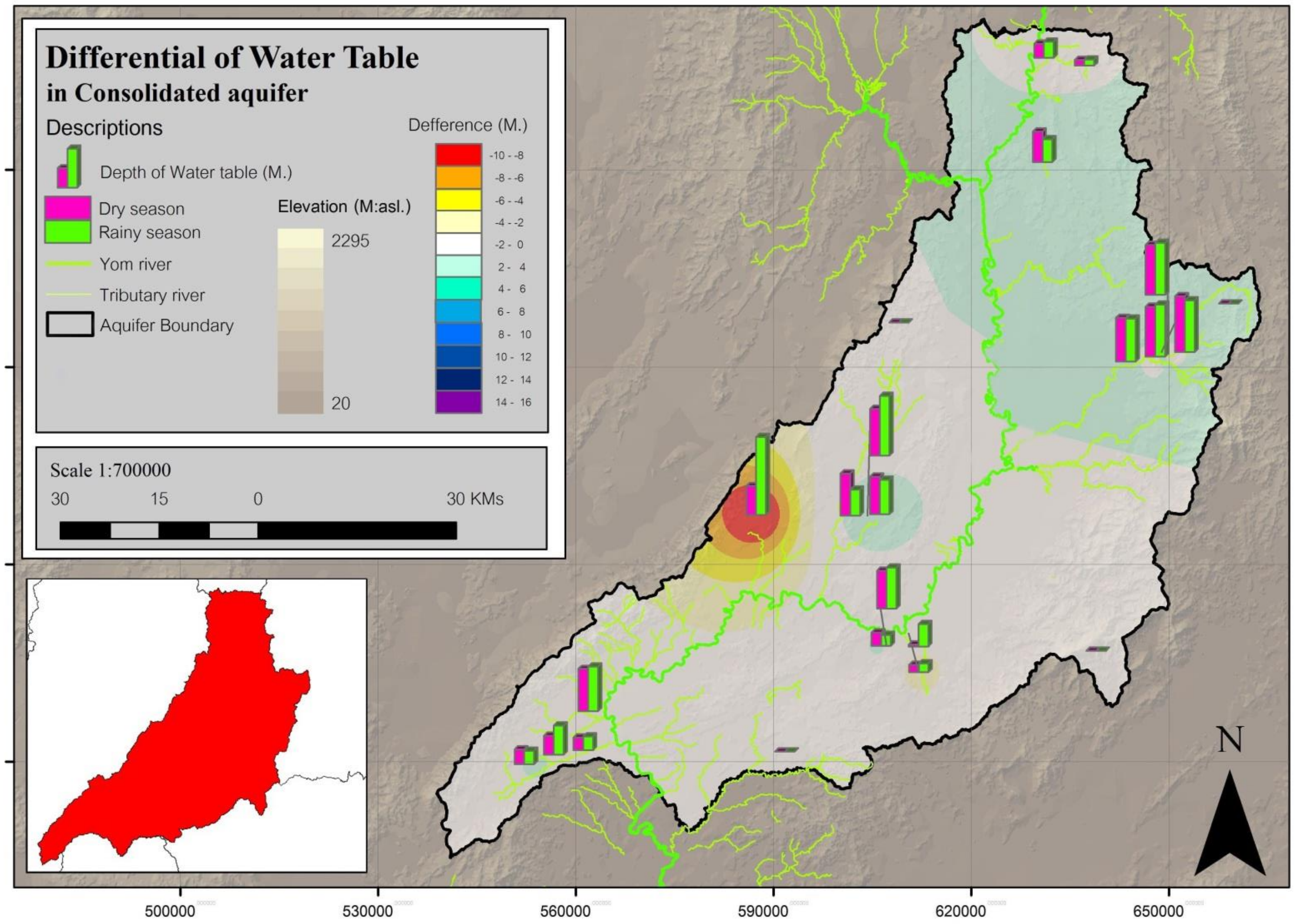

Figure 5. 6 Differential of groundwater level in consolidated aquifer (Trjik, Pc and PCms).

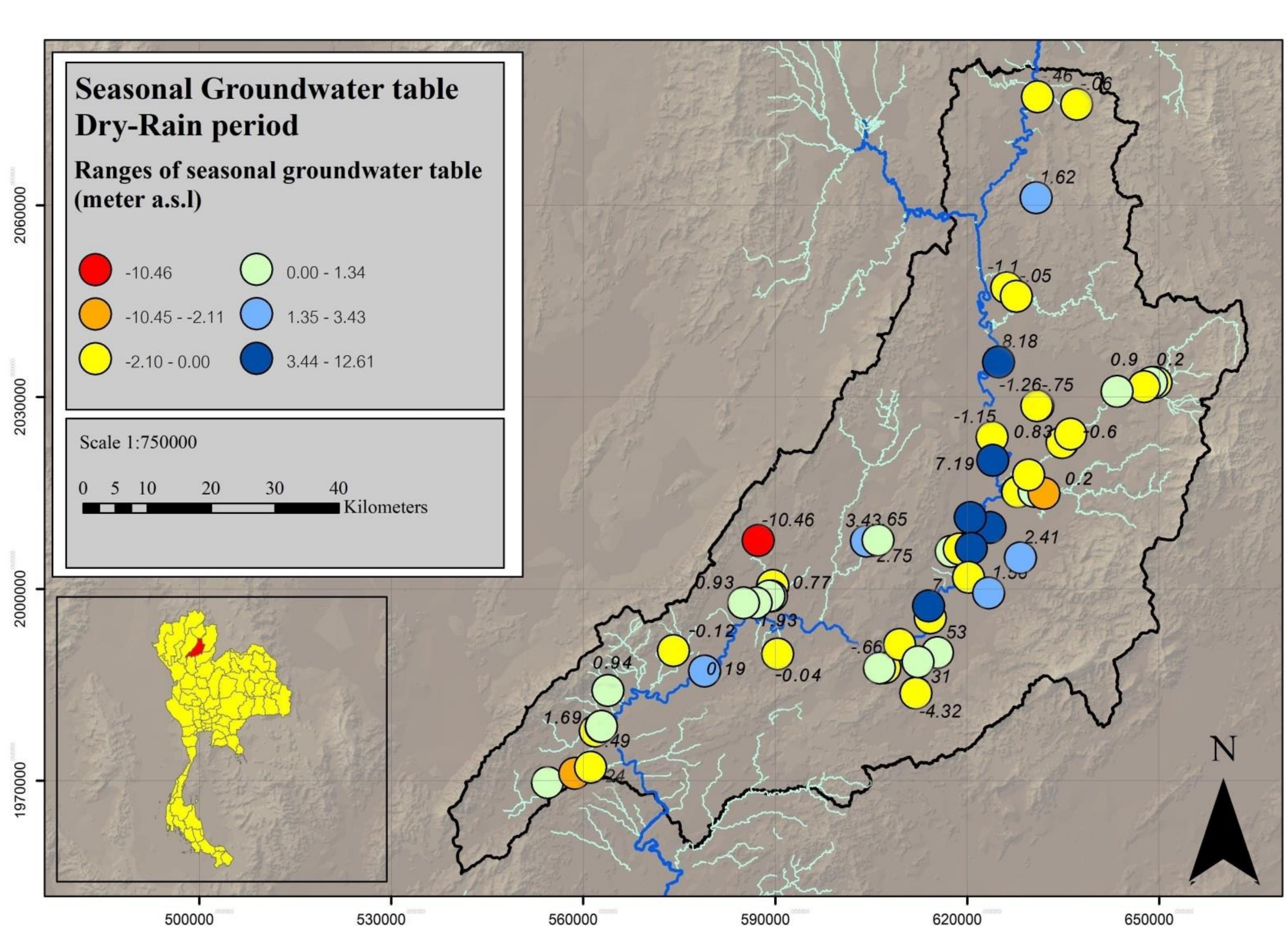

Figure 5. 7 Differential of the Seasonal Groundwater level of Observation wells in Changwat Phrae.

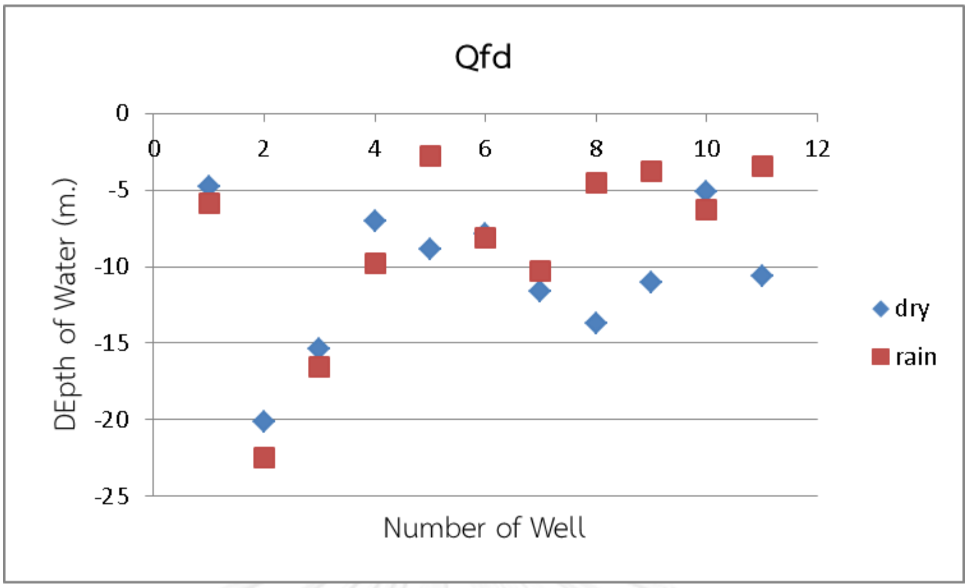

Figure 5. 8 Groundwater table in Quaternary Floodplain deposited (Qfd).

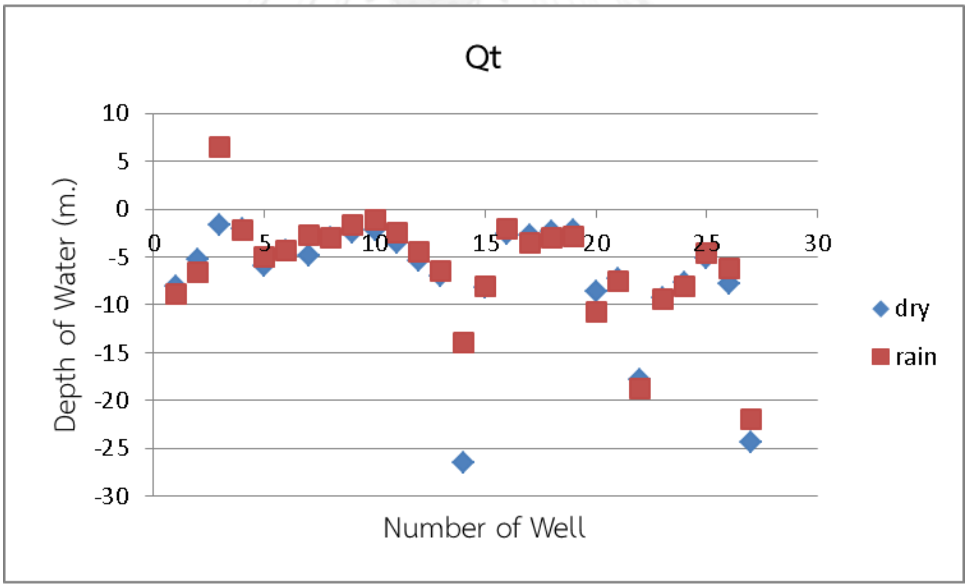

Figure 5. 9 Groundwater table in Quaternary Terrace deposited (Qt).

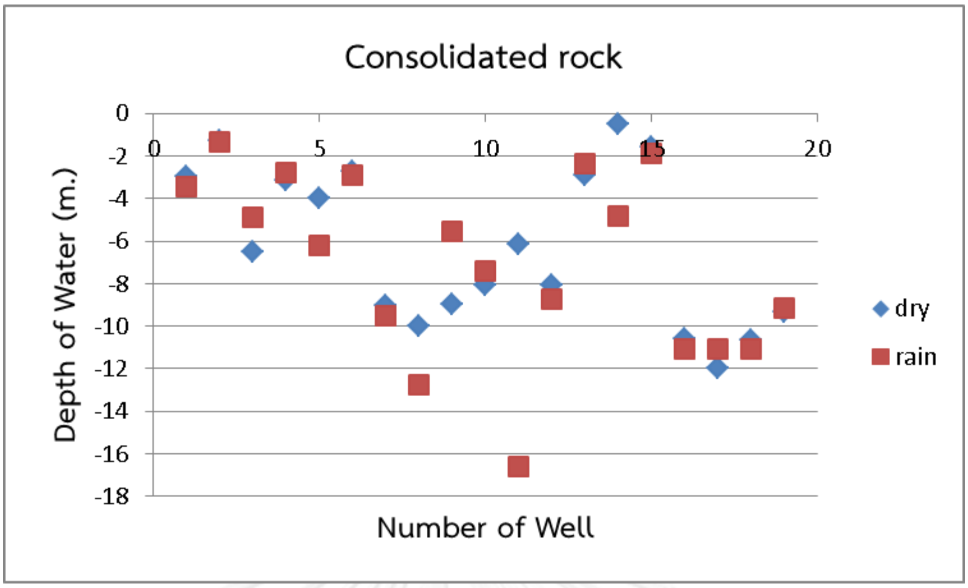

Figure 5. 10 Groundwater table in consolidated rock.

5.2 Groundwater recharge estimations

In the overlay analysis of relevant variables, groundwater recharge equation was used for groundwater recharge estimation. This section showed the quantity of groundwater recharge in the study area, which represented as the dynamic pattern for the dry periods and wet periods, the results were shown in Table 5.3.

5.2.1 Annual groundwater recharge

Because of the seasonal rainfall variations and high rates of evapotranspiration, the groundwater recharge of Phrae province varies from 0 to 630 mm. per year with an average recharge value of 315 mm. of an average value. The annually groundwater recharge has a value of 8.80 % of the average rainfall. The results were shown in Figure 5.11.

5.2.2 Seasonal groundwater recharge

The results of seasonal groundwater recharge ranges from 0 to 95 mm with an average value of 47.5 mm (0.16 % of the summer rainfall), and range from 0 to 720 mm. per year with an average of 360 mm (20.87% of the In rainy rainfall). Approx. 99% of total groundwater recharge in the study area is mainly occurred during the rainy season while the remaining of 1% is occurred in dry season. The results were summarized in Figure 5.12 and Figure 5.13.

Table 5. 3 summary of the groundwater recharge estimation using WetSpass.

Recharge (mm.)	Min.	Max	Average	Mean	Std dev.
Dry Season	0	95.50	47.50	-47.57	75.58
Rainy Season	0	720.56	360.18	58.59	94.93
Annual	0	630.56	315.18	11.02	63.72

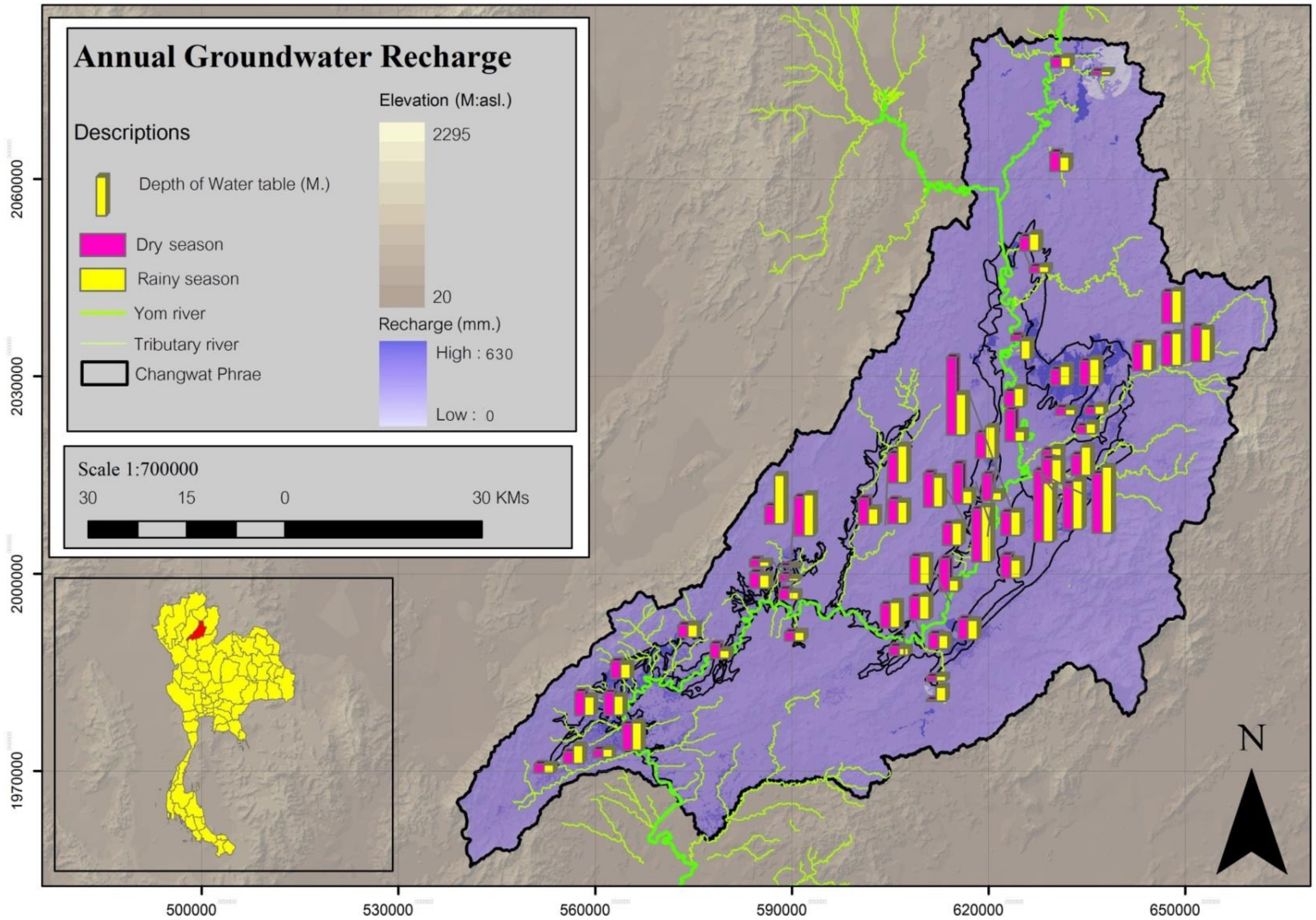

Figure 5. 11 Annual groundwater recharge (mm.)

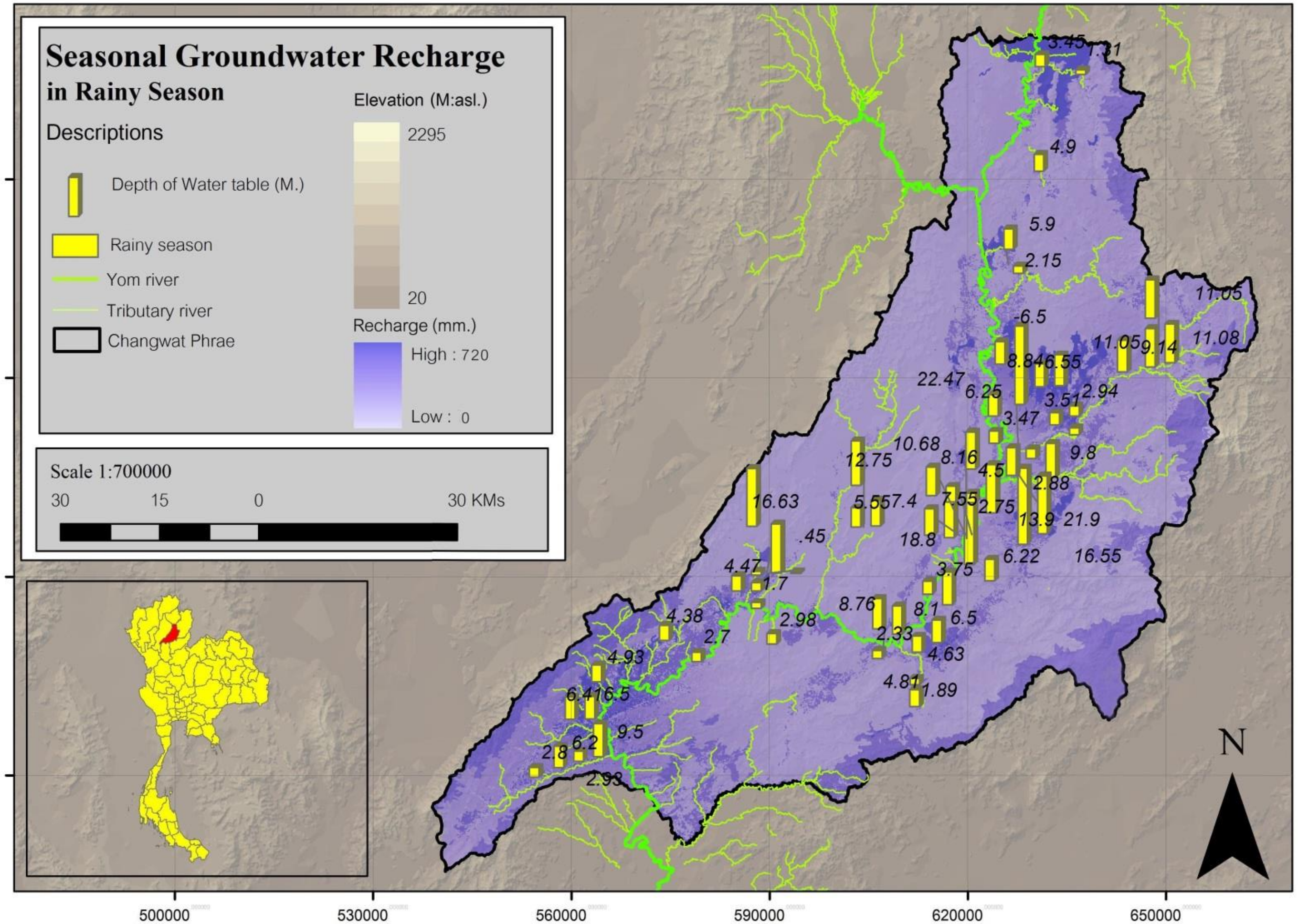

Figure 5. 12 Seasonal groundwater recharge in rainy season (mm.)

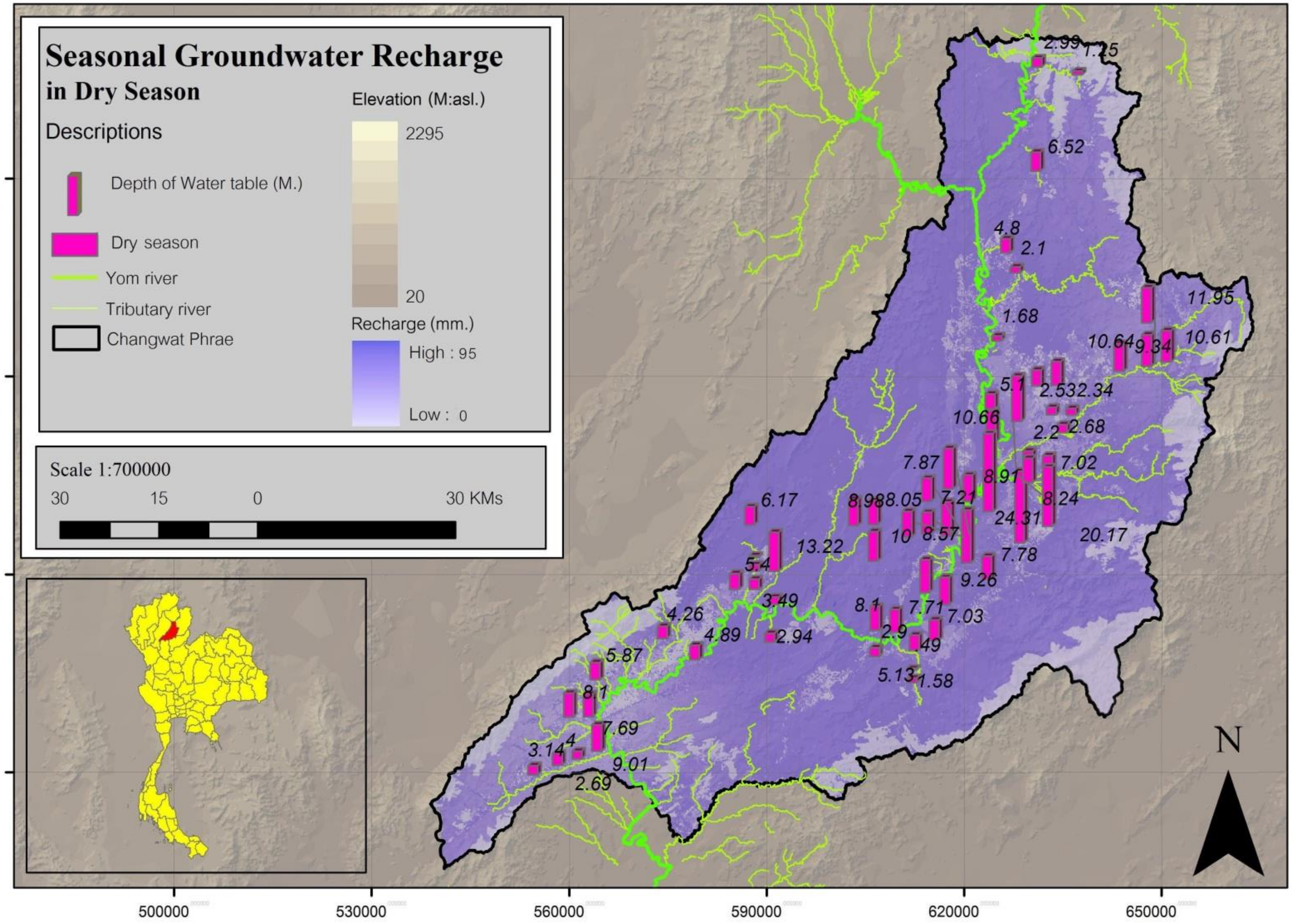

Figure 5. 13 Seasonal groundwater recharge in dry season (mm.)

However, based on the water balance method, if a cell has negative values which there are higher than positive values, indicating that cell may have a negative recharge rate. The raster data of the recharge rate showed negative values in many raster cells, especially the recharge rate in dry season. When the groundwater recharge rate values in dry season was plus with the recharge rate values in rainy season, it should be more reliable to estimate rate of annual groundwater recharge. Hence, the seasonal groundwater recharges data were reclassified by using GIS for data preparation of groundwater modelling. The results reveal that the variations of groundwater charge classes were corresponded with topographic feature as shown in Figure 5.14 and Figure 5.15, and also in Table 5.4 and Table 5.5.

Table 5. 4 Classification of the groundwater recharge rate zone in rainy season.

Class	Recharge rate (mm.)	Count	Area (sq.m.)
1	0	245504	1988,582,400
2	0 - 8.60	157173	1273,101,300
3	8.60 - 40.40	123861	1003,274,100
4	40.40 - 72.23	57770	467,937,000
5	72.23 - 104.01	21835	176,863,500
6	104.01 - 135.80	11325	91,732,500
7	135.80 - 167.58	39380	318,978,000
8	167.58 - 199.36	85913	695,895,300
9	199.36 - 231.15	14666	118,794,600
10	231.15 - 262.93	13229	107,154,900
11	262.93 - 294.71	3231	26,171,100
12	294.71 - 326.50	1282	10,384,200
13	326.50 - 720.56	17337	140,429,700

Table 5. 5 Classification of the groundwater recharge rate zone in dry season.

Class	Recharge rate (mm.)	Count	Area (sq.m.)
1	0	703512	5,698,447,200
2	0 – 10.00	88298	715,213,800
3	10.00 – 20.00	15	121,500
4	20.00 - 30.00	50	405,000
5	30.00 - 40.00	216	1,749,600
6	40.00 - 50.00	353	2,859,300
7	50.00 - 60.00	37	299,700
8	60.00 - 70.00	1	8,100
9	70.00 - 80.00	21	170,100
10	80.00 – 95.50	3	24,300

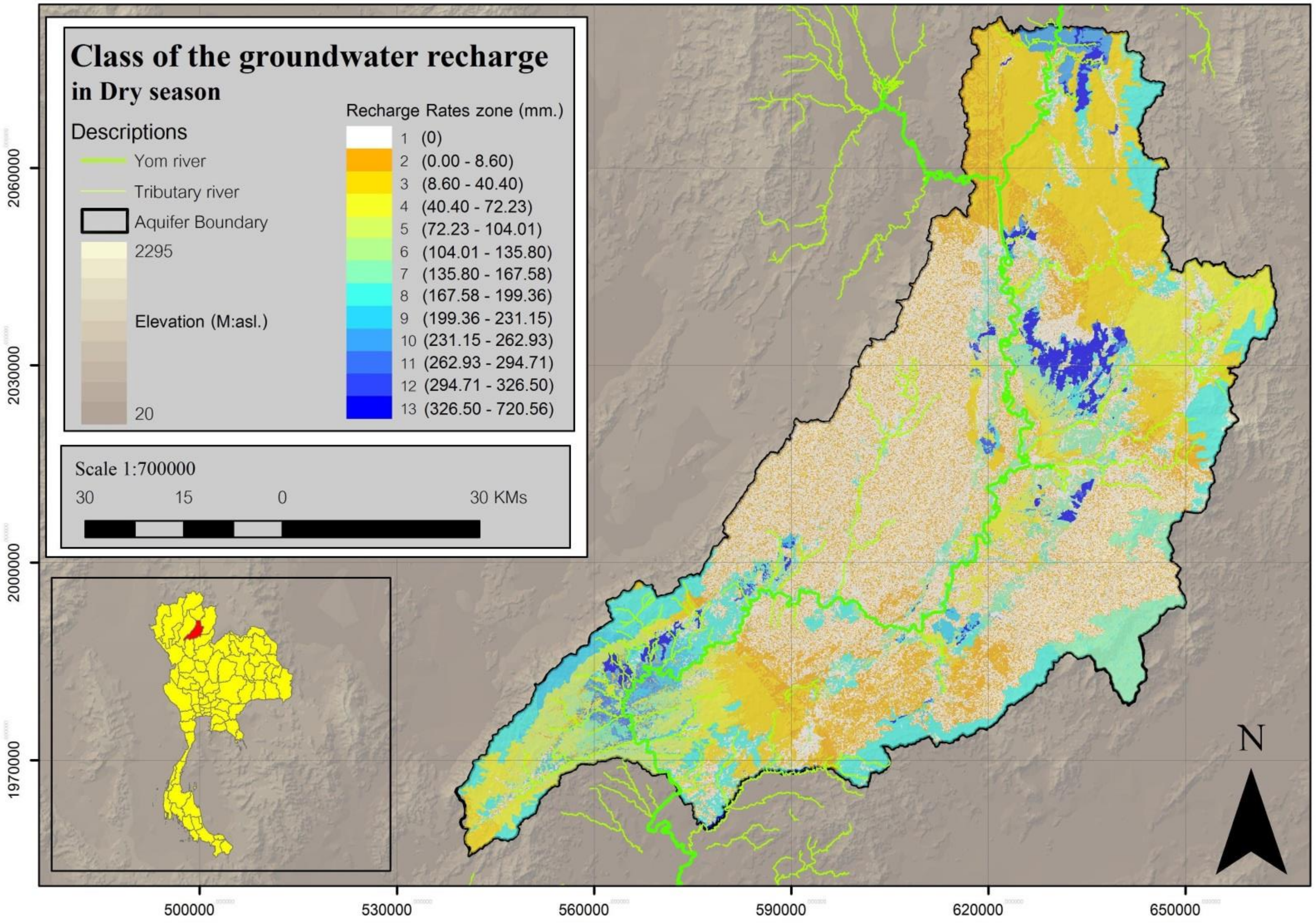

Figure 5. 14 Seasonal groundwater recharge rate zone in rainy season (mm.)

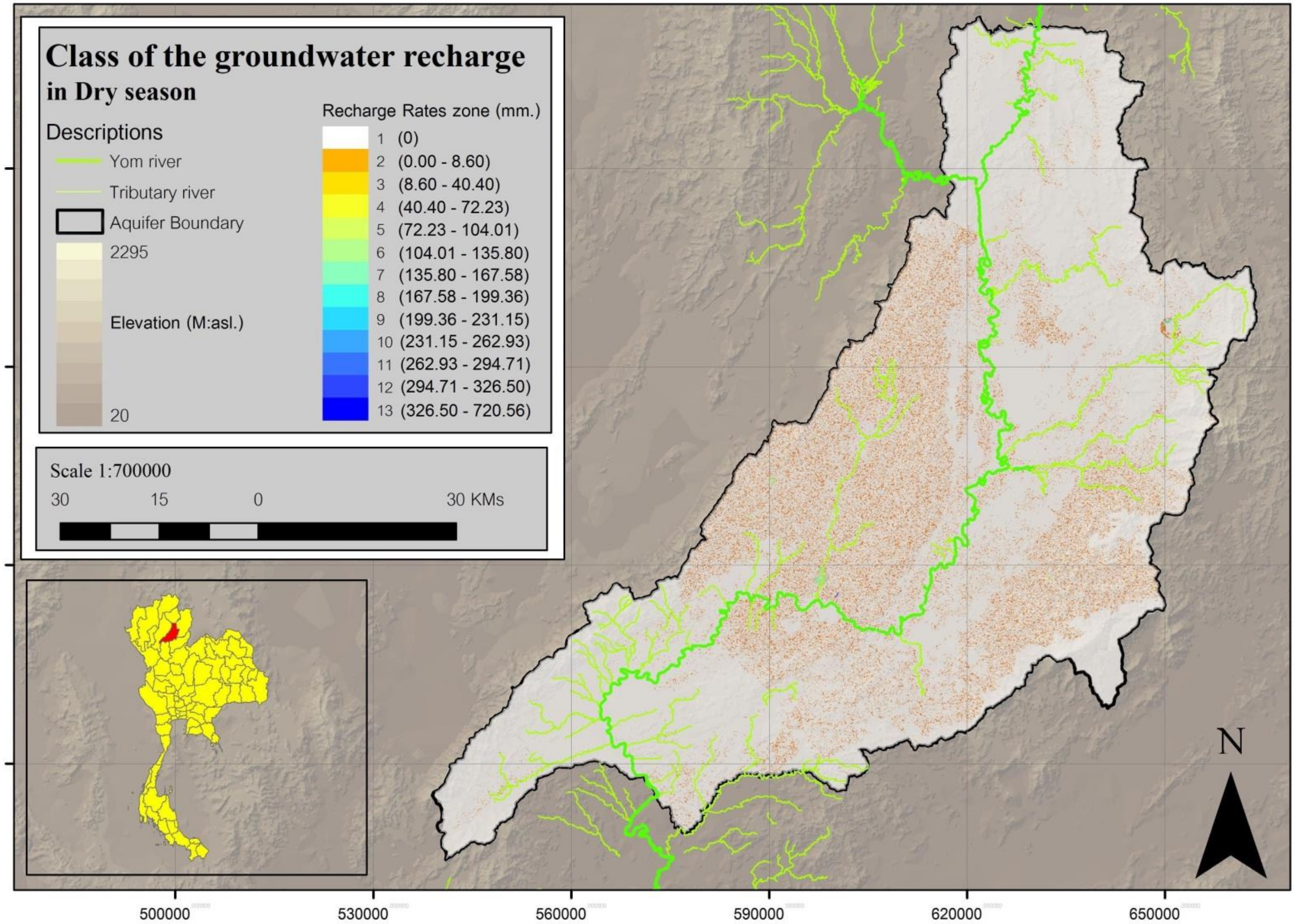

Figure 5. 15 Seasonal Groundwater recharge rate zone in dry season (mm.)

5.3 Groundwater flow modelling

5.3.1 Steady-State calibration

The results of steady-state calibration, 40 observation wells in Changwat Phrae were used to compare with simulated groundwater heads. After parameter estimation, it found that the simulated groundwater heads were corresponded with observed groundwater heads in acceptable level, as shown in Figure 5.16 to Figure 5.17, and Table 5.6 to Table 5.8. The Scattered Plot shows the relationship of simulated groundwater heads and observed groundwater heads along the 1:1 linear line with 95% confidence interval. The residual mean and the absolute residual mean of the groundwater level (after calibration) are 3.37 meters and 5.52 meters, respectively. Also the root mean squared is 6.68 meters. The reliability of modelling appeared to be more reliable because the Maximum Permissible Error should not be over than 5%. Moreover, for ensuring correction of the schematic model and parameter values, the percentage of discrepancy in steady-state appeared to be nearly approx. 0.00% that the steady-state condition is equilibrium conditions and the mathematical modeling derived is relatively more reliable.

Table 5. 6 Description of the steady-state condition.

Descriptions	Values (m.)
Mean Residual (Head)	3.37
Mean Absolute Residual (Head)	5.56
Root Mean Squared Residual (Head)	6.68
Mean Weighted Residual (Head+Flow)	6.60
Mean Absolute Weighted Residual (Head+Flow)	10.81
Root Mean Squared Weighted Residual (Head+Flow)	13.09
Sum of Squared Weighted Residual (Head+Flow)	6345.32

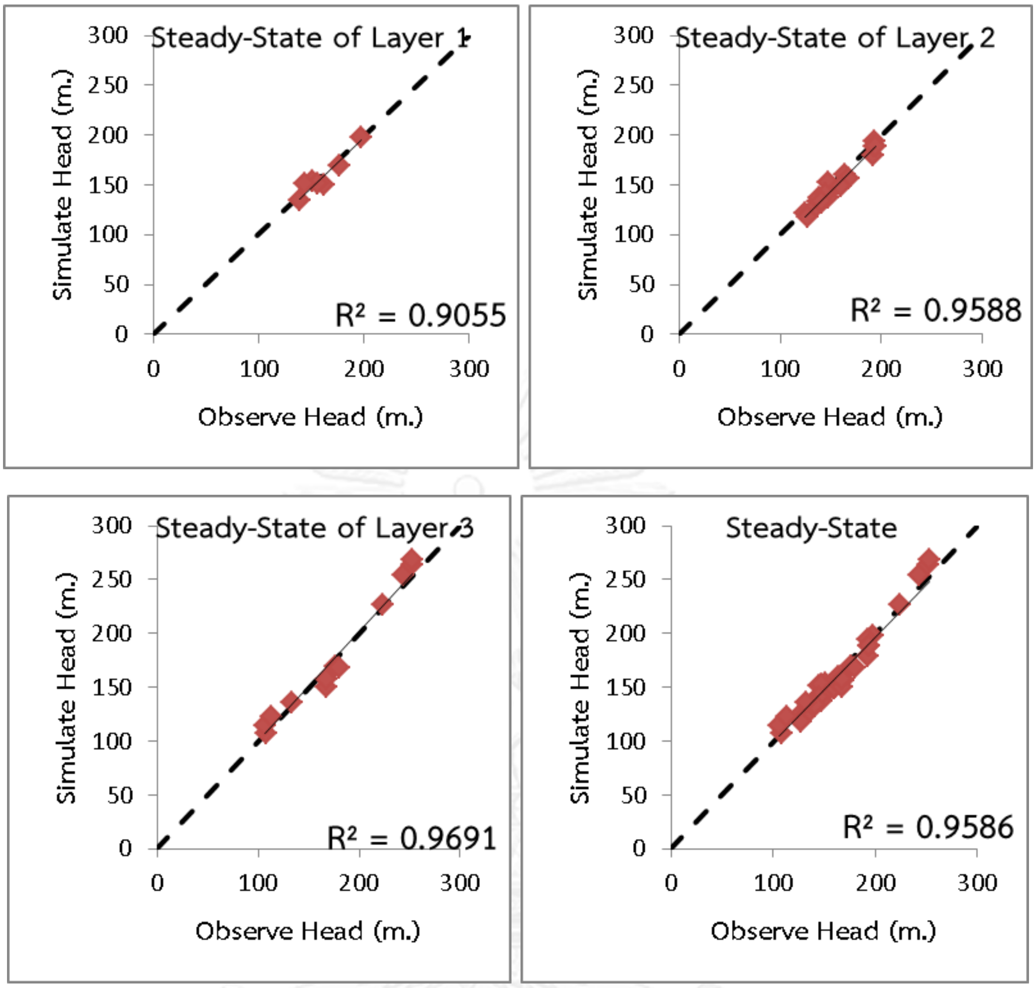

Figure 5. 16 Scattered Plot between simulated and observed heads in steady-state condition.

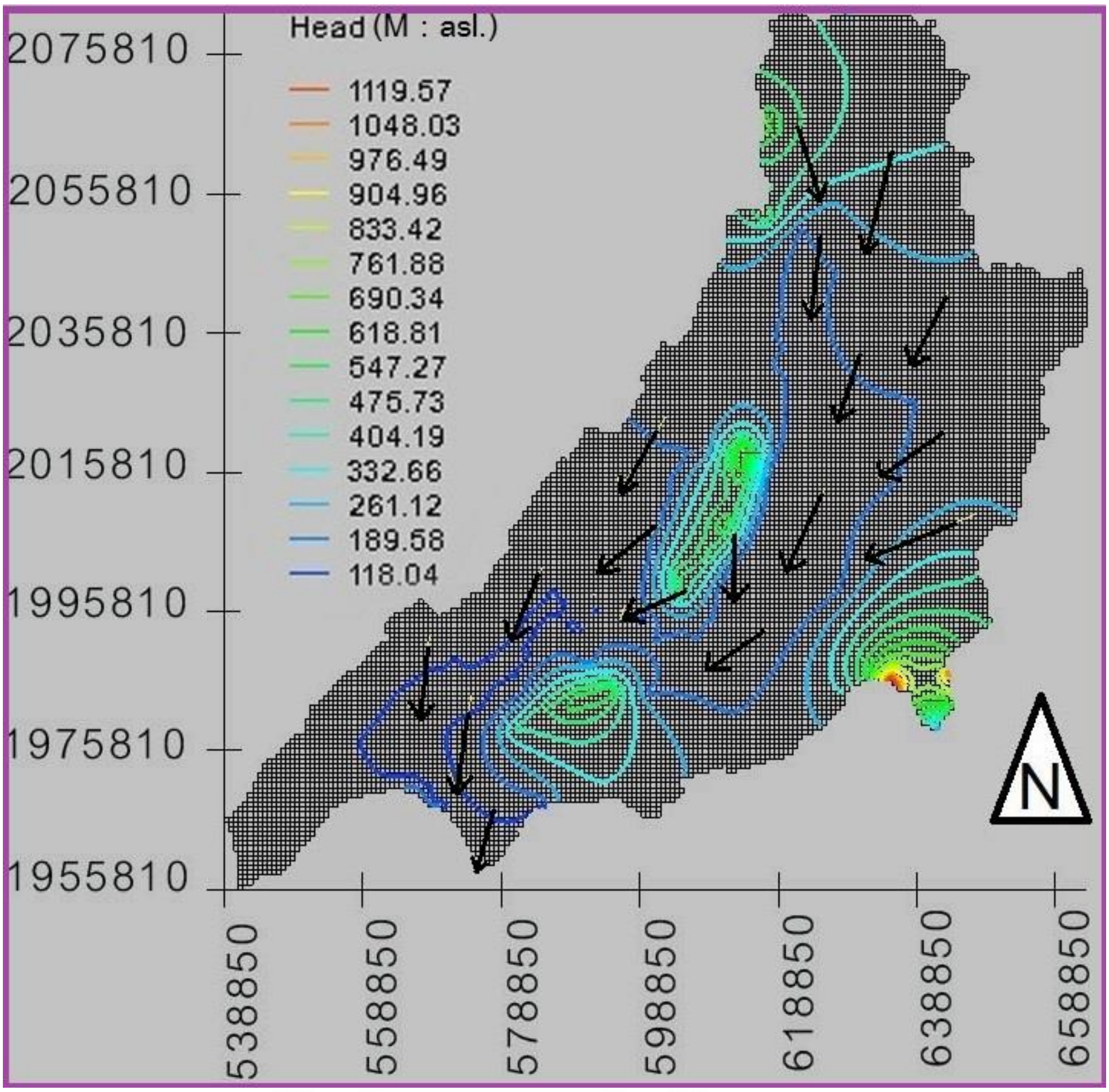

Figure 5. 17 Groundwater flow in Changwat Phrae, Under Steady-State Condition.

Table 5. 7 The groundwater balance in Changwat Phrae under steady-state condition.

IN (flow m^3/ day)		OUT (flow m^3/ day)	
Constant heads	21,360,551	Constant heads	88,657
Drains	0	Drains	49,651,865
General heads	35,298,639	General heads	1,139,548
Rivers	632,662	Rivers	6,911,519
Wells	0	Wells	58,951
Recharge	561,151	Recharge	0
Total IN	57,852,965	Total OUT	57,850,560
SUMMARY:			
IN - OUT	2,404		
Percent Discrepancy	0.00		

Table 5. 8 Summary of the groundwater balance in Changwat Phrae under Steady-state.

Summary (m^3/ day)	
Storage	-
Constant heads	(+) 21,271,894
Drains	(-) 49,651,865
General heads	(+) 34,159,091
Rivers	(-) 6,278,857
Wells	(-) 58,951
Recharge	(+) 617,805
Total IN	2,404 m^3/day or 877,460 m^3/year

5.3.2 Transient-State Calibration

The result of transient-state calibration, the model was separated to 2 stress periods as May 2012 to October 2012 in rainy season and November 2012 to April 2013 in dry season. 40 observation wells in Changwat Phrae were used to compare with simulated groundwater heads. After parameter estimation, it found that the simulated groundwater heads were corresponded with observed groundwater heads in acceptable level, as shown in Figure 5.18, and Table 5.9 to Table 5.10. The Scattered Plot shows the relationship of simulated groundwater heads and observed groundwater heads along the 1:1 linear line with 95% confidence interval. The residual mean and the absolute residual mean of the groundwater level (after calibration) are 6.29 meters and 8.61 meters, respectively. Also the root mean squared is 12.20 meters. The reliability of modelling appeared to be more reliable because the Maximum Permissible Error should not be over than 5%. Moreover, for ensuring correction of the schematic model and parameter values, the percentage of discrepancy in steady-state appeared to be nearly approx. 0.00% that the steady-state condition is equilibrium conditions and the mathematical modeling derived is relatively more reliable.

Table 5. 9 Description of the transient-state condition.

Descriptions	Values (m.)
Mean Residual (Head)	6.29
Mean Absolute Residual (Head)	8.61
Root Mean Squared Residual (Head)	12.21
Mean Weighted Residual (Head+Flow)	12.34
Mean Absolute Weighted Residual (Head+Flow)	16.88
Root Mean Squared Weighted Residual (Head+Flow)	23.93
Sum of Squared Weighted Residual (Head+Flow)	41,221.42

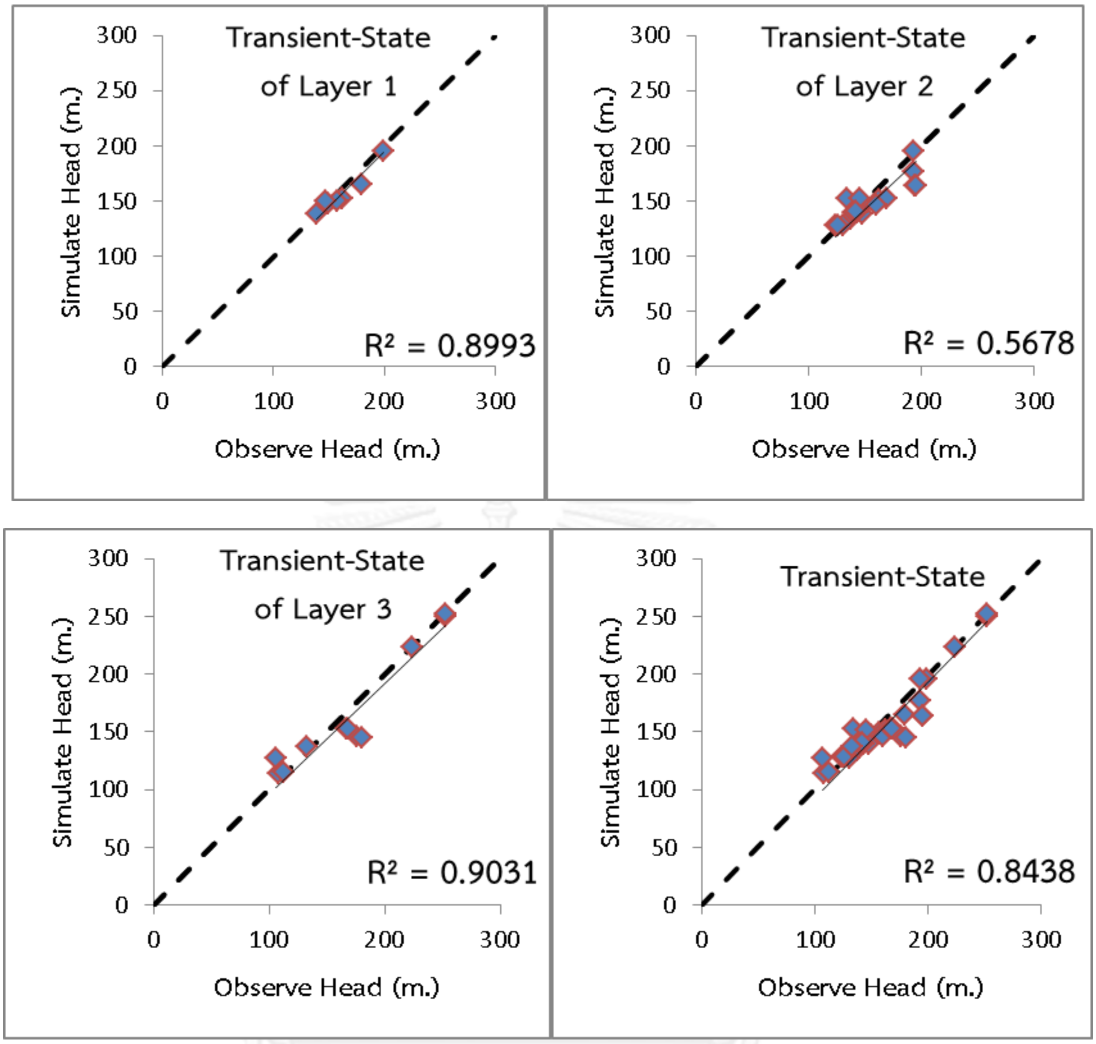

Figure 5. 18 Scattered Plot between simulated and observed heads in transient-state condition.

Table 5. 10 The annual groundwater balance in Changwat Phrae under transient-state condition.

IN (MCM/ year)		OUT (MCM/ year)	
Storage	18,457.50	Storage	2,242.95
Constant heads	3,457.66	Constant heads	12,461.58
Drains	0	Drains	18,179.94
General heads	1,272.99	General heads	19.36
Rivers	241.82	Rivers	3,067.13
Wells	0	Wells	21.69
Recharge	113.68	Recharge	0
Total IN	23,543.65	Total OUT	23,543.58
SUMMARY:			
IN - OUT	111,320 m^3/ year		
Percent Discrepancy	0.00		

Table 5. 11 Ranges of various parameter values in groundwater flow modelling.

Aquifers	Qfd	Qt	Consolidated
Hydraulic Conductivity (m /day)	6.69 – 9.68	9.68	8.53
Primary Storage Coeff	0.15-0.21 **(Sy)**	0.000254 – 0.0002 (S)	0.03 – 6.963 (S)
Recharge (mm/ day)	0 - 326 mm/ year		

5.4 Groundwater balance assessment

5.4.1 Annual groundwater balance

The annual groundwater balance in transient-state (during 2012-2013) shows that the groundwater inflow in Changwat Phrae is 23,543 MCM. Mostly inflow occurs by groundwater flow into the storage as 18,457 MCM. In addition, the inflow from groundwater recharge and river are 113 and 241 MCM, respectively. In groundwater outflow, mainly occurs in drainage region at the Floodplain deposited, approx. 18,179 MCM. Additionally, the outflow from domestic well is 21 MCM, and the outflow from the Yom River is 3,067 MCM. In conclusion, the inflow groundwater is higher than the outflow groundwater in Changwat Phrae that means total of groundwater balance is approx.. +111,320 MCM/ year.

5.4.2 Groundwater balance in rainy season

The seasonal groundwater balance in rainy season (during May-October) shows that the groundwater inflow in Changwat Phrae is 18,343 MCM. Mostly groundwater inflow occurs flow into the storage approx. 14,147 MCM. In addition, the inflow from groundwater recharge and river are 113 and 129 MCM, respectively. In groundwater outflow, mainly in drainage region on the Floodplain deposited approx. 14,848 MCM. In addition, the outflow from domestic well is 10 MCM, and the outflow from the Yom River is 1,796 MCM. In conclusion, the total of groundwater balance in Changwat Phrae during the rainy season is +111,872 m^3/ season. That means the inflow groundwater is higher than the outflow groundwater, as show in Figure 5.19 and Table 5.12 to Table 5.13.

Table 5. 12 The groundwater balance in Changwat Phrae under transient-state in rainy season.

IN (m^3/ day)		OUT (m^3/ day)	
Storage	85,265,003	Storage	8,375,317
Constant heads	9,387,899	Constant heads	41,527
Drains	0	Drains	80,697,105
General heads	3,719,940	General heads	55,637
Rivers	703,672	Rivers	10,465,173
Wells	0	Wells	58,951
Recharge	617,805	Recharge	0
Total IN	99,694,321	Total OUT	99,693,712
SUMMARY:			
IN - OUT	608		
Percent Discrepancy	0.00		

Table 5. 13 Summary of the groundwater balance in Changwat Phrae under transient-state in rainy season.

Summary (m^3/ day)	
Storage	(+) 76,889,686 or 14,147 MCM/ season
Constant heads	(+) 9,346,372 or 1,719 MCM/ season
Drains	(-) 80,697,105 or 14,848 MCM/ season
General heads	(+) 3,664,303 or 674 MCM/ season
Rivers	(-) 9,761,501 or 1,796 MCM/ season
Wells	(-) 58,951 or 10 MCM/ season
Recharge	(+) 617,805 or 113 MCM/ season
Total	(+) 608 m^3/day or 111,872 m^3/season

5.4.2 Groundwater balance in dry season

The seasonal groundwater balance in dry season (during November-April) shows that the groundwater inflow in Changwat Phrae is 5,115 MCM. Mostly groundwater inflow occurs flow into the storage approx. 2,033 MCM. In addition, the inflow from groundwater recharge and river are 0 and 110 MCM, respectively. Groundwater outflow mainly in drainage region, the Floodplain deposited approx. 3,277 MCM. Additionally, the outflow from domestic well and Yom river is 10 and 1,112 MCM, respectively. In conclusion, the inflow groundwater is higher than the outflow groundwater in Changwat Phrae that means the total of groundwater balance in Changwat Phrae during the rainy season is -5,115 m^3/ season, as shown in Figure 5.20 and Table 5.14 to 5.15.

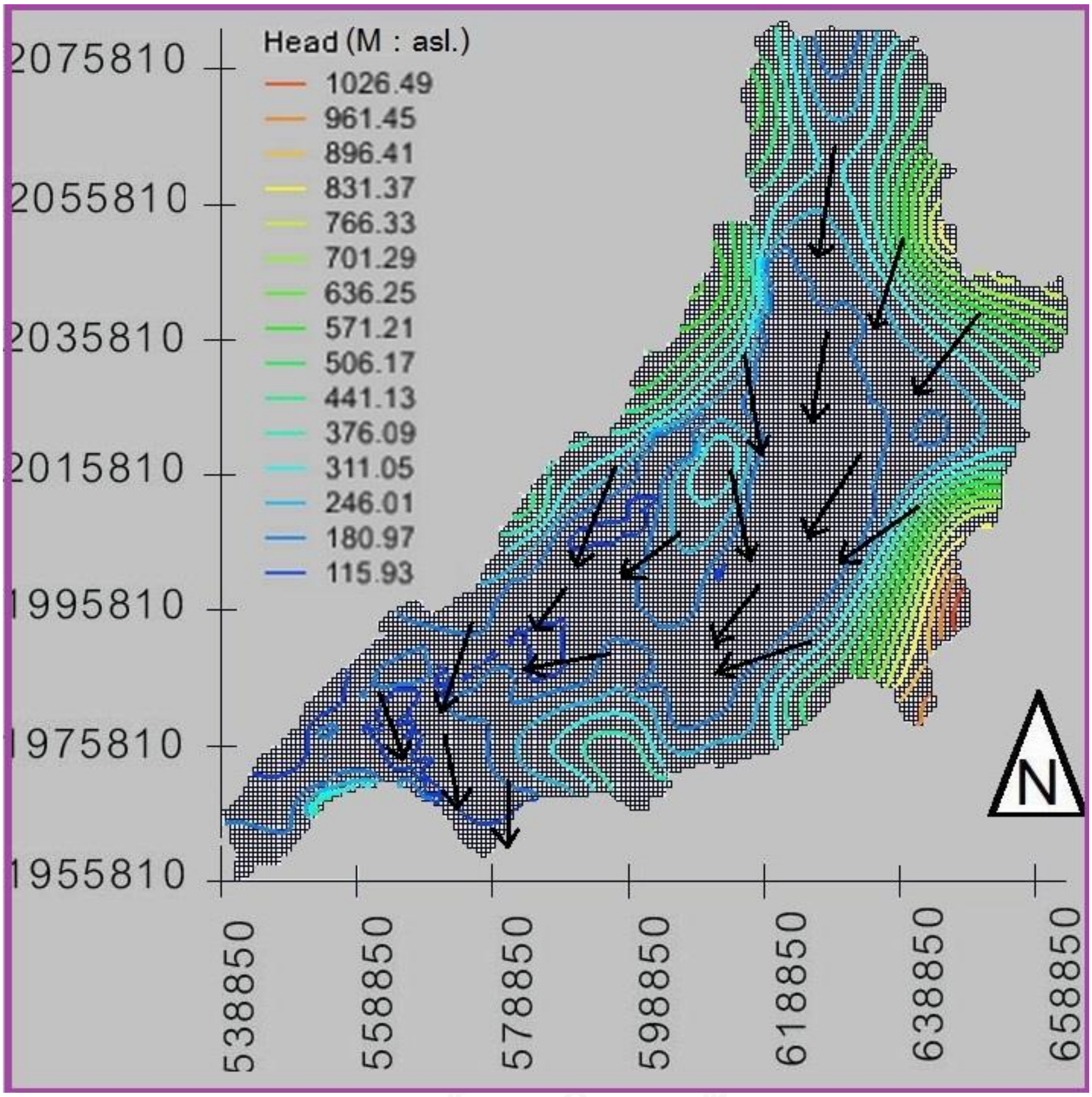

Figure 5. 19 Groundwater flow in Changwat Phrae during rainy season, Under Transient-State Condition.

Table 5. 14 The groundwater balance in Changwat Phrae under transient-state in dry season.

IN (m^3/ day)		OUT (m^3/ day)	
Storage	15,047,493	Storage	3,814,612
Constant heads	9,403,729	Constant heads	26,199
Drains	0	Drains	18,106,944
General heads	3,198,500	General heads	49,596
Rivers	610,569	Rivers	6,203,992
Wells	0	Wells	58,951
Recharge	0	Recharge	0
Total IN	28,260,293	Total OUT	28,260,297
SUMMARY:			
IN - OUT	-3		
Percent Discrepancy	0.00		

Table 5. 15 Summary of the groundwater balance in Changwat Phrae under transient-state in dry season.

Summary (m^3/ day)	
Storage	(+) 11,232,881 or 2,033 MCM/ season
Constant heads	(+) 9,377,530 or 1,697 MCM/ season
Drains	(-) 18,106,944 or 3,277 MCM/ season
General heads	(+) 3,148,904 or 569 MCM/ season
Rivers	(-) 5,593,423 or 1,012 MCM/ season
Wells	(-) 58,951 or 10 MCM/ season
Recharge	(-) 0 or 0 MCM/ season
Total	(-) 3 m^3/day or 543 m^3/season

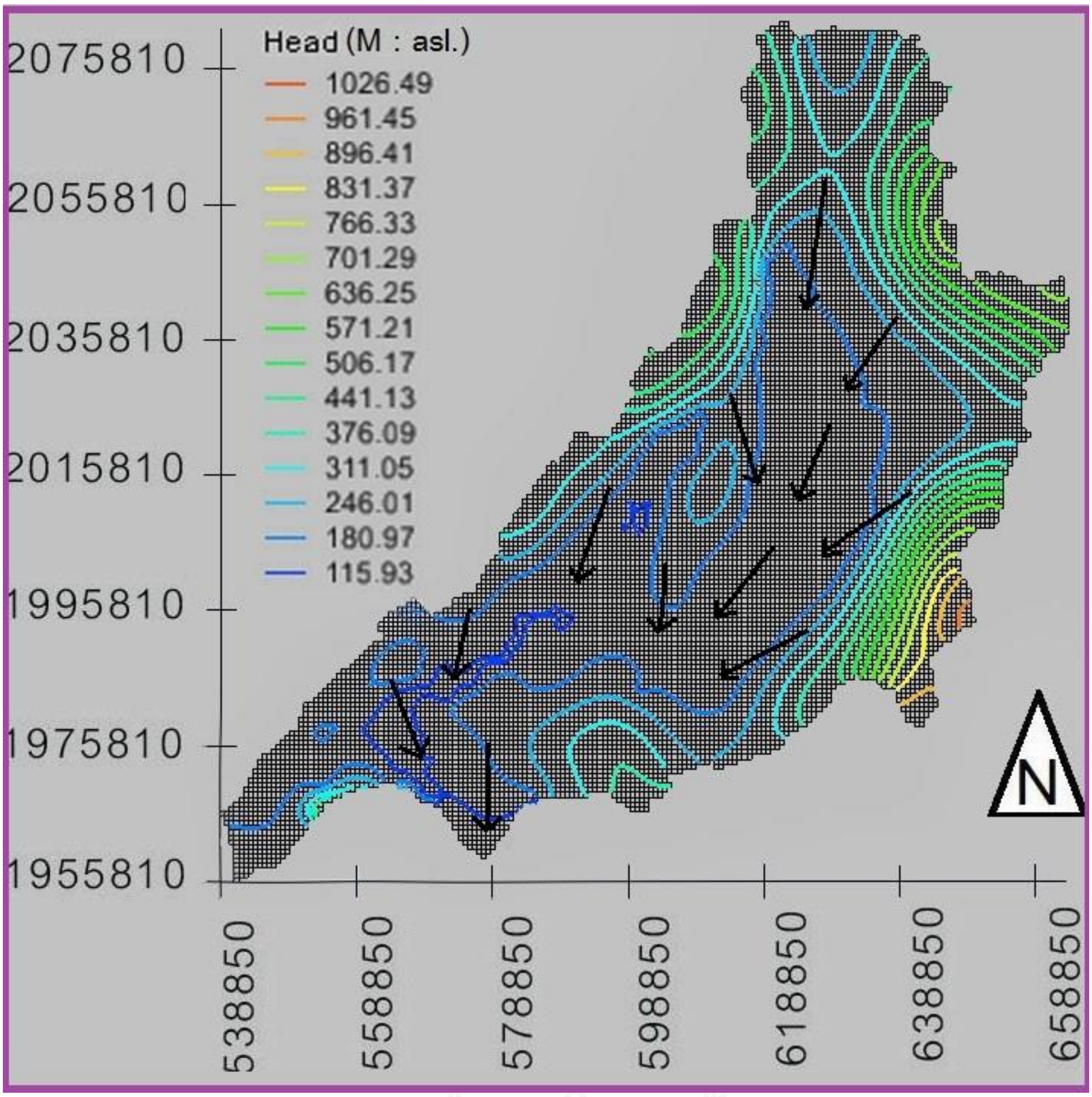

Figure 5. 20 Groundwater flow in Changwat Phrae during dry season, under Transient-State Condition.

5.5 Groundwater safe yield simulation

According to the Department of Irrigation Resource [47], the irrigation development plan in the future (5-10 years plan) will improve. Two irrigate canals are constructing at eastern part and western part of the intermontane basin which surround the Quaternary floodplain aquifer (Qfd). In addition, canals range from the north to the south of Phrae province. An aim of the irrigation development project was to improve surface water supply for agriculture, both dry season and rainy season. Furthermore, an aim of the irrigation development project was to expand the irrigate zone to remote areas which overlapped on the Quaternary Terrace aquifer (Qt). It may influence to the decreasing of groundwater supply rate for agriculture. Meanwhile, according to the secondary data of Provincial Waterworks Authority in Phrae province during years 1998-2013 as shows in Figure 5.21, the rates of water supply are clearly increase every year. The water supply is increasing as 228 m^3/ day or 83,220 m^3/ year, especially in Municipal of Phrae in Amphoe Muang. Moreover, because of the lacking of surface water during dry season, the domestic use in the region has been increasing. Hence, the groundwater model simulation was focused on the groundwater supply for groundwater use policy. After the calibration and verification step, Situations in transient state were separated into two cases as short-term and long-term. Amphoe Muang in Phrae province was chose to simulate area.

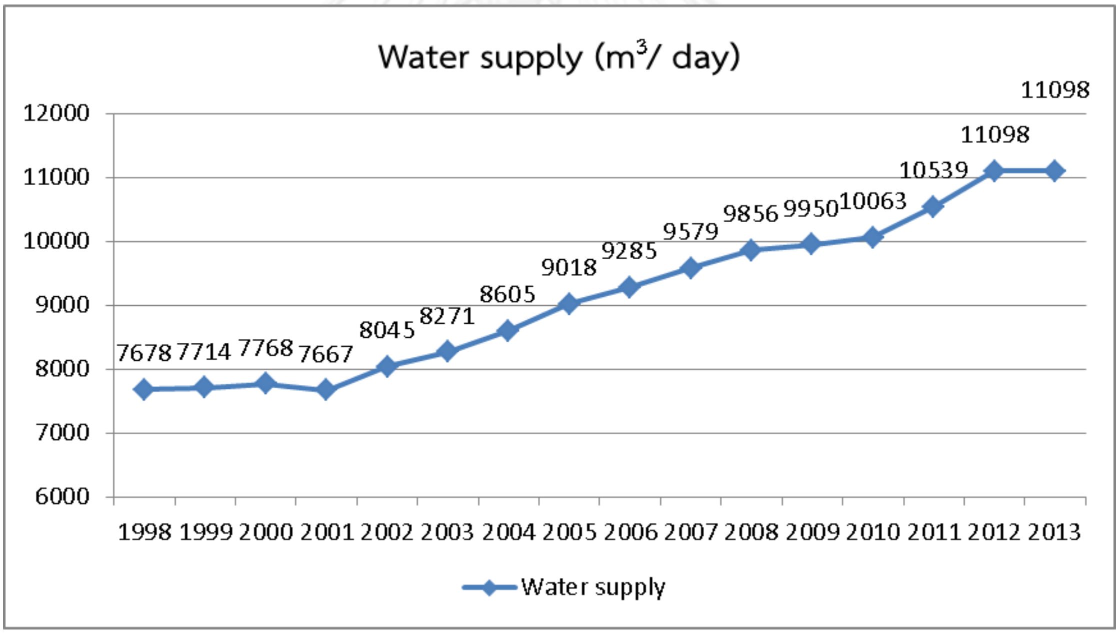

Figure 5. 21 Increasing of the water supply in Changwat Phrae during years 1998-2013.

5.5.1 Short-term situation

In short-term, after the decreasing of the recharge in dry season, the groundwater for domestic use in Phrae province was assuming high necessary. The volume of pumping wells increased as the rate 50 percent and 100 percent from the original rates. The results can show the changing of groundwater level of two cases, which the safe yield level should not change more than 5 meters. The result of short-term condition is show in Figure 5.22 and Figure 5.23. In Figure 5.22, it shows the variation of the normal and 100 percent condition which the drawdrawn is lower than 5 meters. It means the availability of safe yield in dry season should not much higher than 50 percent.

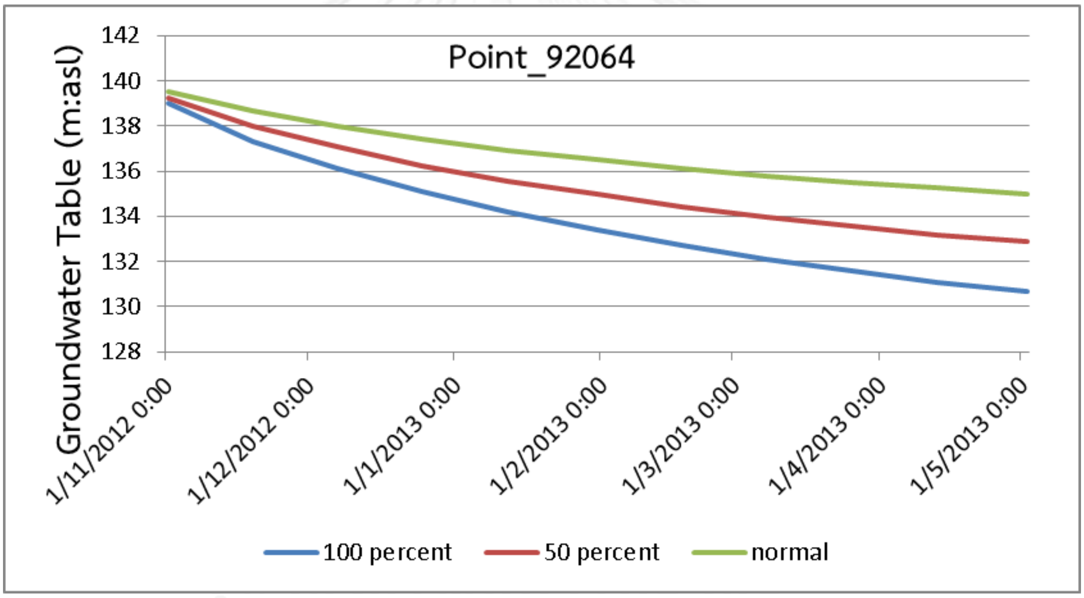

Figure 5. 22 Changing of the groundwater table in short-term situation in sampling point 92064 at Amphoe Muang, Changwat Phrae.

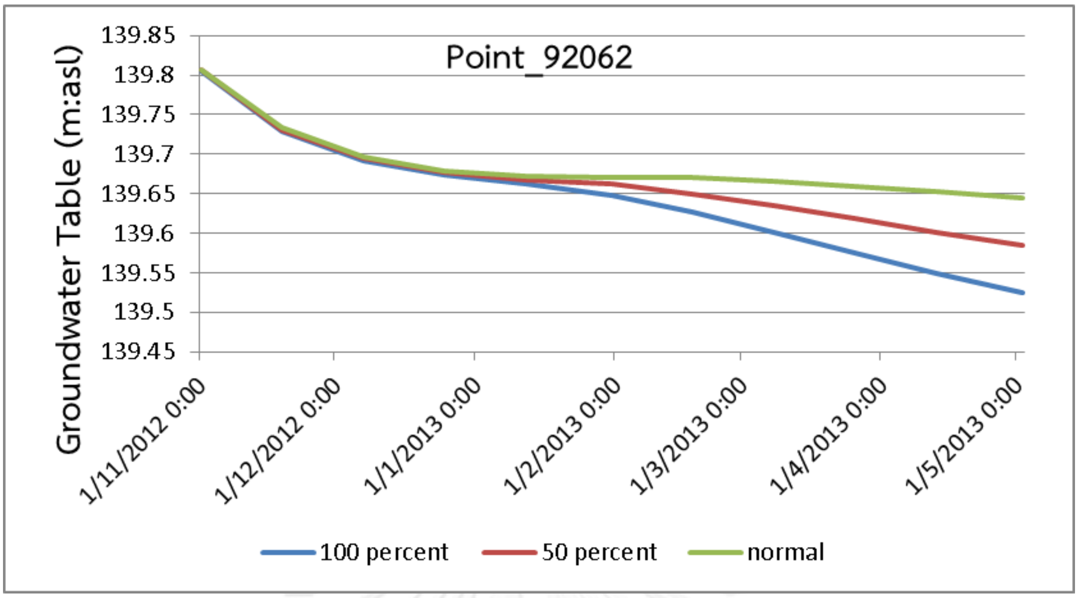

Figure 5. 23 Changing of the groundwater table in short-term situation in sampling point 92062 at Amphoe Muang, Changwat Phrae.

5.5.2 Long-term situation

As same as in the long-term, assuming the groundwater recharge is constant, the volume of pumping wells increased as the rate 25 percent, 50 percent and 100 percent along 5 years in the future. The results can show the changing of groundwater level of three cases, which the safe yield level should not change more than 5 meters. The result of long-term condition is show in Figure 5.24 to Figure 5.27. In Figure 5.28, it shows the variation of the normal and 100 percent condition which the drawdrawn is lower than 5 meters. It means the availability of safe yield in the long-term condition should not much higher than 25 percent.

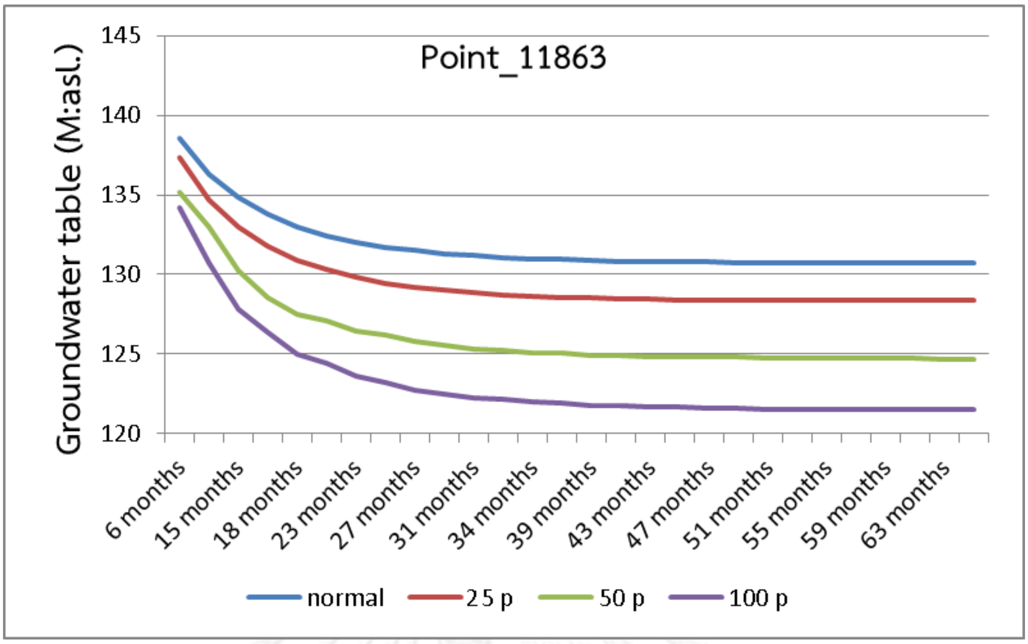

Figure 5. 24 Changing of the groundwater table in long-term situation in sampling point 11863.

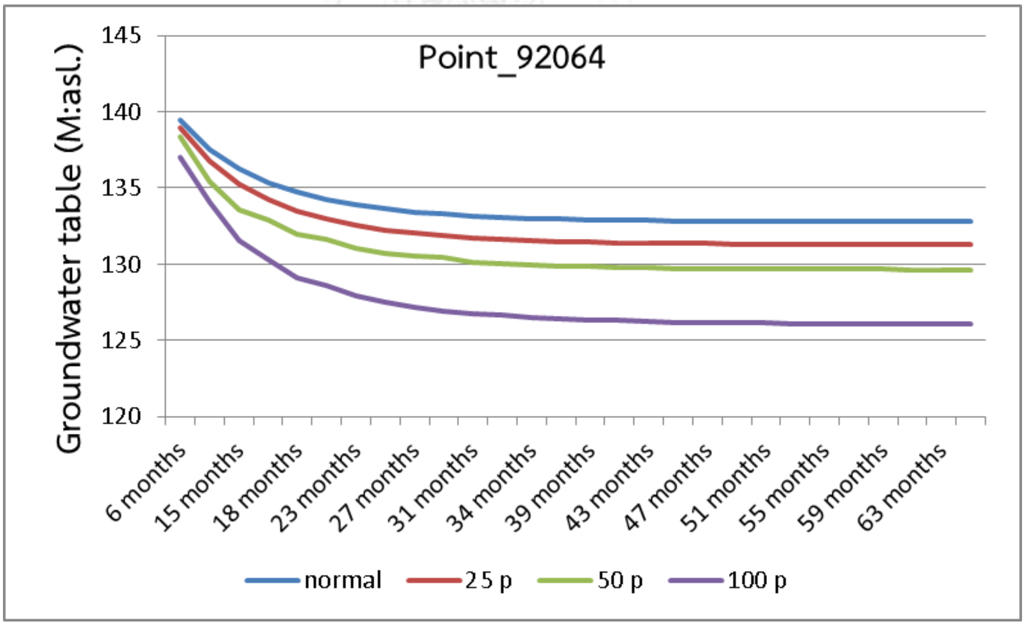

Figure 5. 25 Changing of the groundwater table in long-term situation in sampling point 92064.

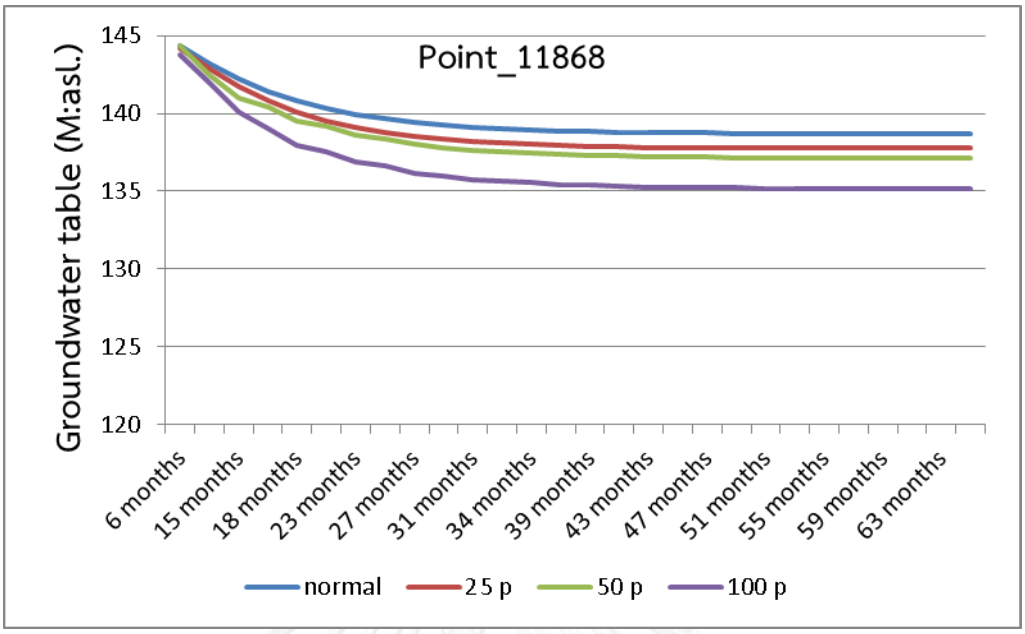

Figure 5. 26 Changing of the groundwater table in long-term situation in sampling point 11868.

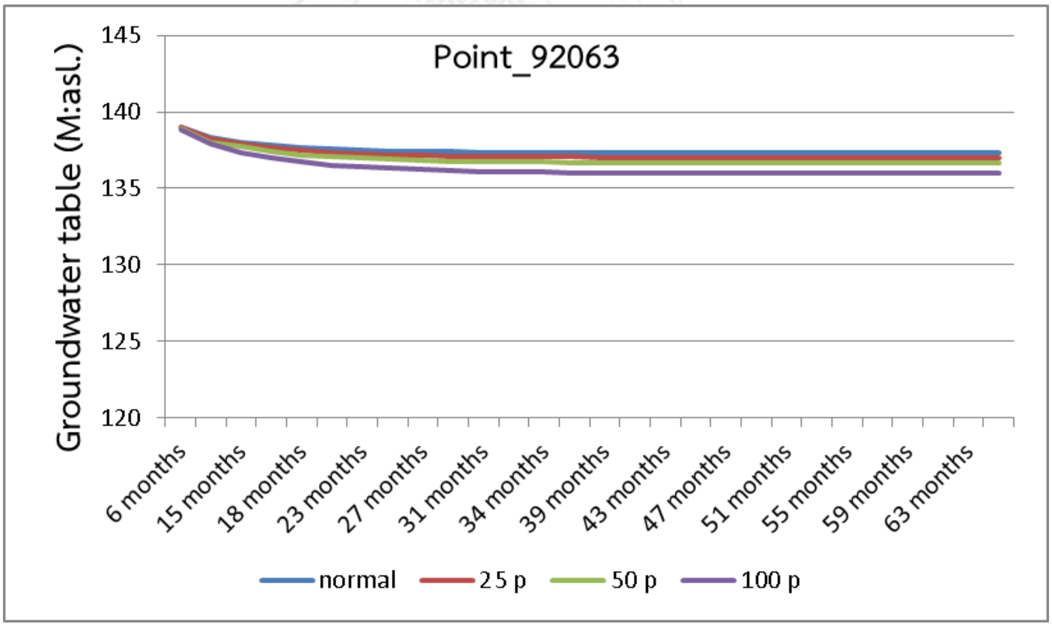

Figure 5. 27 Changing of the groundwater table in long-term situation in sampling point 92063.

According to results of groundwater simulation both short-term and long-termperiods, it revealed the decreasing of groundwater level especially in Amphoe Muang, Phrae province, where the region is high rate of water use is relatively high. But, other groundwater wells around the area are not shown the high rate of decreasing level of groundwater because the study area has the low rate of groundwater usage, for example, groundwater well no.92062 decrease only approx.. 0.30 m. from origin level, except for areas nearby groundwater well no. 92064 which locate at urban zone. For groundwater management, multiple ring buffer technique was used to determine the groundwater critical zone. The result shown the distance from the highest of groundwater use zone to the lowest of groundwater use zone, which those were corresponded with sampling points in modelling as shown in Figure 5.28.

The high and moderate critical zones are Tumbon Pa Mat and Tumbon Nai Wiang, and the low critical zone is Tumbon Pa Mat, Tumbon Nai Waing, Tumbon Tuang Kwaw, Tumbon Muang Mor, Tumbon Na Chak and Tumbon Wiang Thong.

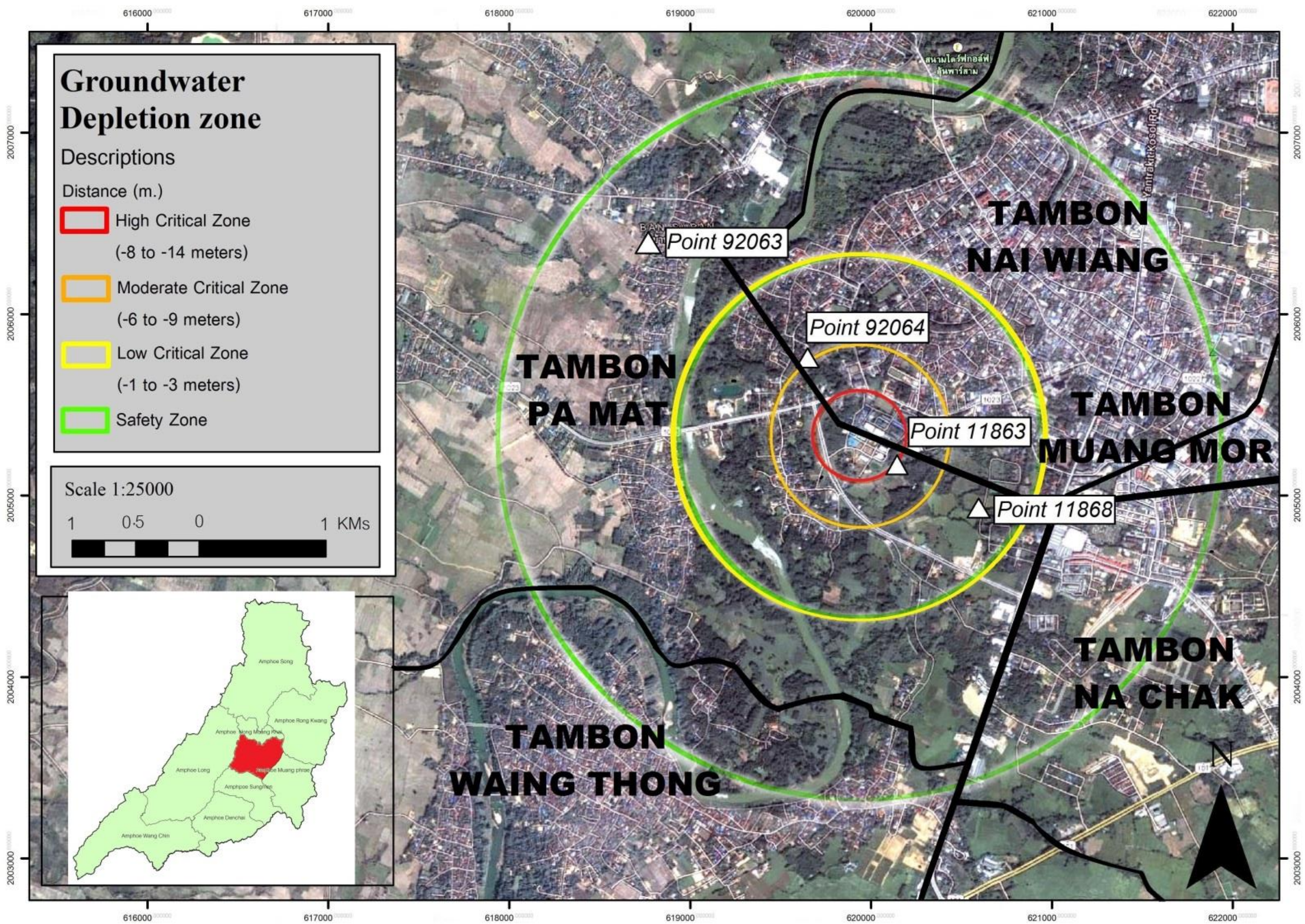

Figure 5. 28 Groundwater Depletion map in Amphoe Muang, Changwat Phrae. It shows the risk zone of groundwater depletion in Tambon Nai Wiange, Tambon Pa Mat Tambon Waing Thong, Tambon Na Chak and Tambon Muang mor.

CHAPTER VI
DISCUSSIONS AND CONCLUSION

6.1 Discussions

6.1.1 The groundwater flow in Changwat Phrae

For groundwater flow modeling, construction of schematic model is quite important. The secondary data from government and private sector were interpreted, prepared and used to construct the schematic model and groundwater flow model in GIS and GMS-MODFLOW. Three types of aquifers classified as two unconsolidated, floodplain deposited (Qfd) and Terrace deposited aquifers (Qyt and Qot) and the consolidated aquifers are derived from the hydrogeological characteristic results in the study area. The unconsolidated aquifers were distributed over the central part of the study area along with Yom River, while the consolidated aquifer represents the bed rock underneath the unconsolidated aquifers in the study area. The groundwater flows significantly toward the slope of hydraulic gradient. The main direction of groundwater movement is clearly conformed to topography features along north-south direction, and flow towards the central part of the area.

Following the geologic cross-section in Figure 6.1 and Figure 6.2, schematic diagram was illustrated to understand the relationship between aquifers in Figure 6.3. In three Quaternary aquifers (the Quaternary floodplain Deposits (Qfd), the Quaternary Young Terrace (Qyt) and the uppermost of Quaternary Old Terrace (Qot)), which were a multi-aquifer. Winter et al. [67] described the interaction between groundwater and surface activities, especially the interaction between streams with groundwater in all types of landscapes. In the Phrae intermontane basin, the interaction had three basic ways as gaining stream, losing stream and they do both. In the altitude of the groundwater table in the nearness of the stream is higher than the altitude of the stream-water surface, streams gained water from inflow of groundwater through the streambed. In other words, these streams were a discharge characteristic especially in the Yom River. Conversely, intermittent rivers in the highland were a recharge characteristic, and acted like gaining stream during rainy season. The assumption was correlated with the results of *5.1.2 Change in* *groundwater table levels* which showed the different of seasonal groundwater levels. The groundwater tables in rainy season were lower than the groundwater tables in dry season especially in margin of the Phrae intermontane basin. Meanwhile, the groundwater tables in dry season were lower than the groundwater tables in rainy season especially in the central part of Phrae intermontane basin. All of the above, it clearly is that the hydrogeologic characteristic in Changwat Phrae had a correlation with groundwater movement and groundwater supply. The Quaternary terrace which the depth was higher than 300 meters was a good source of groundwater. The interaction between groundwater and surface activities were found in the Quaternary floodplain Deposits (Qfd), the Quaternary Young Terrace (Qyt) and the uppermost of Quaternary Old Terrace (Qot). However, in the consolidated rock, it was more complicated than the Quaternary multi-aquifer.

The hard rock aquifers consist of Permian-Carbonates aquifers (Pc), Permian-Carboniferous Metasediments aquifers (PCms), Triassic Lampang group aquifers (TRlp), Triassic Lower Korat group aquifers (TRJlk) and volcanic aquifers (Vc). They are corresponded to related studies of Robin [68] , Saha et al. [69] and related field investigation of the National Research Council of Thailand [51]. Groundwater occurrence in these aquifers mostly occurs in secondary porosity of fractured rock. Groundwater flow paths appear to be different distances and shallow level depending on fracture density and direction. But, in the regional scale, the groundwater movement is able to flow with the steepest hydraulic gradient, which takes a long-period of time to for arrive the Upper Chao Phraya aquifers and the Quaternary Terrace aquifer with deep fractures of rocks [70]. In addition, according to Dewandel et al. [71], groundwater in consolidated aquifers may possibly correspond to a laterite type weathering profile in the uppermost of the Quaternary Old Terrace deposits.

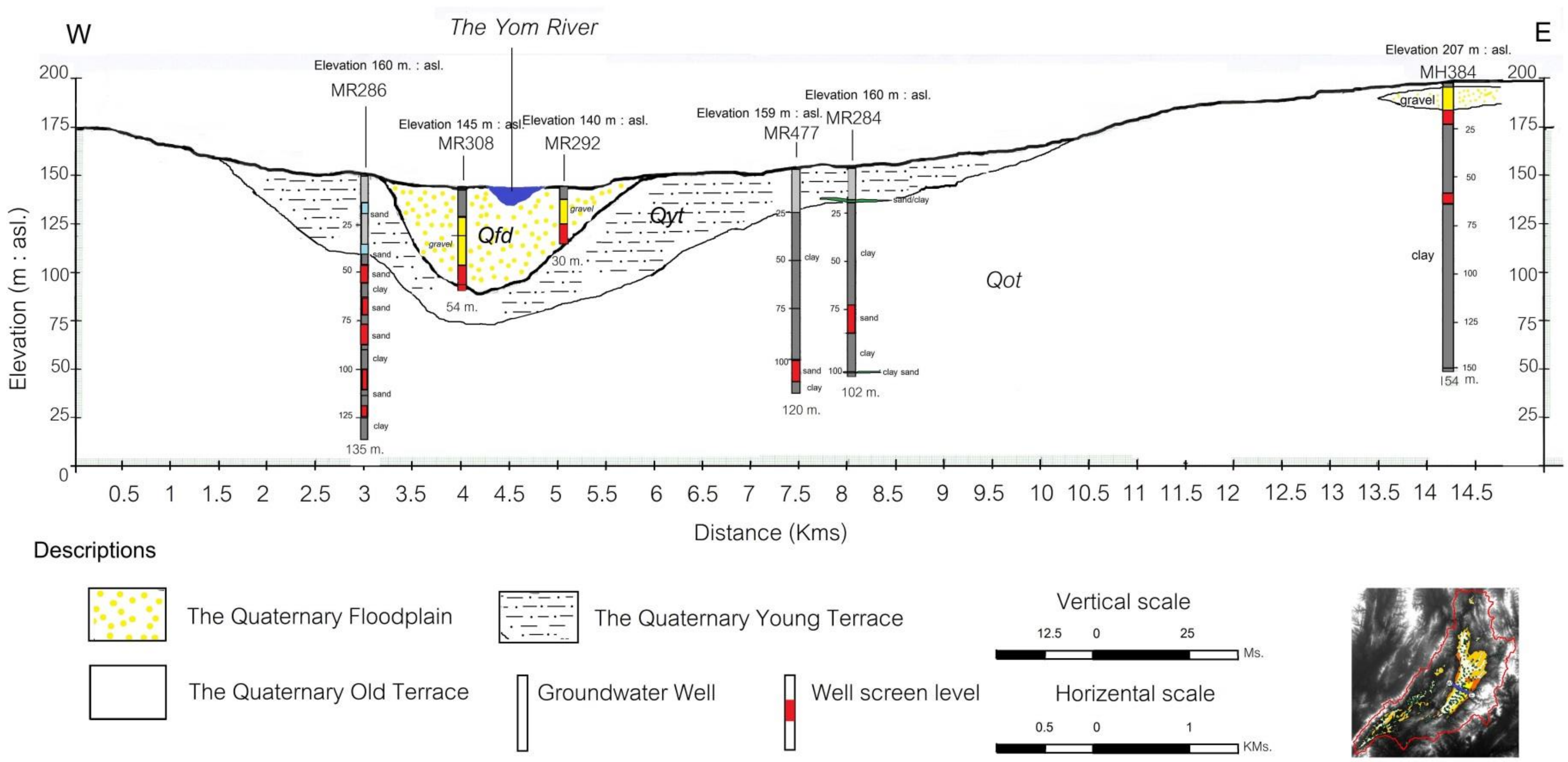

Figure 6. 1 Geologic cross-sections in Line the West to the East of Changwat Phrae.

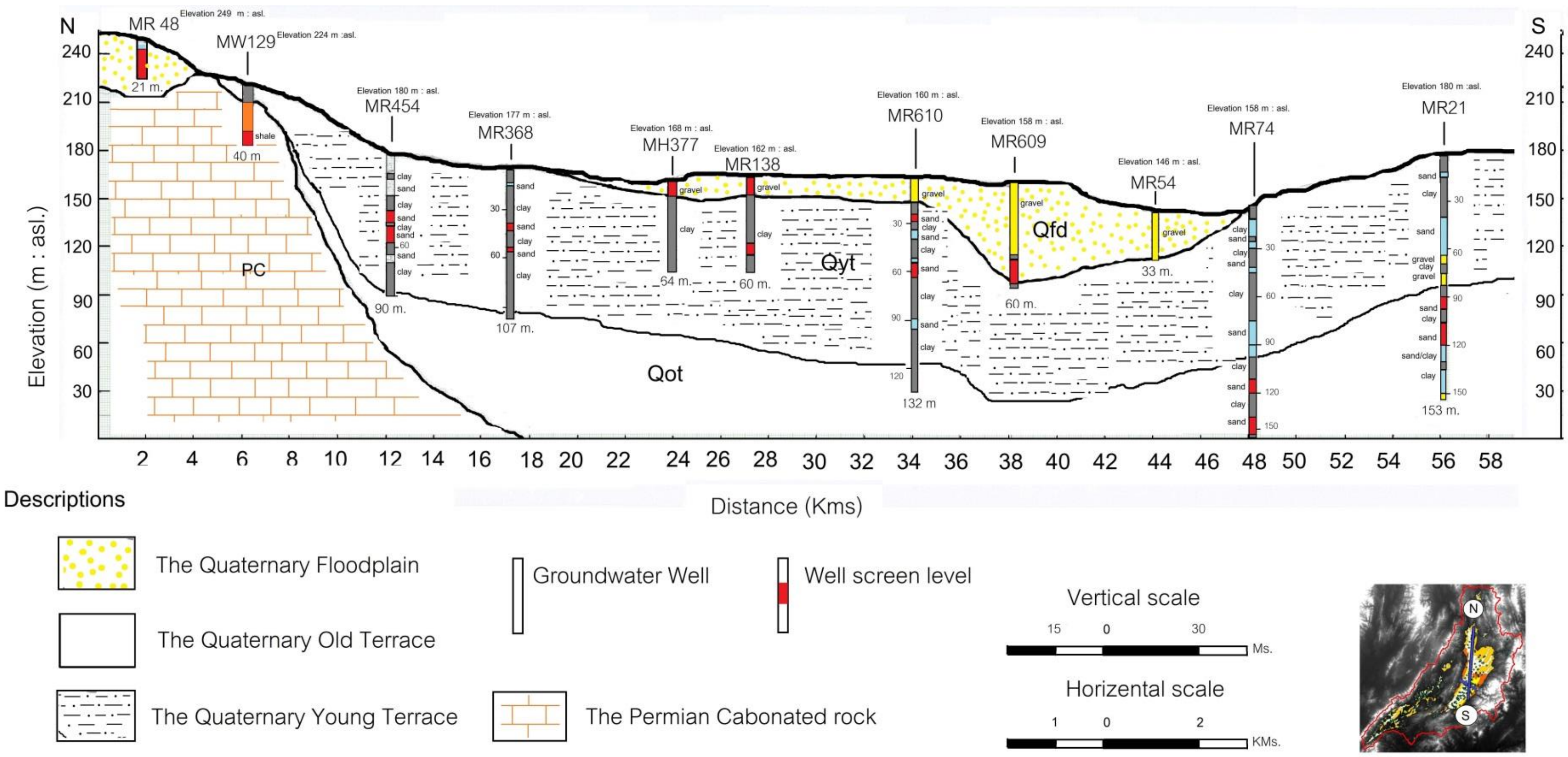

Figure 6. 2 Geologic cross-sections in Line the North to the South of Changwat Phrae.

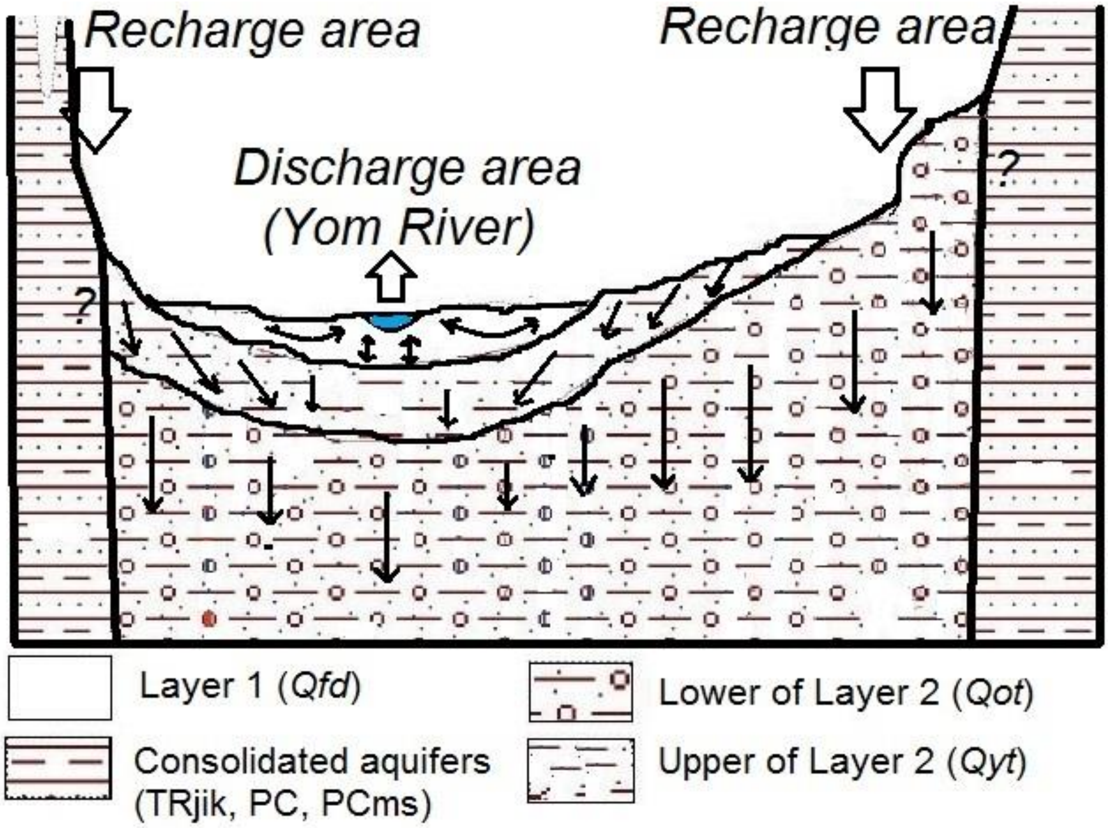

Figure 6. 3 Schematic diagram shows the interaction of aquifers in Changwat Phrae.

Meanwhile, in the Quaternary deposited aquifer, especially in the Quaternary floodplain deposited aquifer (Qfd), it seems very complicated between aquifers and topographic features. Two aquifers exist within the Quaternary deposited, which can be separated by their material properties (gravel mixing with sand or silt in Qfd, and the gravel beds in Qt), that is widespread in the central area of the region. Groundwater levels and flow in the quaternary aquifers follow the topography under convertible conditions in this system. In addition, environmental factors can directly affect to these aquifers such as groundwater recharge, groundwater discharge from Yom River and groundwater pumping, which is related to studies of Flugel and Michl [6] and Jackson [72]. However, because Changwat Phrae is mainly located in a rural region, thus a groundwater abstraction has insignificantly affected on groundwater levels.

6.1.2 The groundwater recharge in Changwat Phrae

6.1.2.1 The relationship between groundwater recharge and groundwater balance components

The results of the groundwater recharge in Changwat Phrae show the corresponding of this study and related study in the region. In dry season, the results were correspoding to studies of Amares [7] and Wiroj [8] who's studied the hydrologic characteristic in the Yom watershed. Changwat Phrae experiences the drought problem every year, especially in dry season because there are no medium and large reservoirs in the river, causing water insufficient. In dry season, low rates of precipitation affect onto low amounts of surface runoff and groundwater recharge. Meanwhile, in the rainy season, high rates of precipitation can cause flash flood and landslide in the region, which related to studies of the National Research Council of Thailand [51] And the Department of Water Resource [73]. In summary, the dynamic of hydrological characteristics mainly follows the rate of precipitation. The less precipitation during dry season cause the drought effect and less surface runoff, and the exceed precipitation during rainy season cause high surface runoff, which the recharge varies on this dynamic. About 99% of total groundwater recharge in the study area is occurred during the rainy season while the remaining 1% is occurred in dry season. The study of Wiroj [8] and Vaji and Somchai [58] found that the annual recharge rates in the tropical zone have ranges from 2-10 % amount of rainfall. The summary of seasonal water balance components was showed in Table 6.1

Table 6. 1 Summary of the seasonal various water balance components from WetSPASS.

Various parameters	Dry season (mm.)				Rainy season (mm.)			
	Min.	Max.	Avg.	Vol. (MCM)	Min.	Max	Avg.	Vol. (MCM)
Precipitation	109.70	164.86	110.01	133.72	817.54	1360.62	951.85	1,787.68
Runoff	0.00	658.62	329.31	174.59	0.00	780.80	390.40	1,447.21
Recharge	0.00	95.50	47.50	0	0.00	720.56	360.00	373.10

All of the above, it clearly is that water balance component is significantly for groundwater recharge occurrence. In hydrological processes, the primary source of the recharge is infiltration of the precipitation and the majority of drainage process is evapotranspiration. In semi-arid region, the evapotranspiration has a critical rate for hydrologic output ([74]; [75] and [44]). However, this process is not operating every time. In rainy season, the exceed precipitation is significantly influence to surface runoff and groundwater recharge, and groundwater discharge from evapotranspiration became a minor effect [76]. In rainy season, the primary source of the discharge depends on topography features as groundwater seepage to Yom River. In addition, the central part was found to act as a groundwater sink, which cause the water is logging in some parts of the region. Moreover, the annual evapotranspiration rate and annual surface runoff from WetSPASS module were compared with the previous studies.

From Figure 6.4, the results showed the annual evapotranspiration rates, where a concordant justification was considerably closed to the annual evapotranspiration rates of [8], which the annual evapotranspiration rates in the Yom watershed have ranges for 170-1850 mm. per year following evapotranspiration by land use classifications in Thailand of TDRI. Moreover, according to the rates of evapotranspiration with land use pattern in Table 6.2, it can be described that is the water body is the highest of evaporation rate, and in the urban area, the evapotranspiration is the lowest. The result was clearly that land use pattern is significantly for evapotranspiration rates. In the tropical zone, the evapotranspiration activity not always occurred, especially in the area which had water such as lake, reservoir and river. The evaporation process can be operated depend on humidity of surface [74]. Meanwhile, the urban area had less humidity or hydrologic activity. It influence to the evapotranspiration process. However, the evapotranspiration rates from WetSPASS module were higher than the rate of previous study. The evapotranspiration should be studying in detail carry on by further study.

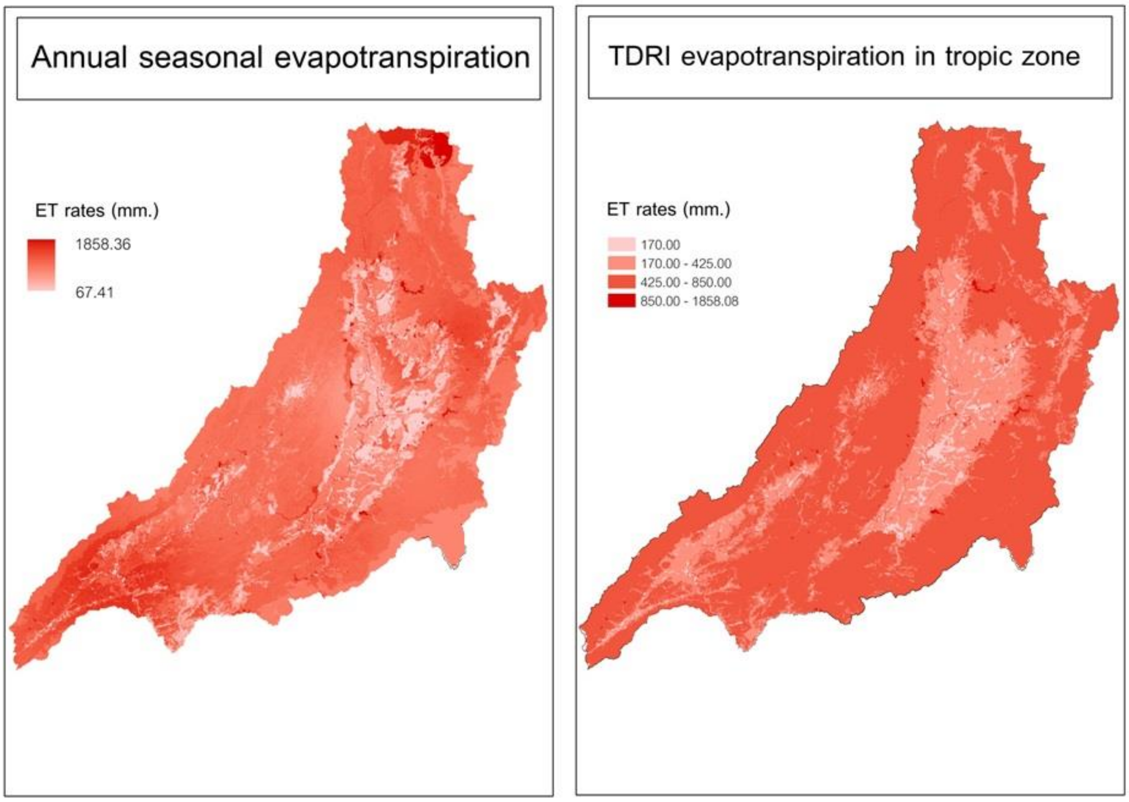

Figure 6. 4 Spatial comparison of evapotranspiration rate in WetSPASS module with the rate of evapotranspiration in tropical zone (adapted from Wiroj [8]).

Table 6. 2 Comparison of evapotranspiration rate in WetSPASS module with the rate of evapotranspiration in tropical zone (adapted from Wiroj [8]).

Land use	**WetSPASS** (mm./ year)			**Tropical zone** (mm./ year)		
	Min.	Max.	Mean	Min.	Max	Mean
Forest	541.24	1577.46	1005.76	425.00	850.00	637.50
Agriculture	460.01	1857.75	874.91	170.00	425.00	297.50
Urban	67.41	975.74	538.06	0	170.00	85.00
Water	1729.64	1858.36	1829.18	850.00	1858.08	1354.00

In the comparison of surface runoff from WetSPASS, the results were showed in Figure 6.5. It showed the annual rate of surface runoff in WetSPASS was corresponding with runoff data in the study area. The result was clearly that the surface runoff estimation in Changwat Phrae could be successfully simulated for annual and seasonal conditions using the water balance method. However, in the groundwater recharge rate, it was difficult to determine and comparison of the real recharge rate in the region. It is essential of studying in the future.

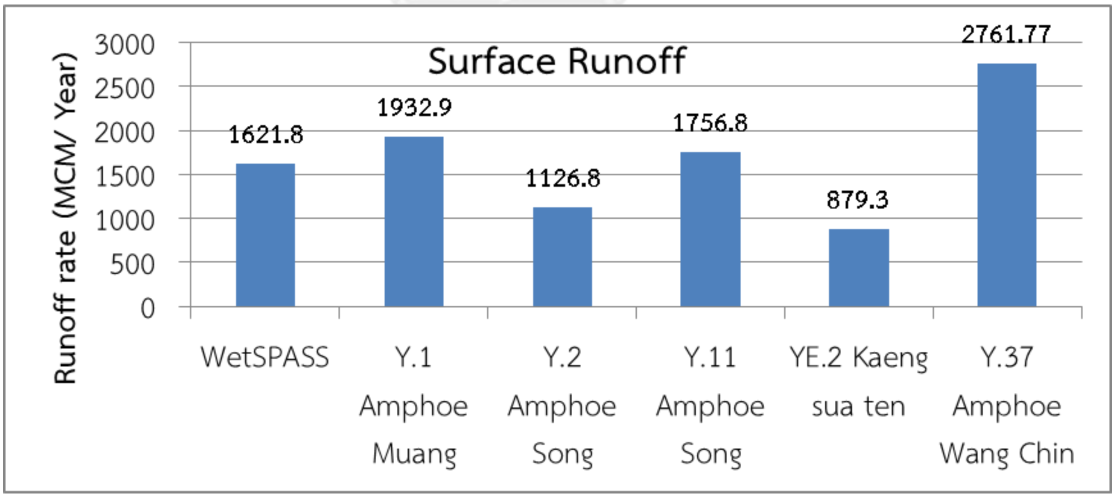

Figure 6. 5 Comparison of surface runoff rate in WetSPASS module with runoff data in the study area (data from the Royal irrigation Department, 1980-2010).

6.1.2.2 The relationship between groundwater recharge and surface features

In the relationship between landuse and groundwater balance, this is considered that the land use patterns influence to hydrologic processes, which affect significantly to for groundwater recharge. In the building-up land, surface water is difficult to infiltrate through an unsaturated zone [40], and in the case of forest area, results from high interception, high actual evapotranspiration, high shallower rooting depths, which influence to reduced recharge rates [74]. Thus, the results are also correlated with land use and terrain slope.

The relationship between land use and groundwater recharge are shown in Table 6.4 and Figure 6.6. In the agriculture area type, recharge rates is the highest average (47.06 mm. per year), and lowest average of recharge rates is the water body (9.70 mm. per year). In addition, in the forest area type, recharge rates were range from 0 to 630 mm. with 33.36 mm. of an average value, and recharge rates were range from 0 to 627 mm. with 40.89 mm. of an average value in the urban area type.

All of the above, it clearly is that land use patterns are significantly for groundwater recharge rates. Almost 74.88 percent of mountainous forest, 21.31 percent of agriculture area and 3.02 percent of build-up land. Thus, average recharge rates in the study varied from 9.70 to 47.06 mm. depending on land use type. In dry season, groundwater recharge generally had a zero values in the environment because of higher evapotranspiration rates than surface runoff rates. However, in rainy season, groundwater recharge was increasing. The greater recharge occurred in the floodplain area that has the lowest average slope and agriculture area [67]. According to Batelaan and Smedt [77], who described the relationship between land use and groundwater recharge. The agriculture area was the highest of groundwater recharge rate area because of low interception and low shallower rooting depths, which influence to increased recharge rates. On the other hand, low infiltration in the urban area and high shallower rooting depths in the forest area were influence to reduced recharge rates. In addition, groundwater recharge in the water body area had low values because of the consideration that the water body area was a discharge zone, which showed the correlation of land use type in Figure 6.7.

However, recharge rates are also appeared as zero values in rainy season, especially in the region which the hard rock units covered. It can be described following to Vaji and Somchai [58] described the relationship between groundwater recharge and aquifer type. In the consolidated aquifer which covered with the forest area, groundwater recharge rates should not higher than 5% of the precipitation (Table 6.3).

Furthermore, the topographic features also influence on groundwater recharge in the study area. According to Schilling [78] who described a study of groundwater recharge along a topographic gradient. In the steepest area, the potential of groundwater recharge is 14 percentage of precipitation. But, in the floodplain area, the potential of groundwater recharge is 44 percentage of precipitation. This consideration is corresponded to this region. In rainy season, recharge rates are also appeared as zero values in the many zones in the study area because in the complex slope zone, surface runoff is quite high and water infiltration to ground surface is very low. Almost 50 percent of Phrae province is covered by complex slope areas, usually with slope greater than 35%, the soil group characteristics depending on type of terrain, parent materials and vegetative cover, unsuitability for agriculture, high erosion, these characteristics influenced onto surface runoff and infiltration.

Table 6. 3 The relationship between groundwater rate and aquifer types (Vaji and Somchai, 2002).

Aquifer type	**Recharge rate (% of precipitation)**
Unconsolidated aquifer	10
High capacity consolidated aquifer	5
Intermediate capacity consolidated aquifer	3
low capacity consolidated aquifer	2

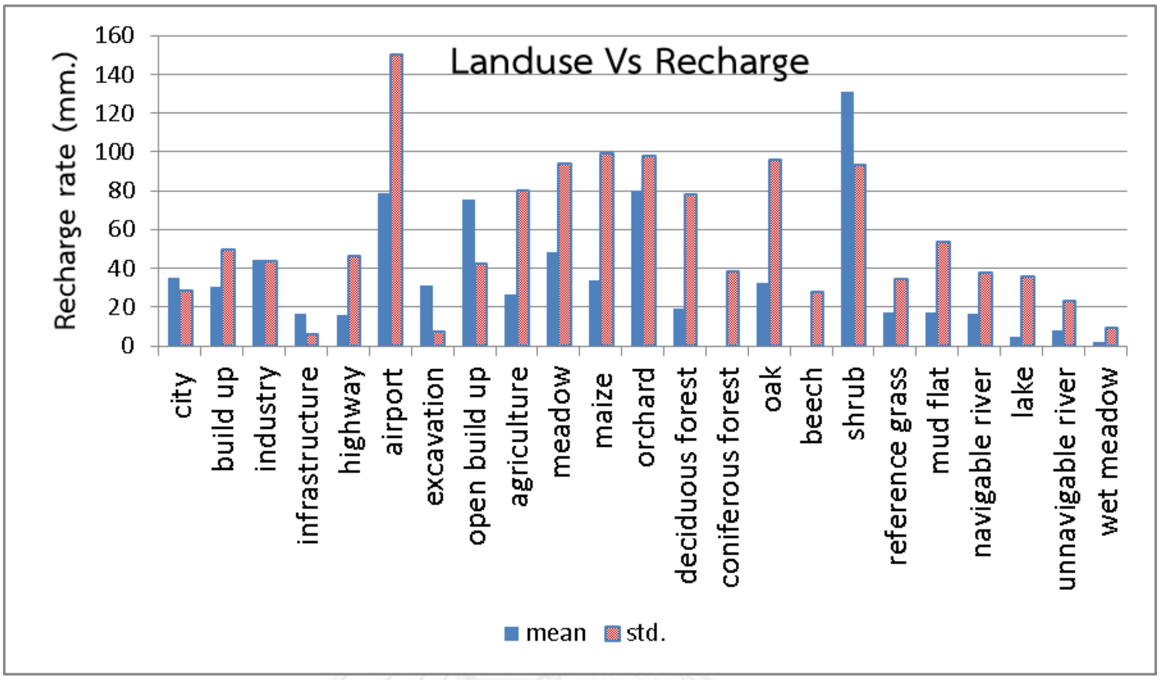

Figure 6. 6 Mean and standard deviation of WetSpass simulated recharge per land cover.

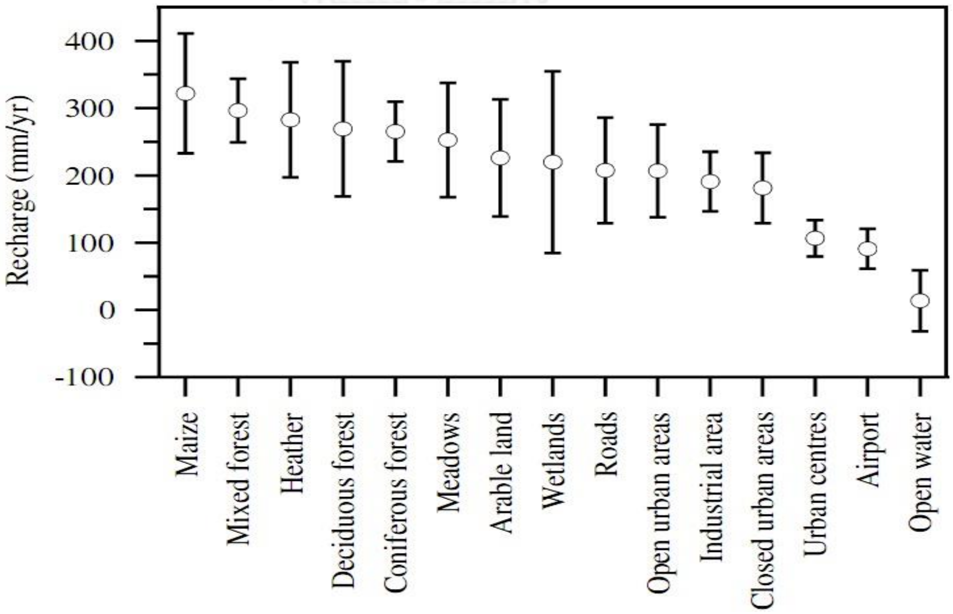

Figure 6. 7 Mean and standard deviation of WetSpass simulated recharge per land cover and soil texture class [77].

Table 6. 4 The relationship between land use patterns and recharge rates.

Land use			Recharge (mm. per year)			
Type	Area (sq.m.)	Area (%)	min	max	std.	mean
city	31,886,682.83	0.49	0	455.49	28.11	34.94
build up	139,361,835.30	2.17	0	616.27	49.44	30.22
industry	5,900,490.75	0.09	0	627.09	43.66	44.57
infrastructure	21,298.09	0	10.61	22.64	6.01	16.62
airport	592,708.92	0.01	0	462.44	149.96	78.82
excavation	7,151,112.99	0.11	3.81	33.29	7.17	30.96
open build up	9,296,965.69	0.14	0	433.33	41.97	75.12
agriculture	590,561,775.00	9.19	0	630.55	80.21	26.60
meadow	9,077,673.71	0.14	0	427.73	93.58	48.07
maize	453,870,892.50	7.06	0	604.99	99.11	33.57
wet meadow	3,101,201.18	0.05	0	57.43	9.21	1.85
orchard	188,113,810.80	2.93	0	622.02	97.76	80.02
deciduous forest	183,347,205.70	2.85	0	568.42	77.97	19.38
coniferous forest	3,812,993,575	59.35	0	607.37	38.27	0
shrub	154,995,429.70	2.41	0	629.94	93.19	131.14
mud flat	2,863,448.15	0.04	0	425.12	53.58	17.36
navigable river	16,887,466.44	0.26	0	393.61	37.74	16.69
lake	25,139,742.67	0.39	0	598.98	35.55	4.63
unnavigable river	2,967,423.78	0.04	0	199.75	23.31	7.99
highway	701,581.49	0.01	0	356.4	45.91	15.70
beech	527,442,357.30	8.21	0	163.47	27.63	0
oak	128,181,442.10	1.99	0	615.72	95.89	32.56
reference grass	129,643,216.00	2.02	0	322.5	34.33	17.11
Total	**6,424,099,336.00**	**100**				

6.1.3 The groundwater balance for suggestions of groundwater management in Changwat Phrae

The results of seasonal hydrologic process in the area influence to the seasonal groundwater balance in Changwat Phrae. Both the steady-state and transient-State conditions, it showed that the groundwater inflow is higher than groundwater outflow. However, it is difficult to determine the groundwater storage in the region, especially the groundwater storage in hard rock aquifer. Additionally, the Block-Center flow formula is useful to solve the groundwater storage and groundwater flow under the complex geologic setting as in Changwat Phrae. The results of groundwater verification, both the steady-state and transient-State conditions were showed in Figure 6.8 and Figure 6.9.

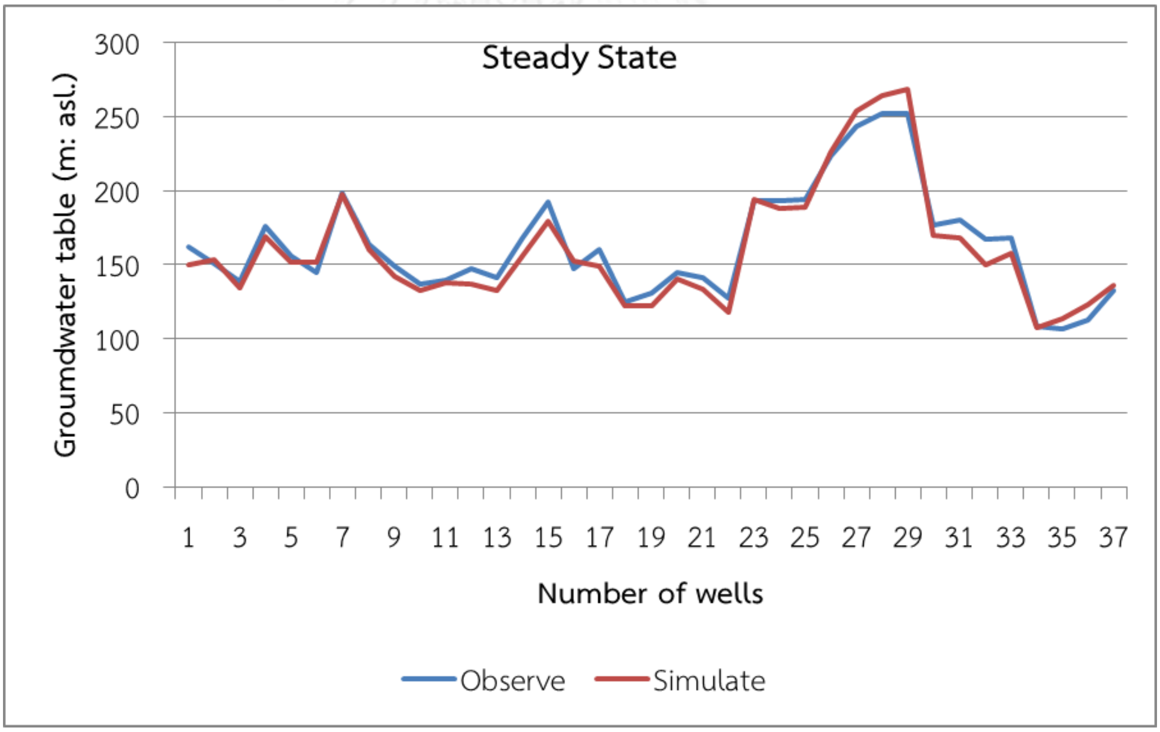

Figure 6. 8 Groundwater Model verification in steady-state.

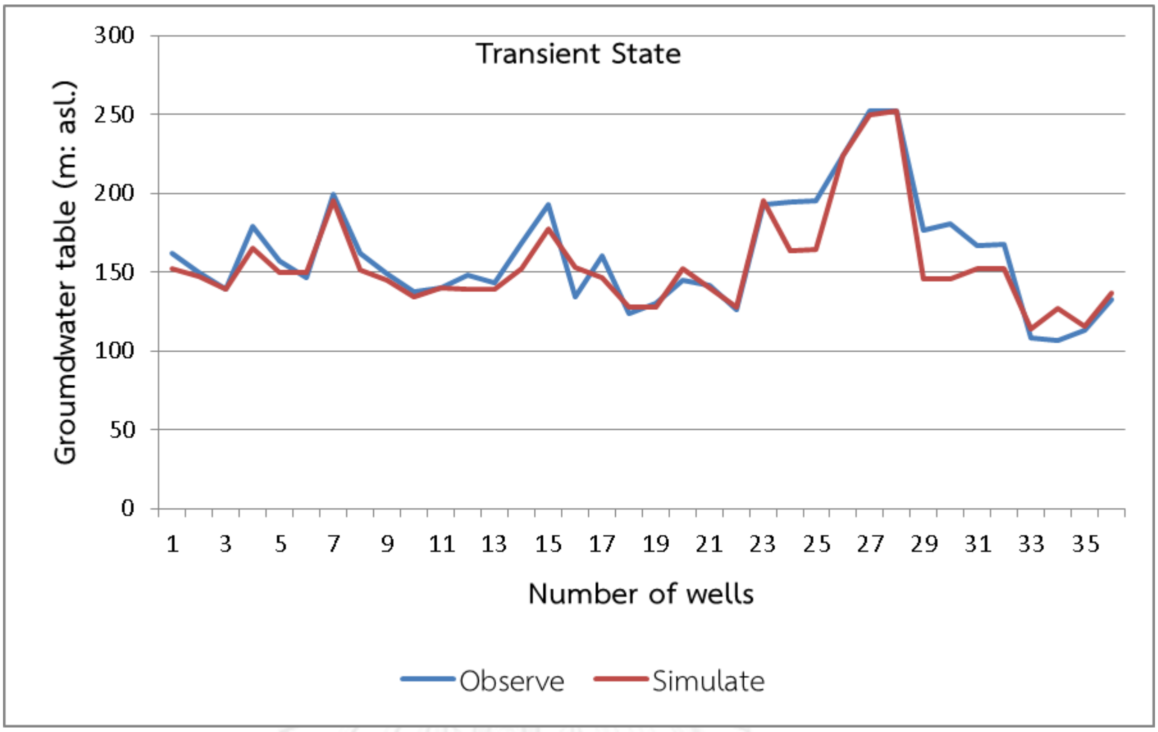

Figure 6. 9 Groundwater Model verification in transient-state.

Following to the results of groundwater balance modelling, it makes a written summary of the study as in the steady-state (or annual period), the groundwater inflow is higher than outflow. But, the results of seasonal groundwater balance show the non-equilibrium condition, the low rate of groundwater recharge in dry season which causes of the water shortage problem in the mountainous area. Moreover, the high rates of groundwater pumping in Amphoe Muang, it causes the groundwater depression zone in long-term. In groundwater pumping term, because the region is a rural area, groundwater discharge from pumping has a very low effect. However, the remote areas which far from irrigation system and water supply from Yom River, they face water shortage occurrence, due to poor groundwater quality and lack of groundwater in the hard rock aquifer. The primary solving of government mitigates the water shortage problem by extracting groundwater water from the Quaternary.

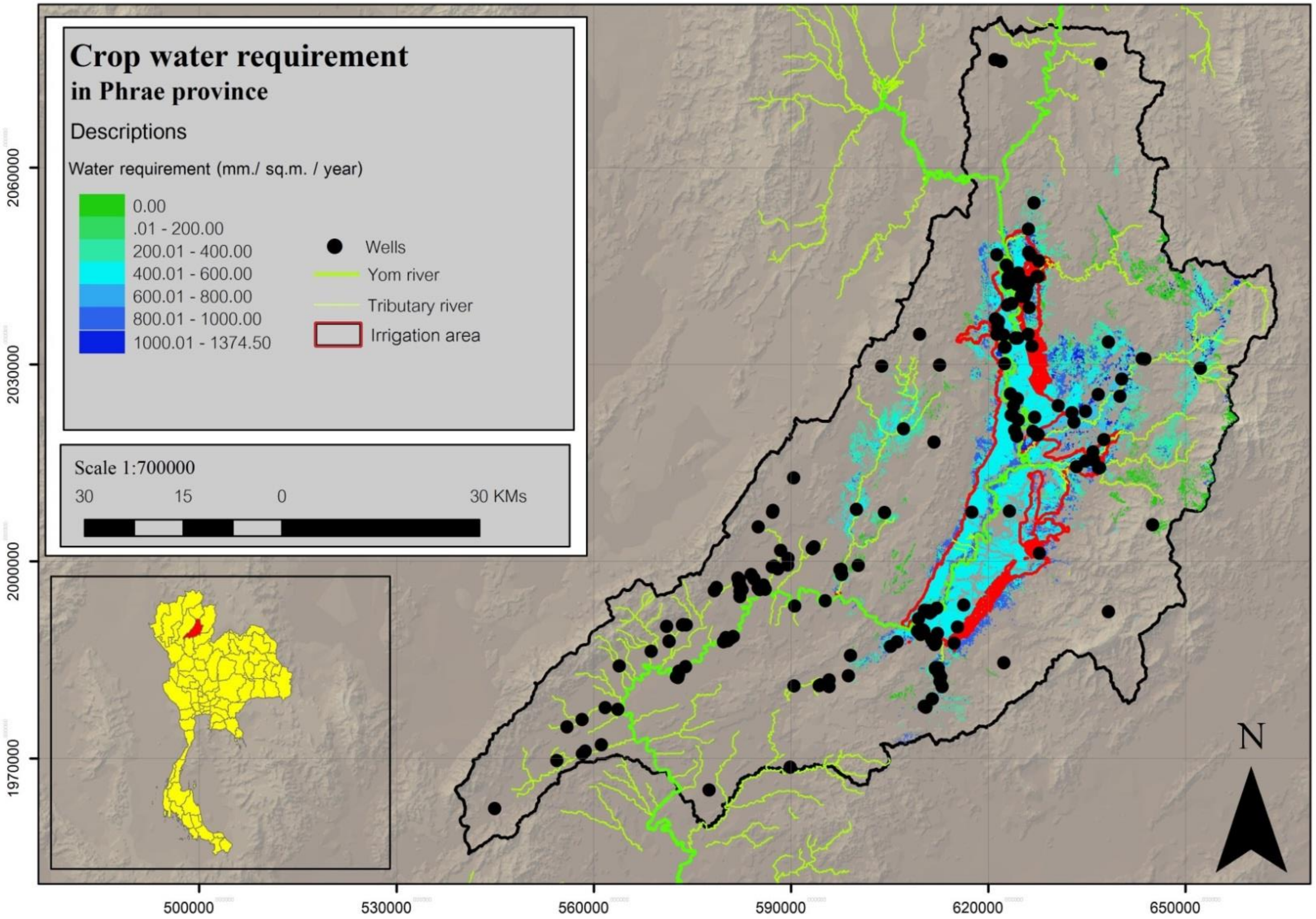

Figure 6. 10 Crop water requirement in Changwat Phrae shows the deficit zone of surface water supply for agriculture.

Following to the results of water supply for agriculture in Figure 6.10, it was corresponding to a water shortage problem in the study area. According to reports of Maeyom Operation and Management Irrigation project [47], Changwat Phrae has surface water supply in the irrigation area, which covered the Quaternary Floodplain Deposits of approx. 224,000 Rai or 358 square kilometers. Water supply for Irrigation was separated into two periods as in rainy season (June - November) and dry season (December-March). In irrigate areas, agricultural pattern was a paddy field in rainy season, and soy bean, maize and out-of-season rice in dry season. However, the water shortage still occurrence. During December-March, the surface water had a low rate but water requirement for agriculture is very important especially in remote area and non-irrigate area, which were correspond to seasonal variation of surface runoff and precipitation as Figure 6.11 and Figure 6.12.

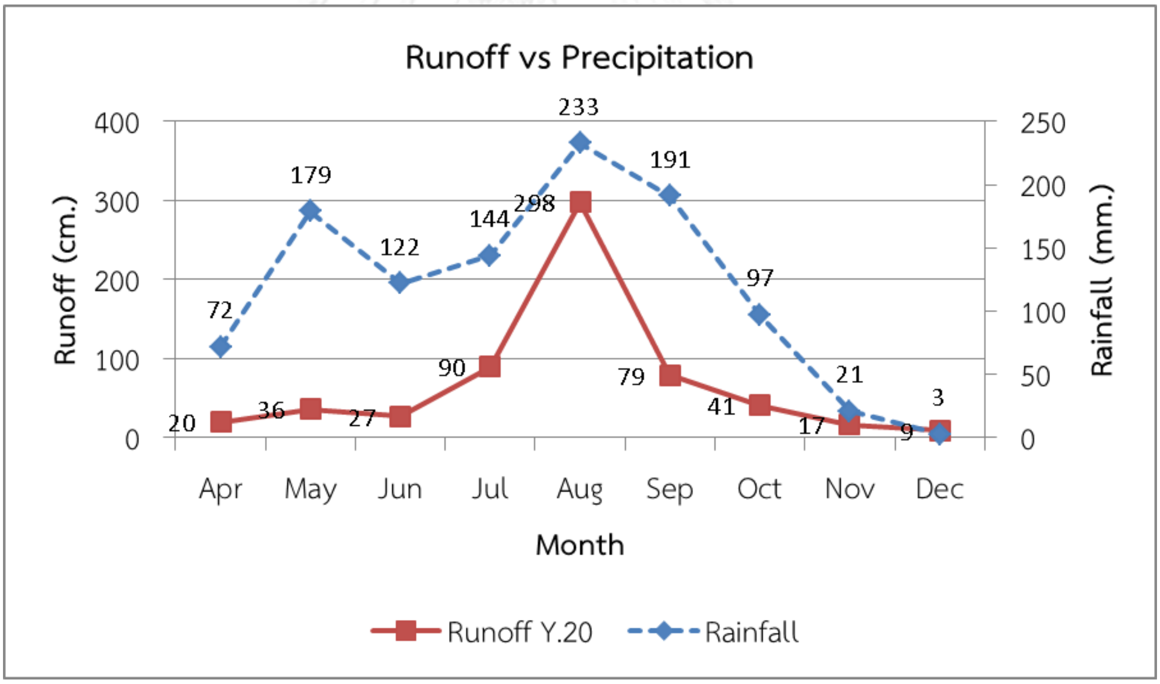

Figure 6. 11 The correlation between annual variation of surface runoff and precipitation.

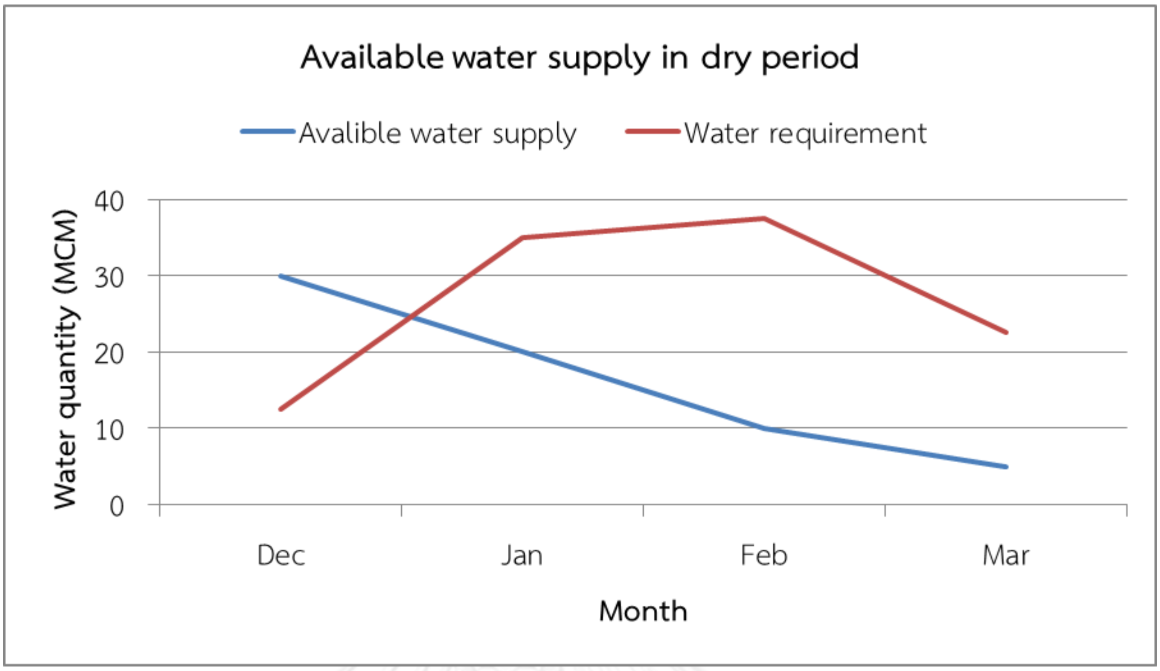

Figure 6. 12 The available water supplies in dry period of Maeyom Operation and Management Irrigation project [47].

For sustainability and surface water-groundwater consumption use, groundwater resource may able to supply the agricultural in the study area especially in non-irrigate area irrigate area during dry period. CROPWAT 8.0 was used to calculate the water requirement for agriculture and GIS was used to represent the results in term of spatial. Moreover, the groundwater quantity in the Quaternary deposits which the most potential aquifers was used to manage lack of surface water in term of consumption use. The results showed in Table 6.5, The Quaternary aquifers had the specific storage of 505 million cubic meters (MCM), and specific yield in the basin was 101 MCM per year. Meanwhile, the shortage of irrigate water in dry season was 95 MCM. Which the potential yield of the Quaternary aquifers may able to carry on the water shortage problem. However, the results of groundwater simulation showed the rate of the groundwater usage should not higher than 50% of groundwater available for migration the problem of groundwater abstraction.

Table 6. 5 The available groundwater supplies under safe yield conditions in dry period.

<table>
<tr><th>Descriptions</th><th>Conditions</th><th>Quantity rate (MCMs)</th></tr>
<tr><td rowspan="2">Water requirement</td><td>Irrigate area</td><td>559.43</td></tr>
<tr><td>Non-irrigate area</td><td>5.31</td></tr>
<tr><td colspan="2">Irrigation Water deficit in dry season (irrigate area)</td><td>95.00</td></tr>
<tr><td colspan="2">Groundwater Storage</td><td>505.39</td></tr>
<tr><td colspan="2">Groundwater potential (20% of groundwater storage)</td><td>101.08</td></tr>
<tr><td rowspan="3">Groundwater safe yield</td><td>25 percent</td><td>25.26</td></tr>
<tr><td>50 percent</td><td>50.54</td></tr>
<tr><td>100 percent</td><td>101.08</td></tr>
</table>

6.2 Conclusions

In this research, existing data from government, private sector and field investigated were integrated to prepare the database input, consisting of thematic (GIS and remote sensing) data and statistical data for groundwater balance assessment in the study area. Furthermore, the purpose is to analyze the parameters influencing the groundwater recharge and to simulate the groundwater flow under the saturated zone in Phrae province, Northern Thailand.

This study used the spatial GIS database, such as topography, meteorology, geology, hydrology, hydrogeology and land use to construct the thematic map and GRID data for the groundwater recharge estimation with WetSPASS module. According to the study, this study area consist of 25 landuse classes and 12 soil textures classes on the differential landforms. It could be identified as paddy field and field crops on the floodplain deposits, evergreen forest, deciduous forest and forest plantation on the high mountainous area, urban and built-up land along the Yom River. Furthermore, data from field investigations were used to better understanding about topographic pattern and were used to test the accuracy against with the LV 2 land use spatial data from the Department of Land Development, Furthermore, groundwater levels were measured in summer and rainy seasons during year 2012-2013.

The groundwater recharge estimation was analyzed using water balance overlaying technique. The results revealed that the groundwater recharge of Phrae province varies from 0 to 630 mm. per year with 11.02 mm. of an average value. The annual groundwater recharge has a 8.80 % of the average rainfall, which is lined with the study of Thailand Development Research Institute, which the annual recharge rates in the tropical zone have ranges from 8-10 % amount of rainfall. For seasonal variation, about 99% of total groundwater recharge in the study area is occurred during the rainy season while the remaining 1% is occurred in dry season. In summer season, the groundwater recharge is about a 0.16 % of the summer rainfall and ranges from 0 to 95 mm. / season with 0.00 mm. of an average value. In rainy season, the groundwater recharge is around 20.87 % of the rainfall in the rainy season, and ranged from 0 to 720 mm. / season with 58 mm. of an average value.

The quantitative analysis of significantly factors of groundwater recharge showed that the effective factors that significantly influence water balance components are: elevation, slope, landuse and soil. It can be described as the rates of groundwater recharge are also found to be remarkably higher in poor-vegetated land use than that vegetated land use and build-up land. Eventually, the results analysis reveals that precipitation is the most important hydrologic process in the study area, and evapotranspiration is great significantly for reduce the recharge rates. In addition, complex slopes of soil type have an effect on zero recharge in the region. However, recharge may take many years to pass through the unsaturated zone to archive. Thus, the rate of movement depends on the hydraulic conductivities and hydrogeologic characteristic of aquifers, and it is difficult to determine the groundwater movement. In further step, numerical groundwater modelling used to tackle the variations of hydraulic conductivities and hydrogeologic characteristics.

For groundwater modeling, schematic model construction is necessary. In the study area, there are three types of aquifers as follows: two unconsolidated, floodplain deposited (Qfd) and terrace deposited aquifers (Qyt and Qot) and the consolidated hard rock aquifers. The unconsolidated aquifers were distributed over the central part of the study area, while the hard rock aquifer lies underneath Qyt and Qot and act as the bed rock in the study area. The main groundwater direction flows from the northern part to the southern part. The yield potential of the groundwater is relatively different in each different aquifers and the highest potential found in Quaternary aquifers (Qyt and Qot).

According to results of groundwater balance in transient-state (2012-2013), it showed that the groundwater inflow in Changwat Phrae is 23,543 MCM. Groundwater inflow occurs by groundwater flow into the storage about 18,457 MCM. In addition, the inflow from groundwater recharge and river are 113 and 241 MCM. In groundwater outflow, mostly is drainage region in the Floodplain deposited about 18,179 MCM. The outflow from domestic well and Yom River are 21 and 3,067 MCM, respectively. In summary, the groundwater inflow is higher than outflow that means the total of groundwater balance in Changwat Phrae is +111,320 MCM.

But, in the results of seasonal groundwater balance (Dry and Rainy seasons), it shows that the groundwater inflow in rainy season is higher than that in dry season. The groundwater inflow in rainy season is approx. 18,343 MCM, but the groundwater inflow in dry season is 5,115 MCM. The main loss from Changwat Phrae mainly is evapotranspiration and drainage area in the central part of the region.

In the study of groundwater assessment, the combination of various models is very useful to assess the groundwater. Example in the combination of various models in this study, "Cropwat 8.0" an irrigation model was used to estimate a potential evapotranspiration as an input parameter for "WetSpass" water balance model. The groundwater recharge estimation in Changwat Phrae could be successfully simulated for annual and seasonal conditions incorporated with GMS-MODFLOW. Finally, the seasonal recharge rate from water balance model was used to simulate the groundwater flow and groundwater balance in the region, and the last processing was visually presented by using GIS which was used to improves, interprets and demonstrate the parameter inputs. Furthermore, the combination of various models can help for the groundwater study in complex regions with, in dynamic patterns such as land use change and/ or climate variations, which the results corresponded to the observed groundwater level in the study area.

6.3 Recommendations

1. In the study of groundwater assessment, the combination of various models is very useful to assess the groundwater, in terms of both quantity and quality. This study is useful to develop further in the future. For example, the combination of other various models such as "SWAT" hydrological model, "CLUE-S" land use prediction model, will be taken into model simulation as the fundamental data for groundwater assessment for properly sustainable management.

2. The data screening, field study as well as, conceptual design and modeling are essential for credibility of the studying. Furthermore, further studies of groundwater assessment in Changwat Phrae should be recollecting the secondary data for database updating and improve the reliability of the further research. Moreover, the long-term of groundwater resource studying has been increased the importance in Thailand. The long-term groundwater data collecting and reupdating are useful to process and analysis the long-term hydrogeologic characteristic.

3. The groundwater model development is necessary for further studies. The block-center flow package and others solving method must be study in details for reliability of the groundwater modelling which correlation with geologic boundary, hydrogeologic characteristic and areal topology in the nature. Moreover, in the studying of groundwater balance assessment, the interaction between aquifers and surface activities should be identifying such as surface water interaction, land use pattern, irrigation planning and behavior of water supply for domestic use.

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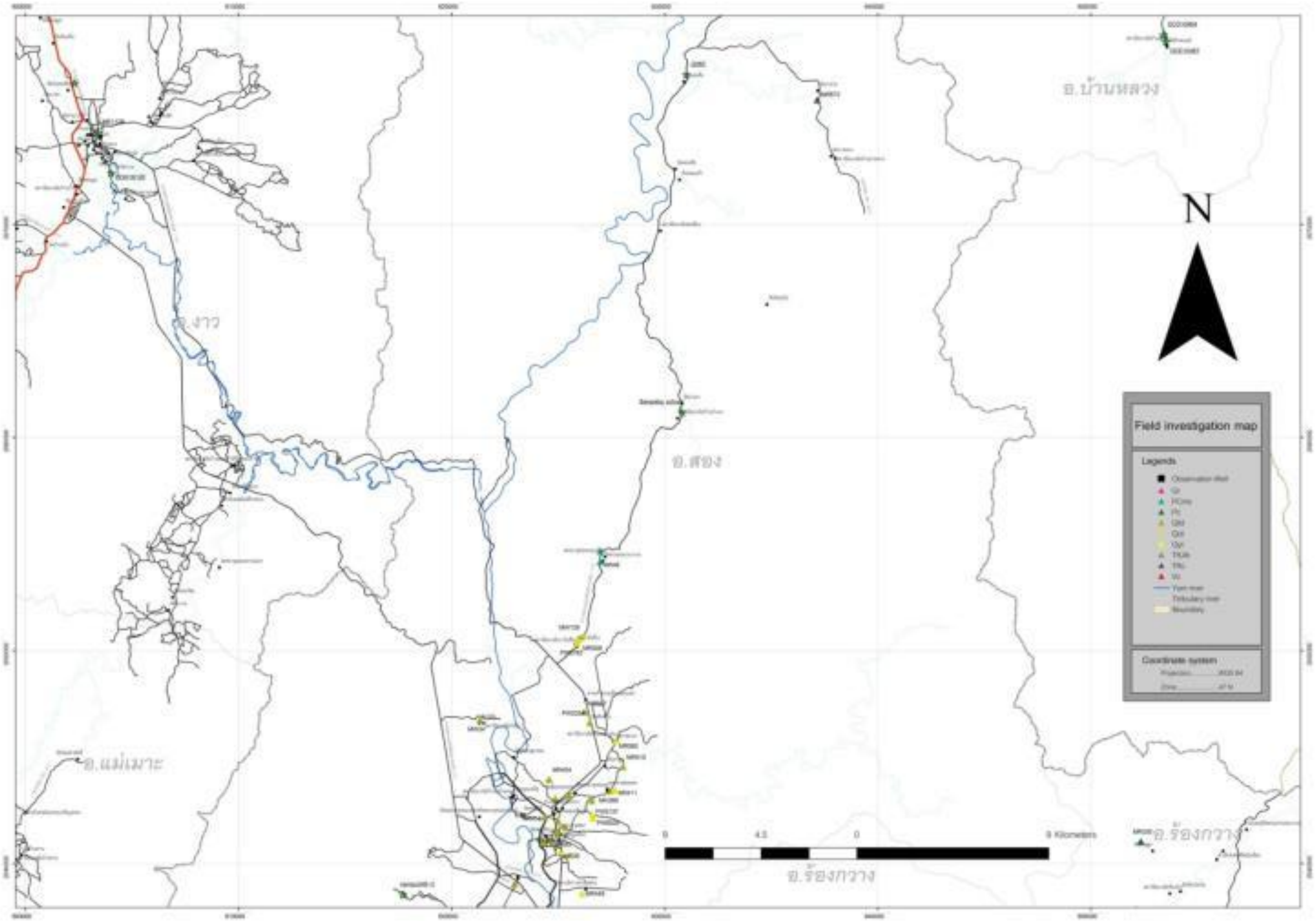
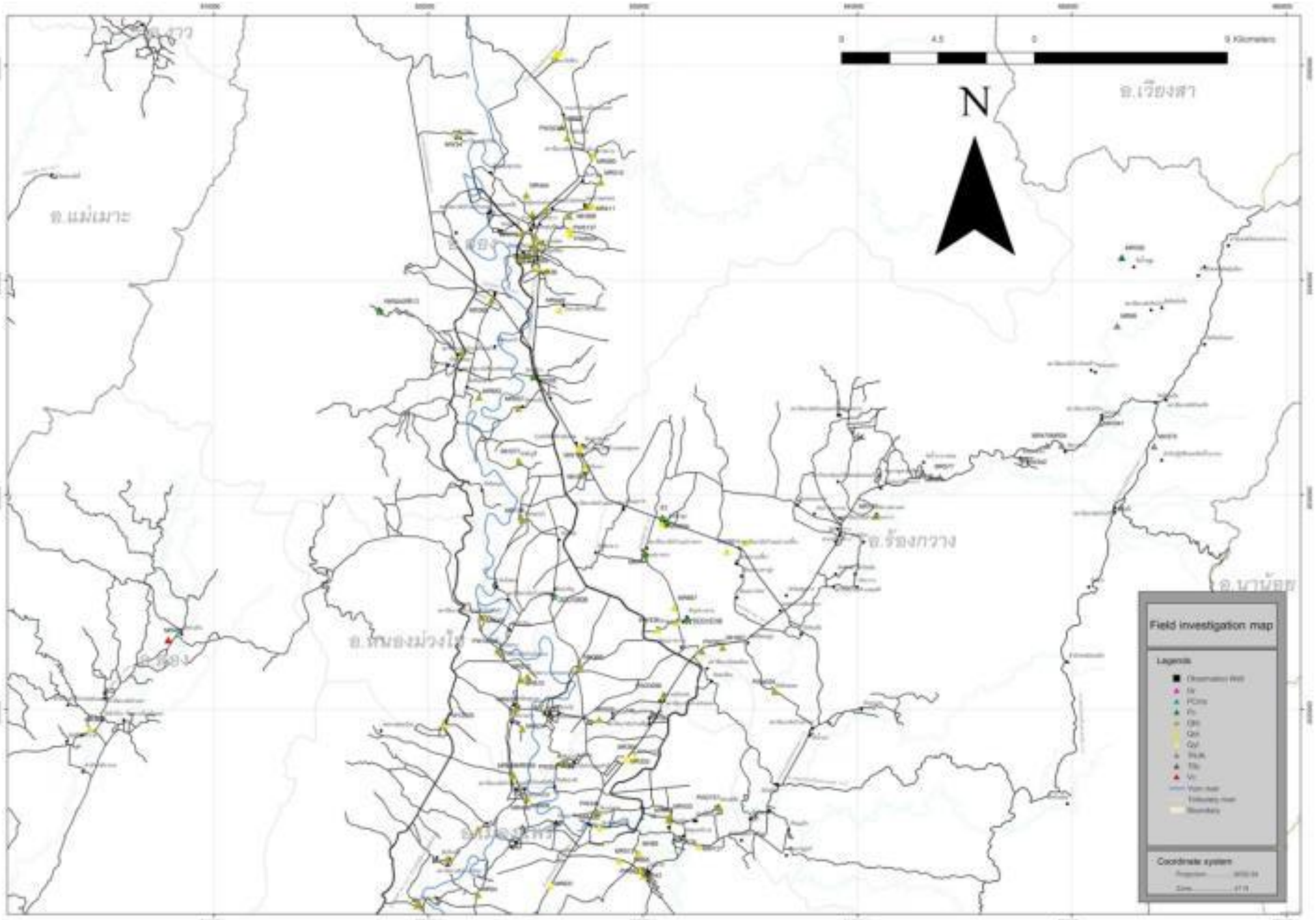
APPENDIX

APPENDIX A

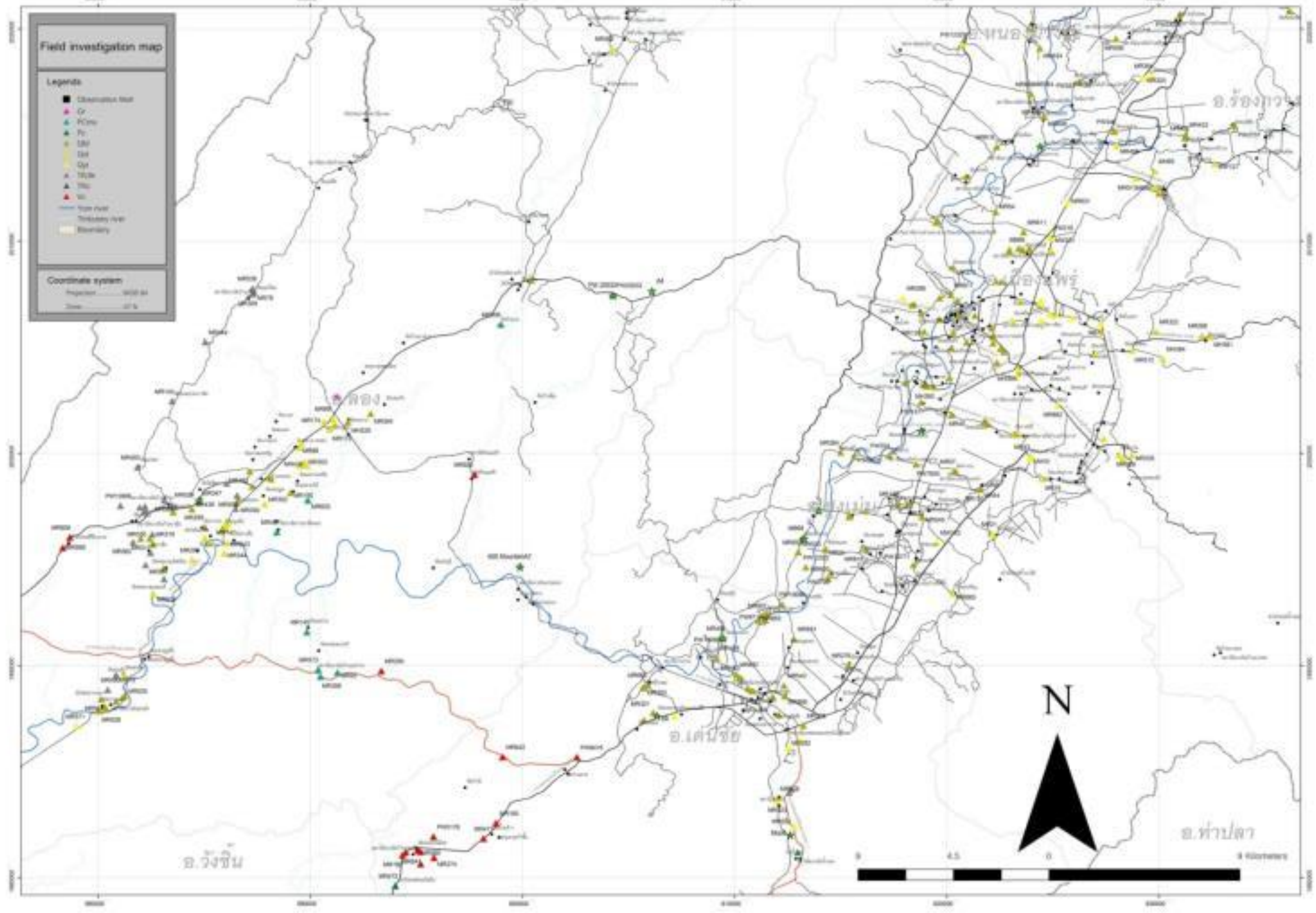
Field investigation mapping in Changwat Phrae



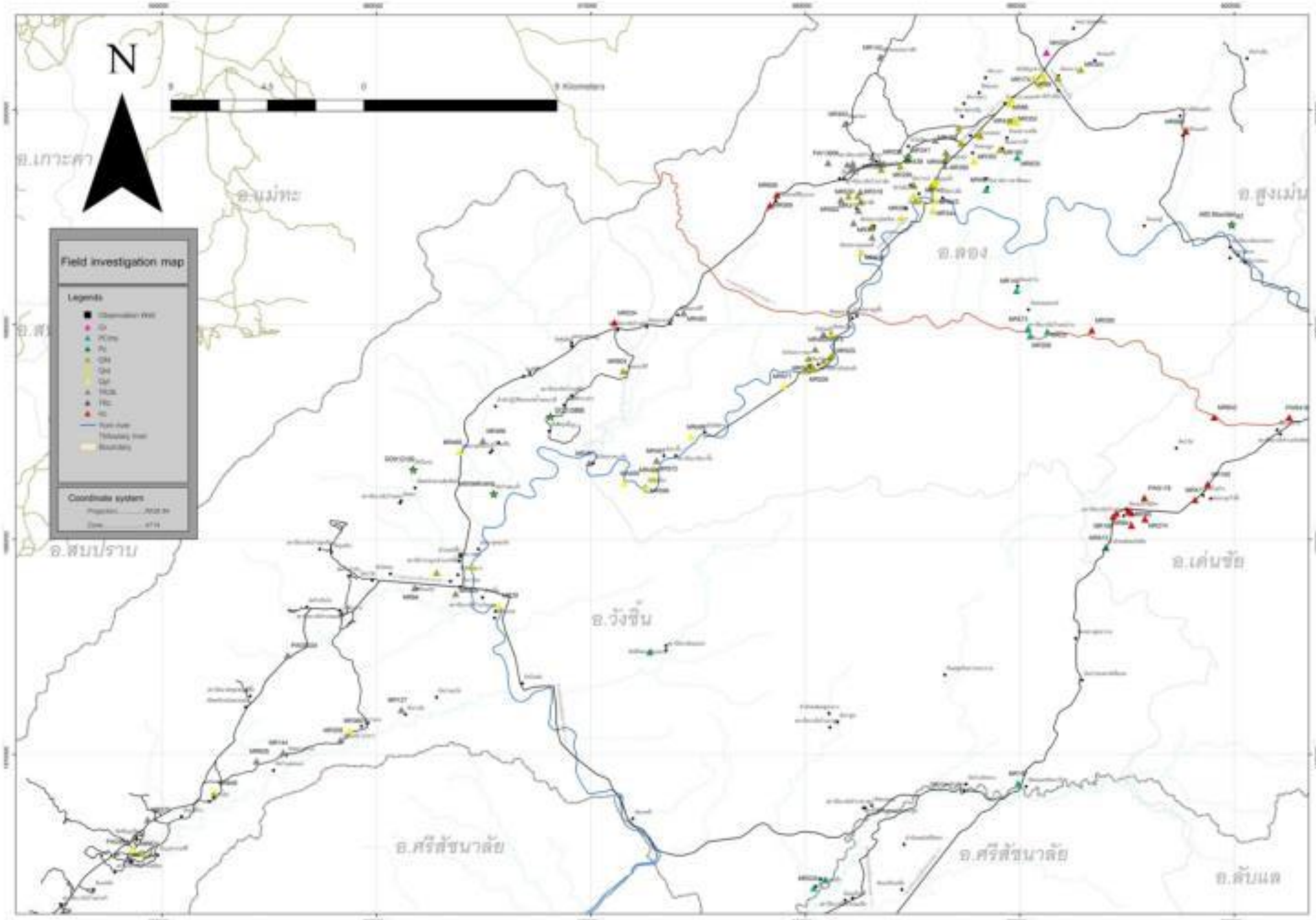
Field investigation map in Amphoe Song, Changwat Phrae.



Field investigation map in Amphoe Song, Amphoe Rong Kwang, Amphoe Nong Muangkai and Amphoe Mueang, Changwat Phrae.



Field investigation map in Amphoe Nong Muangkai, Amphoe Mueang, Amphoe Sung Men and Amphoe Den Chai Changwat Phrae.



Field investigation map in Amphoe Long and Amphoe Wang Chin, Changwat Phrae.

APPENDIX B

Parameters database in WetSPASS

Land use parameter database in summer season.

NO.	LUSE_TYPE	RUNOFF_ VEG	NUM_ VEG_RO	NUM_ IMP_RO	VEG_ AREA	BARE_ AREA	IMP_ AREA	OPENW_ AREA	ROOT_ DEPTH	LAI	MIN_ STOM	INTERC_ PER	VEG_ HEIGHT
1	city center build up	grass	2	1	0.20	0.00	0.80	0.00	0.30	2.00	100.00	10.00	0.12
2	build up	grass	2	2	0.50	0.00	0.50	0.00	0.30	2.00	100.00	10.00	0.12
10	open build up	grass	2	3	0.60	0.10	0.30	0.00	0.30	2.00	100.00	10.00	0.12
4	infrastructure	grass	2	4	0.60	0.10	0.30	0.00	0.30	2.00	100.00	10.00	0.12
201	highway	grass	2	5	0.60	0.10	0.30	0.00	0.30	2.00	100.00	10.00	0.12
202	district road	grass	2	6	0.60	0.10	0.30	0.00	0.30	2.00	100.00	10.00	0.12
5	sea harbor	grass	2	7	0.60	0.10	0.30	0.00	0.30	2.00	100.00	10.00	0.12
6	airport	grass	2	8	0.20	0.00	0.80	0.00	0.30	2.00	100.00	10.00	0.12
3	industry	grass	2	9	0.40	0.00	0.60	0.00	0.30	2.00	100.00	10.00	0.12
7	excavation	bare soil	4	0	0.00	1.00	0.00	0.00	0.05	0.00	110.00	0.00	0.00
21	agriculture	crop	1	0	0.80	0.20	0.00	0.00	0.40	4.00	180.00	15.00	0.60
27	maize and tuberous	crop	1	0	0.80	0.20	0.00	0.00	0.30	4.00	180.00	15.00	1.50
23	meadow	grass	2	0	1.00	0.00	0.00	0.00	0.30	2.00	100.00	10.00	0.20
28	wet meadow	grass	2	0	1.00	0.00	0.00	0.00	0.30	2.00	100.00	10.00	0.30
29	orchard	forest	3	0	0.80	0.20	0.00	0.00	0.80	6.00	150.00	25.00	3.00
31	deciduous forest	forest	3	0	1.00	0.00	0.00	0.00	2.00	5.00	250.00	25.00	18.00
32	coniferous forest	forest	3	0	1.00	0.00	0.00	0.00	2.00	6.00	500.00	45.00	15.00
33	mixed forest	forest	3	0	1.00	0.00	0.00	0.00	2.00	5.00	375.00	35.00	16.00
36	shrub	grass	2	0	1.00	0.00	0.00	0.00	0.60	6.00	110.00	15.00	2.00
35	heather	grass	2	0	1.00	0.00	0.00	0.00	0.20	6.00	110.00	15.00	0.75
54	sea	water	5	0	0.00	0.00	0.00	1.00	0.05	0.00	110.00	0.00	0.00
53	estuary	water	5	0	0.00	0.00	0.00	1.00	0.05	0.00	110.00	0.00	0.00

Land use parameter database in summer season (Continue).

NO.	LUSE_TYPE	RUNOFF_ VEG	NUM_ VEG_RO	NUM_ IMP_RO	VEG_ AREA	BARE_ AREA	IMP_ AREA	OPENW_ AREA	ROOT_ DEPTH	LAI	MIN_ STOM	INTERC_ PER	VEG_ HEIGHT
44	mud flat/salt marsh	water	5	0	0.40	0.20	0.00	0.40	0.30	2.00	110.00	10.00	0.50
37	beach/dune	bare soil	4	0	0.30	0.70	0.00	0.00	0.50	2.00	110.00	15.00	1.00
51	navigable river	water	5	0	0.00	0.00	0.00	1.00	0.05	0.00	110.00	0.00	0.00
55	unnavigable river	water	5	0	0.00	0.00	0.00	1.00	0.05	0.00	110.00	0.00	0.00
52	lake	water	5	0	0.00	0.00	0.00	1.00	0.05	0.00	110.00	0.00	0.00
301	spruce	forest	3	0	1.00	0.00	0.00	0.00	2.00	12.00	320.00	55.00	13.00
302	pine	forest	3	0	1.00	0.00	0.00	0.00	2.00	6.00	550.00	40.00	15.00
303	beech	forest	3	0	1.00	0.00	0.00	0.00	2.00	6.00	320.00	25.00	20.00
304	birch	forest	3	0	1.00	0.00	0.00	0.00	2.00	5.00	320.00	25.00	16.00
305	oak	forest	3	0	1.00	0.00	0.00	0.00	2.00	4.00	150.00	25.00	17.00
306	poplar	forest	3	0	1.00	0.00	0.00	0.00	2.00	5.00	250.00	30.00	18.00
307	reference grass	grass	2	0	1.00	0.00	0.00	0.00	0.30	2.00	140.00	10.00	0.12

Land use parameter database in rainy season.

NO	LUSE_TYPE	RUNOFF_ VEG	NUM_ VEG_RO	NUM_ IMP_RO	VEG_ AREA	BARE_ AREA	IMP_ AREA	OPENW_ AREA	ROOT_ DEPTH	LAI	MIN_ STOM	INTERC_ PER	VEG_ HEIGHT
1	city center build up	grass	2	1	0.2000	0.0000	0.8000	0.0000	0.3000	2.00	100.00	10.00	0.1200
2	build up	grass	2	2	0.5000	0.0000	0.5000	0.0000	0.3000	2.00	100.00	10.00	0.1200
10	open build up	grass	2	3	0.6000	0.1000	0.3000	0.0000	0.3000	2.00	100.00	10.00	0.1200
4	infrastructure	grass	2	4	0.6000	0.1000	0.3000	0.0000	0.3000	2.00	100.00	10.00	0.1200
201	highway	grass	2	5	0.6000	0.1000	0.3000	0.0000	0.3000	2.00	100.00	10.00	0.1200
202	district road	grass	2	6	0.6000	0.1000	0.3000	0.0000	0.3000	2.00	100.00	10.00	0.1200
5	sea harbor	grass	2	7	0.6000	0.1000	0.3000	0.0000	0.3000	2.00	100.00	10.00	0.1200
6	airport	grass	2	8	0.2000	0.0000	0.8000	0.0000	0.3000	2.00	100.00	10.00	0.1200
3	industry	grass	2	9	0.4000	0.0000	0.6000	0.0000	0.3000	2.00	100.00	10.00	0.1200
7	excavation	bare soil	4	0	0.0000	1.0000	0.0000	0.0000	0.0500	0.00	110.00	0.00	0.0010
21	agriculture	crop	1	0	0.0000	1.0000	0.0000	0.0000	0.3500	0.00	180.00	0.00	0.6000
27	maize and tuberous	crop	1	0	0.0000	1.0000	0.0000	0.0000	0.4000	0.00	180.00	0.00	1.5000
23	meadow	grass	2	0	1.0000	0.0000	0.0000	0.0000	0.3000	2.00	100.00	10.00	0.2000
28	wet meadow	grass	2	0	1.0000	0.0000	0.0000	0.0000	0.3000	2.00	100.00	10.00	0.3000
29	orchard	forest	3	0	0.2000	0.8000	0.0000	0.0000	0.8000	0.00	200.00	10.00	3.0000
31	deciduous forest	forest	3	0	0.2000	0.8000	0.0000	0.0000	2.0000	0.00	250.00	10.00	18.0000
32	coniferous forest	forest	3	0	0.9000	0.1000	0.0000	0.0000	2.0000	4.50	500.00	45.00	15.0000
33	mixed forest	forest	3	0	0.5000	0.5000	0.0000	0.0000	2.0000	4.50	500.00	38.00	15.0000
36	shrub	grass	2	0	0.2000	0.8000	0.0000	0.0000	0.6000	0.00	110.00	5.00	2.0000
35	heather	grass	2	0	0.2000	0.8000	0.0000	0.0000	0.2000	4.00	110.00	15.00	0.7500
54	sea	water	5	0	0.0000	0.0000	0.0000	1.0000	0.0500	0.00	110.00	0.00	0.0000
53	estuary	water	5	0	0.0000	0.0000	0.0000	1.0000	0.0500	0.00	110.00	0.00	0.0000

Land use parameter database in rainy season (continue).

NO	LUSE_TYPE	RUNOFF_ VEG	NUM_ VEG_RO	NUM_ IMP_RO	VEG_ AREA	BARE_ AREA	IMP_ AREA	OPENW_ AREA	ROOT_ DEPTH	LAI	MIN_ STOM	INTERC_ PER	VEG_ HEIGHT
44	mud flat/salt marsh	water	5	0	0.4000	0.2000	0.0000	0.4000	0.3000	2.00	110.00	10.00	0.5000
37	beach/dune	bare soil	4	0	0.3000	0.7000	0.0000	0.0000	0.5000	2.00	110.00	15.00	1.0000
51	navigable river	water	5	0	0.0000	0.0000	0.0000	1.0000	0.0500	0.00	110.00	0.00	0.0000
55	unnavigable river	water	5	0	0.0000	0.0000	0.0000	1.0000	0.0500	0.00	110.00	0.00	0.0000
52	lake	water	5	0	0.0000	0.0000	0.0000	1.0000	0.0500	0.00	110.00	0.00	0.0000
301	spruce	forest	3	0	0.9000	0.1000	0.0000	0.0000	2.0000	11.00	320.00	55.00	13.0000
302	pine	forest	3	0	0.9000	0.1000	0.0000	0.0000	2.0000	4.50	550.00	40.00	15.0000
303	beech	forest	3	0	0.2000	0.8000	0.0000	0.0000	2.0000	0.00	320.00	10.00	20.0000
304	birch	forest	3	0	0.2000	0.8000	0.0000	0.0000	2.0000	0.00	320.00	10.00	16.0000
305	oak	forest	3	0	0.2000	0.8000	0.0000	0.0000	2.0000	0.00	150.00	10.00	17.0000
306	poplar	forest	3	0	0.2000	0.8000	0.0000	0.0000	2.0000	0.00	250.00	10.00	18.0000
307	reference grass	grass	2	0	1.0000	0.0000	0.0000	0.0000	0.3000	2.00	140.00	10.00	0.1200

Soil parameter database.

NO	SOIL	BELGIAN_ SO	CLAY_ FRACT	POROSITY	K_S	SAND_ FRACT	CLAY_ FRAC2	POROS2	K_S_ CM_HR	FIELD CAPAC	WILTIN GPNT	PAW	AVAIL WATER
1	sand	Z	0.03	0.395	63.36	0.92	0.03	0.33	12.04	0.12	0.05	0.07	0.05
2	loamy sand	S	0.06	0.410	56.28	0.82	0.06	0.37	5.73	0.15	0.07	0.08	0.08
3	sandy loam	P	0.09	0.435	12.48	0.58	0.10	0.42	2.64	0.21	0.09	0.12	0.10
4	silty loam	A	0.14	0.485	2.59	0.17	0.13	0.46	2.37	0.29	0.10	0.19	0.19
5	loam	L	0.19	0.451	2.50	0.43	0.18	0.46	1.05	0.25	0.12	0.13	0.16
6	silt		-	-	-	0.10	0.10	0.45	3.36	0.30	0.10	0.20	-
7	sandy clayl		0.28	0.420	2.27	0.58	0.27	0.47	0.35	0.26	0.16	0.10	0.08
8	silty clayl		0.34	0.477	0.61	0.10	0.34	0.52	0.45	0.36	0.19	0.17	0.10
9	clayloam	E	0.34	0.476	0.88	0.32	0.34	0.50	0.29	0.33	0.19	0.14	0.08
10	sandy clay		0.43	0.426	0.78	0.52	0.42	0.50	0.13	0.32	0.23	0.09	0.07
11	silty clay		0.49	0.492	0.37	0.06	0.47	0.54	0.29	0.43	0.27	0.16	0.11
12	clay	U	0.63	0.482	0.46	0.22	0.58	0.54	0.18	0.46	0.33	0.13	0.10

Soil parameter database (Continue).

NO.	SOIL	FCCORFIG	FCASCE	PWPASCE	PAWASCE	PAW EVANS	WICORFIG	RESIDUAL WC	A1	EVAPO DEPTH	TENSION HHT	RESID BCEQN	RESID BCAVG
1	sand	0.08	0.12	0.04	0.08	0.05-0.11	0.04	0.020	0.51	0.05	0.07	0.053	0.020
2	loamy sand		0.14	0.06	0.08	0.09-0.15		0.035	0.47	0.05	0.09	0.058	0.035
3	sandy loam	0.13	0.23	0.10	0.13	0.11-0.15	0.06	0.041	0.44	0.05	0.15	0.060	0.041
4	silty loam	0.27	0.30	0.15	0.15	0.11-0.18	0.12	0.015	0.40	0.05	0.21	0.053	0.015
5	loam	0.22	0.26	0.12	0.15	0.11-0.17	0.09	0.027	0.37	0.05	0.11	0.078	0.027
6	silt		0.32	0.15	0.17			0.040	0.35	0.05	0.61	0.040	0.040
7	sandy clayl					0.09-0.15		0.068	0.32	0.05	0.28	0.105	0.068
8	silty clayl		0.34	0.19	0.15	0.11-0.15		0.040	0.29	0.05	0.33	0.103	0.040
9	clayloam	0.31				0.09-0.16	0.17	0.075	0.27	0.05	0.26	0.108	0.075
10	sandy clay							0.109	0.25	0.05	0.29	0.123	0.109
11	silty clay		0.36	0.21	0.15	0.10-0.16		0.056	0.23	0.05	0.34	0.117	0.056
12	clay	0.34	0.36	0.21	0.15	0.10-0.16	0.22	0.090	0.21	0.05	0.37	0.123	0.090

Soil parameter database (Continue).

NO.	SOIL	BUBPRESEQN	BUBPRESAVG	RESIDUALOR	TENSIONORI	K_S_GRN_AM	P_FRAC_SUM	P_FRAC_WIN
1	sand	0.10	0.07	0.04	0.52	23.56	0.09	0.01
2	loamy sand	0.10	0.09	0.04	0.75	5.98	0.09	0.01
3	sandy loam	0.17	0.15	0.04	1.09	2.18	0.09	0.01
4	silty loam	0.51	0.21	0.04	1.41	0.68	0.26	0.07
5	loam	0.22	0.11	0.04	1.67	1.32	0.15	0.02
6	silt	0.61	0.61	0.04	1.23		0.09	0.01
7	sandy clayl	0.09	0.28	0.04	2.23	0.30	0.54	0.30
8	silty clayl	0.56	0.33	0.04	2.84	0.20	0.62	0.41
9	clayloam	0.30	0.26	0.04	2.77	0.20	0.62	0.41
10	sandy clay	0.11	0.29	0.04	3.25	0.12	0.80	0.68
11	silty clay	0.67	0.34	0.04	3.72	0.10	0.84	0.75
12	clay	0.57	0.37	0.04	4.42	0.06	0.95	0.85

Runoff coefficient database.

LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
crop	<0.5	sand	0.3500	0.4500	city center	0.50
crop	0.5-5	sand	0.4000	0.4800	city center	0.60
crop	5-10	sand	0.4500	0.5300	city center	0.70
crop	>10	sand	0.5000	0.5800	city center	0.80
grass	<0.5	sand	0.1500	0.4800	build up	0.40
grass	0.5-5	sand	0.2000	0.5300	build up	0.50
grass	5-10	sand	0.2500	0.5800	build up	0.60
grass	>10	sand	0.3000	0.6300	build up	0.70
forest	<0.5	sand	0.0500	0.5000	open build u	0.30
forest	0.5-5	sand	0.1000	0.5500	open build u	0.40
forest	5-10	sand	0.1500	0.6000	open build u	0.50
forest	>10	sand	0.2000	0.6500	open build u	0.60
bare soil	<0.5	sand	0.4500	0.5300	infrastructu	0.30
bare soil	0.5-5	sand	0.4800	0.5800	infrastructu	0.40
bare soil	5-10	sand	0.5300	0.6300	infrastructu	0.50
bare soil	>10	sand	0.5800	0.6800	infrastructu	0.60
open water	<0.5	sand	1.0000	0.5000	highway	0.30
open water	0.5-5	sand	1.0000	0.5500	highway	0.40
open water	5-10	sand	1.0000	0.6000	highway	0.50
open water	>10	sand	1.0000	0.6500	highway	0.60
crop	<0.5	loamy-sand	0.3800	0.4800	district roa	0.30
crop	0.5-5	loamy-sand	0.4300	0.5300	district roa	0.40
crop	5-10	loamy-sand	0.4800	0.5800	district roa	0.50
crop	>10	loamy-sand	0.5300	0.6300	district roa	0.60
grass	<0.5	loamy-sand	0.1800	0.5300	sea harbour	0.30
grass	0.5-5	loamy-sand	0.2300	0.5800	sea harbour	0.40
grass	5-10	loamy-sand	0.2800	0.6300	sea harbour	0.50
grass	>10	loamy-sand	0.3300	0.6800	sea harbour	0.60
forest	<0.5	loamy-sand	0.0800	0.5500	airport	0.50
forest	0.5-5	loamy-sand	0.1300	0.5800	airport	0.60

Runoff coefficient database (Continue).

LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
forest	5-10	loamy-sand	0.1800	0.6300	airport	0.70
forest	>10	loamy-sand	0.2300	0.6800	airport	0.80
bare soil	0.5-5	loamy-sand	0.5300	0.6300	industry	0.40
bare soil	5-10	loamy-sand	0.5800	0.6800	industry	0.50
bare soil	>10	loamy-sand	0.6300	0.7300	industry	0.60
open water	<0.5	loamy-sand	1.0000	0.6000		0.00
open water	0.5-5	loamy-sand	1.0000	0.6500		0.00
open water	5-10	loamy-sand	1.0000	0.7000		0.00
open water	>10	loamy-sand	1.0000	0.7500		0.00
crop	<0.5	sandy-loam	0.4000	0.6300		0.00
crop	0.5-5	sandy-loam	0.4500	0.6800		0.00
crop	5-10	sandy-loam	0.5000	0.7300		0.00
crop	>10	sandy-loam	0.5500	0.7800		0.00
grass	<0.5	sandy-loam	0.2000	0.6500		0.00
grass	0.5-5	sandy-loam	0.2500	0.7000		0.00
grass	5-10	sandy-loam	0.3000	0.7500		0.00
grass	>10	sandy-loam	0.3500	0.8000		0.00
forest	<0.5	sandy-loam	0.1000	0.0000		0.00
forest	0.5-5	sandy-loam	0.1500	0.0000		0.00
forest	5-10	sandy-loam	0.2000	0.0000		0.00
forest	>10	sandy-loam	0.2500	0.0000		0.00
bare soil	<0.5	sandy-loam	0.5000	0.0000		0.00
bare soil	0.5-5	sandy-loam	0.5500	0.0000		0.00
bare soil	5-10	sandy-loam	0.6000	0.0000		0.00
bare soil	>10	sandy-loam	0.6500	0.0000		0.00
open water	<0.5	sandy-loam	1.0000	0.0000		0.00
open water	0.5-5	sandy-loam	1.0000	0.0000		0.00
open water	5-10	sandy-loam	1.0000	0.0000		0.00
open water	>10	sandy-loam	1.0000	0.0000		0.00
crop	<0.5	silty-loam	0.4300	0.0000		0.00

Runoff coefficient database (Continue).

LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
crop	0.5-5	silty-loam	0.4800	0.0000		0.00
crop	5-10	silty-loam	0.5300	0.0000		0.00
crop	>10	silty-loam	0.5800	0.0000		0.00
grass	5-10	silty-loam	0.3300	0.0000		0.00
grass	>10	silty-loam	0.3800	0.0000		0.00
forest	<0.5	silty-loam	0.1300	0.0000		0.00
forest	0.5-5	silty-loam	0.1800	0.0000		0.00
forest	5-10	silty-loam	0.2300	0.0000		0.00
forest	>10	silty-loam	0.2800	0.0000		0.00
bare soil	<0.5	silty-loam	0.5300	0.0000		0.00
bare soil	0.5-5	silty-loam	0.5800	0.0000		0.00
bare soil	5-10	silty-loam	0.6300	0.0000		0.00
bare soil	>10	silty-loam	0.6800	0.0000		0.00
open water	<0.5	silty-loam	1.0000	0.0000		0.00
open water	0.5-5	silty-loam	1.0000	0.0000		0.00
open water	5-10	silty-loam	1.0000	0.0000		0.00
open water	>10	silty-loam	1.0000	0.0000		0.00
crop	<0.5	loam	0.4000	0.0000		0.00
crop	0.5-5	loam	0.4500	0.0000		0.00
crop	5-10	loam	0.5000	0.0000		0.00
crop	>10	loam	0.5500	0.0000		0.00
grass	<0.5	loam	0.2000	0.0000		0.00
grass	0.5-5	loam	0.2500	0.0000		0.00
grass	5-10	loam	0.3000	0.0000		0.00
grass	>10	loam	0.3500	0.0000		0.00
forest	<0.5	loam	0.1000	0.0000		0.00
forest	0.5-5	loam	0.1500	0.0000		0.00
forest	5-10	loam	0.2000	0.0000		0.00
forest	>10	loam	0.2500	0.0000		0.00
bare soil	<0.5	loam	0.5000	0.0000		0.00

Runoff coefficient database (Continue).

LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
bare soil	0.5-5	loam	0.5500	0.0000		0.00
bare soil	5-10	loam	0.6000	0.0000		0.00
bare soil	>10	loam	0.6500	0.0000		0.00
open water	5-10	loam	1.0000	0.0000		0.00
open water	>10	loam	1.0000	0.0000		0.00
crop	<0.5	silt	0.3800	0.0000		0.00
crop	0.5-5	silt	0.4200	0.0000		0.00
crop	5-10	silt	0.4800	0.0000		0.00
crop	>10	silt	0.5300	0.0000		0.00
grass	<0.5	silt	0.1700	0.0000		0.00
grass	0.5-5	silt	0.2200	0.0000		0.00
grass	5-10	silt	0.2700	0.0000		0.00
grass	>10	silt	0.3200	0.0000		0.00
forest	<0.5	silt	0.0700	0.0000		0.00
forest	0.5-5	silt	0.1200	0.0000		0.00
forest	5-10	silt	0.1700	0.0000		0.00
forest	>10	silt	0.2200	0.0000		0.00
bare soil	<0.5	silt	0.4800	0.0000		0.00
bare soil	0.5-5	silt	0.5300	0.0000		0.00
bare soil	5-10	silt	0.5800	0.0000		0.00
bare soil	>10	silt	0.6300	0.0000		0.00
open water	<0.5	silt	1.0000	0.0000		0.00
open water	0.5-5	silt	1.0000	0.0000		0.00
open water	5-10	silt	1.0000	0.0000		0.00
open water	>10	silt	1.0000	0.0000		0.00
crop	<0.5	sandy claylo	0.4300	0.0000		0.00
crop	0.5-5	sandy claylo	0.4800	0.0000		0.00
crop	5-10	sandy claylo	0.5300	0.0000		0.00
crop	>10	sandy claylo	0.5800	0.0000		0.00
grass	<0.5	sandy claylo	0.2300	0.0000		0.00

Runoff coefficient database (Continue).

LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
grass	0.5-5	sandy claylo	0.2800	0.0000		0.00
grass	5-10	sandy claylo	0.3300	0.0000		0.00
grass	>10	sandy claylo	0.3800	0.0000		0.00
forest	5-10	sandy claylo	0.2300	0.0000		0.00
forest	>10	sandy claylo	0.2800	0.0000		0.00
bare soil	<0.5	sandy claylo	0.5300	0.0000		0.00
bare soil	0.5-5	sandy claylo	0.5800	0.0000		0.00
bare soil	5-10	sandy claylo	0.6300	0.0000		0.00
bare soil	>10	sandy claylo	0.6800	0.0000		0.00
open water	<0.5	sandy claylo	1.0000	0.0000		0.00
open water	0.5-5	sandy claylo	1.0000	0.0000		0.00
open water	5-10	sandy claylo	1.0000	0.0000		0.00
open water	>10	sandy claylo	1.0000	0.0000		0.00
crop	<0.5	silty claylo	0.4500	0.0000		0.00
crop	0.5-5	silty claylo	0.5000	0.0000		0.00
crop	5-10	silty claylo	0.5500	0.0000		0.00
crop	>10	silty claylo	0.6000	0.0000		0.00
grass	<0.5	silty claylo	0.2500	0.0000		0.00
grass	0.5-5	silty claylo	0.3000	0.0000		0.00
grass	5-10	silty claylo	0.3500	0.0000		0.00
grass	>10	silty claylo	0.4000	0.0000		0.00
forest	<0.5	silty claylo	0.1500	0.0000		0.00
forest	0.5-5	silty claylo	0.2000	0.0000		0.00
forest	5-10	silty claylo	0.2500	0.0000		0.00
forest	>10	silty claylo	0.3000	0.0000		0.00
bare soil	<0.5	silty claylo	0.5500	0.0000		0.00
bare soil	0.5-5	silty claylo	0.5800	0.0000		0.00
bare soil	5-10	silty claylo	0.6300	0.0000		0.00
bare soil	>10	silty claylo	0.6800	0.0000		0.00
open water	<0.5	silty claylo	1.0000	0.0000		0.00

Runoff coefficient database (Continue).

LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
open water	0.5-5	silty claylo	1.0000	0.0000		0.00
open water	5-10	silty claylo	1.0000	0.0000		0.00
open water	>10	silty claylo	1.0000	0.0000		0.00
crop	5-10	clayloam	0.5800	0.0000		0.00
crop	>10	clayloam	0.6300	0.0000		0.00
grass	<0.5	clayloam	0.2800	0.0000		0.00
grass	0.5-5	clayloam	0.3300	0.0000		0.00
grass	5-10	clayloam	0.3800	0.0000		0.00
grass	>10	clayloam	0.4300	0.0000		0.00
forest	<0.5	clayloam	0.1800	0.0000		0.00
forest	0.5-5	clayloam	0.2300	0.0000		0.00
forest	5-10	clayloam	0.2800	0.0000		0.00
forest	>10	clayloam	0.3300	0.0000		0.00
bare soil	<0.5	clayloam	0.5800	0.0000		0.00
bare soil	0.5-5	clayloam	0.6300	0.0000		0.00
bare soil	5-10	clayloam	0.6800	0.0000		0.00
bare soil	>10	clayloam	0.7300	0.0000		0.00
open water	<0.5	clayloam	1.0000	0.0000		0.00
open water	0.5-5	clayloam	1.0000	0.0000		0.00
open water	5-10	clayloam	1.0000	0.0000		0.00
open water	>10	clayloam	1.0000	0.0000		0.00
crop	<0.5	sandy clay	0.5000	0.0000		0.00
crop	0.5-5	sandy clay	0.5500	0.0000		0.00
crop	5-10	sandy clay	0.6000	0.0000		0.00
crop	>10	sandy clay	0.6500	0.0000		0.00
grass	<0.5	sandy clay	0.3000	0.0000		0.00
grass	0.5-5	sandy clay	0.3500	0.0000		0.00
grass	5-10	sandy clay	0.4000	0.0000		0.00
grass	>10	sandy clay	0.4500	0.0000		0.00
forest	<0.5	sandy clay	0.2000	0.0000		0.00

Runoff coefficient database (Continue).

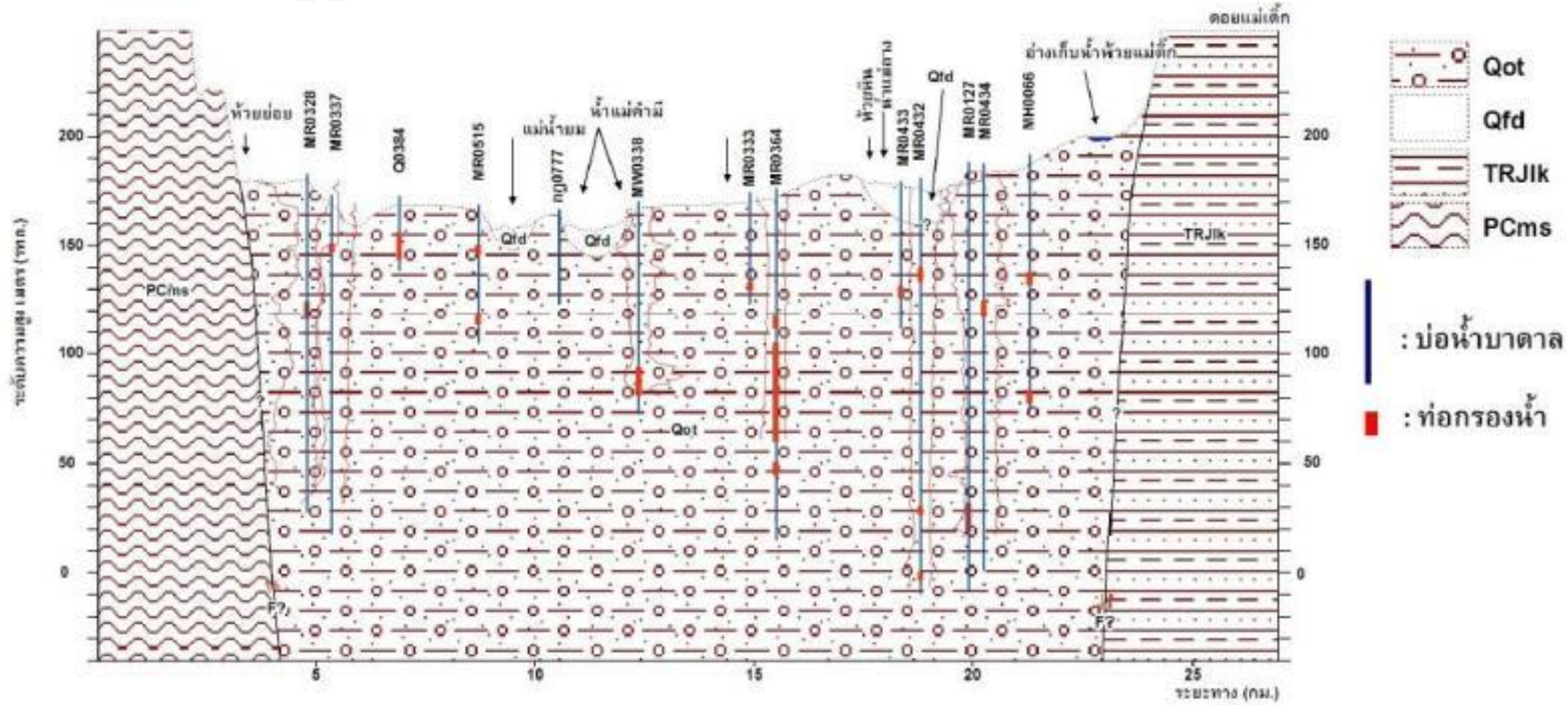
LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
forest	0.5-5	sandy clay	0.2500	0.0000		0.00
forest	5-10	sandy clay	0.3000	0.0000		0.00
forest	>10	sandy clay	0.3500	0.0000		0.00
bare soil	5-10	sandy clay	0.7000	0.0000		0.00
bare soil	>10	sandy clay	0.7500	0.0000		0.00
open water	<0.5	sandy clay	1.0000	0.0000		0.00
open water	0.5-5	sandy clay	1.0000	0.0000		0.00
open water	5-10	sandy clay	1.0000	0.0000		0.00
open water	>10	sandy clay	1.0000	0.0000		0.00
crop	<0.5	siltyclay	0.5300	0.0000		0.00
crop	0.5-5	siltyclay	0.5800	0.0000		0.00
crop	5-10	siltyclay	0.6300	0.0000		0.00
crop	>10	siltyclay	0.6800	0.0000		0.00
grass	<0.5	siltyclay	0.3300	0.0000		0.00
grass	0.5-5	siltyclay	0.3800	0.0000		0.00
grass	5-10	siltyclay	0.4300	0.0000		0.00
grass	>10	siltyclay	0.4800	0.0000		0.00
forest	<0.5	siltyclay	0.2300	0.0000		0.00
forest	0.5-5	siltyclay	0.2800	0.0000		0.00
forest	5-10	siltyclay	0.3300	0.0000		0.00
forest	>10	siltyclay	0.3800	0.0000		0.00
bare soil	<0.5	siltyclay	0.6300	0.0000		0.00
bare soil	0.5-5	siltyclay	0.6800	0.0000		0.00
bare soil	5-10	siltyclay	0.7300	0.0000		0.00
bare soil	>10	siltyclay	0.7800	0.0000		0.00
open water	<0.5	siltyclay	1.0000	0.0000		0.00
open water	0.5-5	siltyclay	1.0000	0.0000		0.00
open water	5-10	siltyclay	1.0000	0.0000		0.00
open water	>10	siltyclay	1.0000	0.0000		0.00
crop	<0.5	clay	0.5500	0.0000		0.00

Runoff coefficient database (Continue).

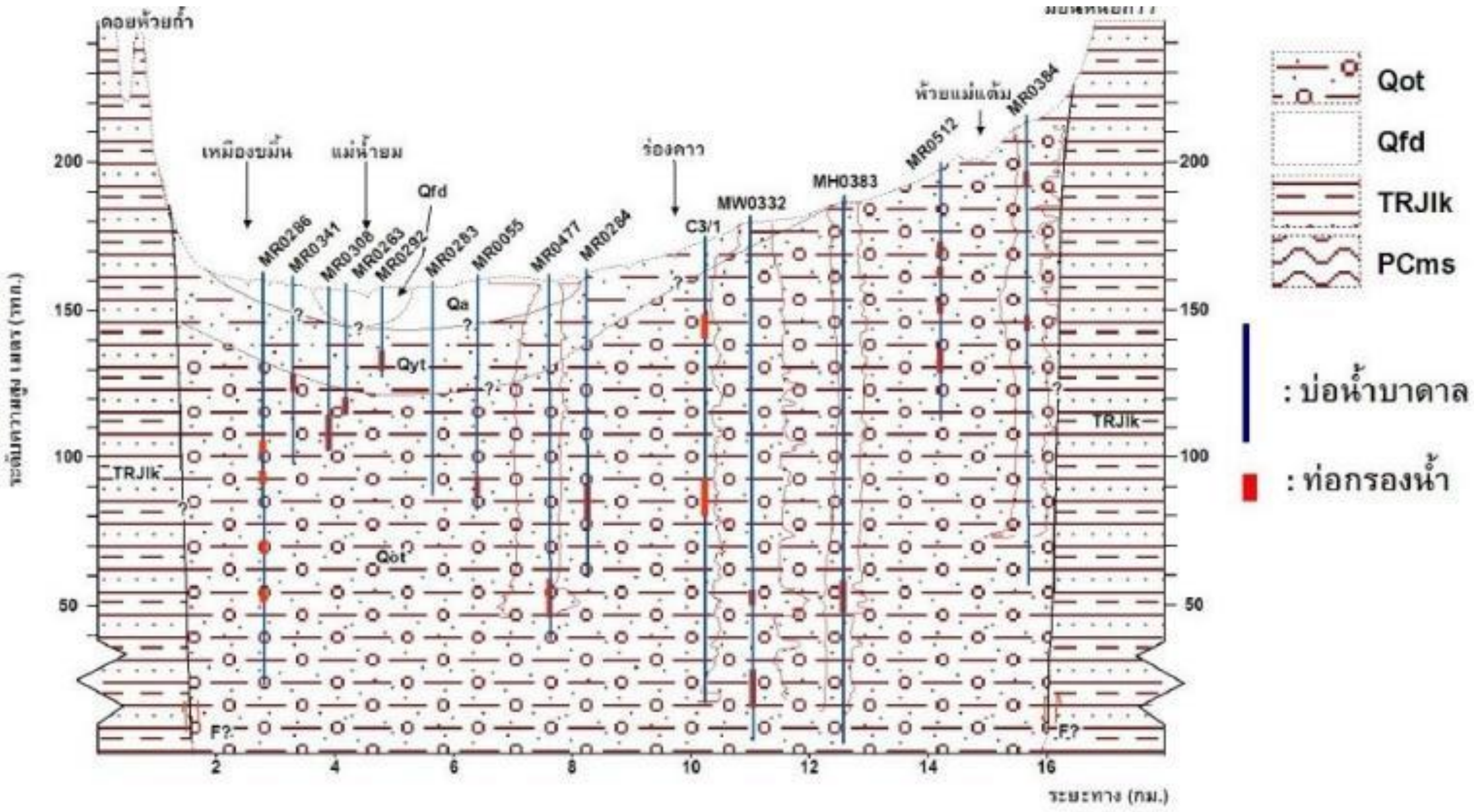
LANDUSERO	SLOPE_[%]	SOILTYPE	RUNOFFCOEF	BAREROCOEF	IMPLUSERO	IMPROCOEF
crop	0.5-5	clay	0.6000	0.0000		0.00
crop	5-10	clay	0.6500	0.0000		0.00
crop	>10	clay	0.7000	0.0000		0.00
grass	5-10	clay	0.4500	0.0000		0.00
grass	>10	clay	0.5000	0.0000		0.00
forest	<0.5	clay	0.2500	0.0000		0.00
forest	0.5-5	clay	0.3000	0.0000		0.00
forest	5-10	clay	0.3500	0.0000		0.00
forest	>10	clay	0.4000	0.0000		0.00
bare soil	<0.5	clay	0.6500	0.0000		0.00
bare soil	0.5-5	clay	0.7000	0.0000		0.00
bare soil	5-10	clay	0.7500	0.0000		0.00
bare soil	>10	clay	0.8000	0.0000		0.00
open water	<0.5	clay	1.0000	0.0000		0.00
open water	0.5-5	clay	1.0000	0.0000		0.00
open water	5-10	clay	1.0000	0.0000		0.00
open water	>10	clay	1.0000	0.0000		0.00

APPENDIX C

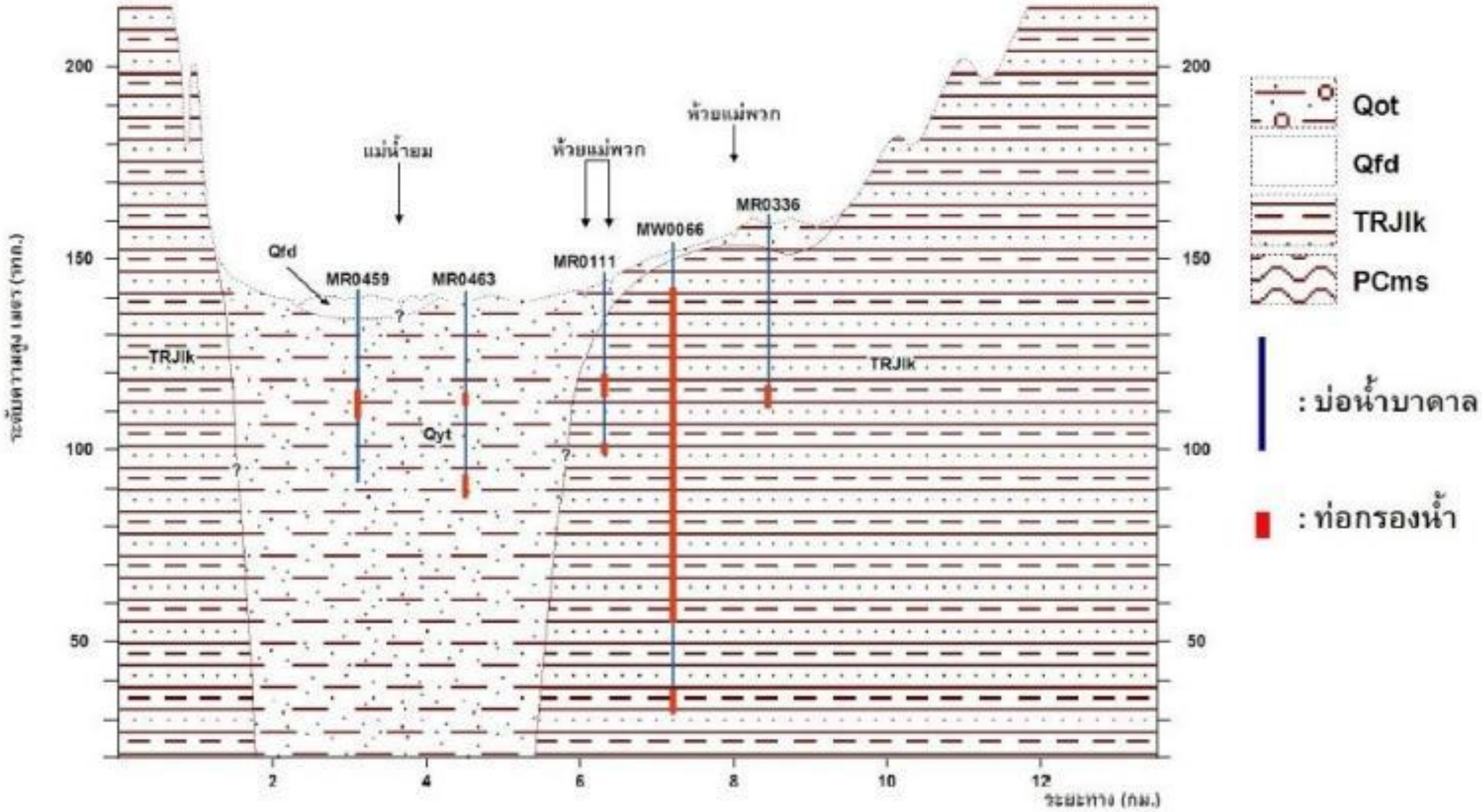
Geologic cross-section in Changwat Phrae



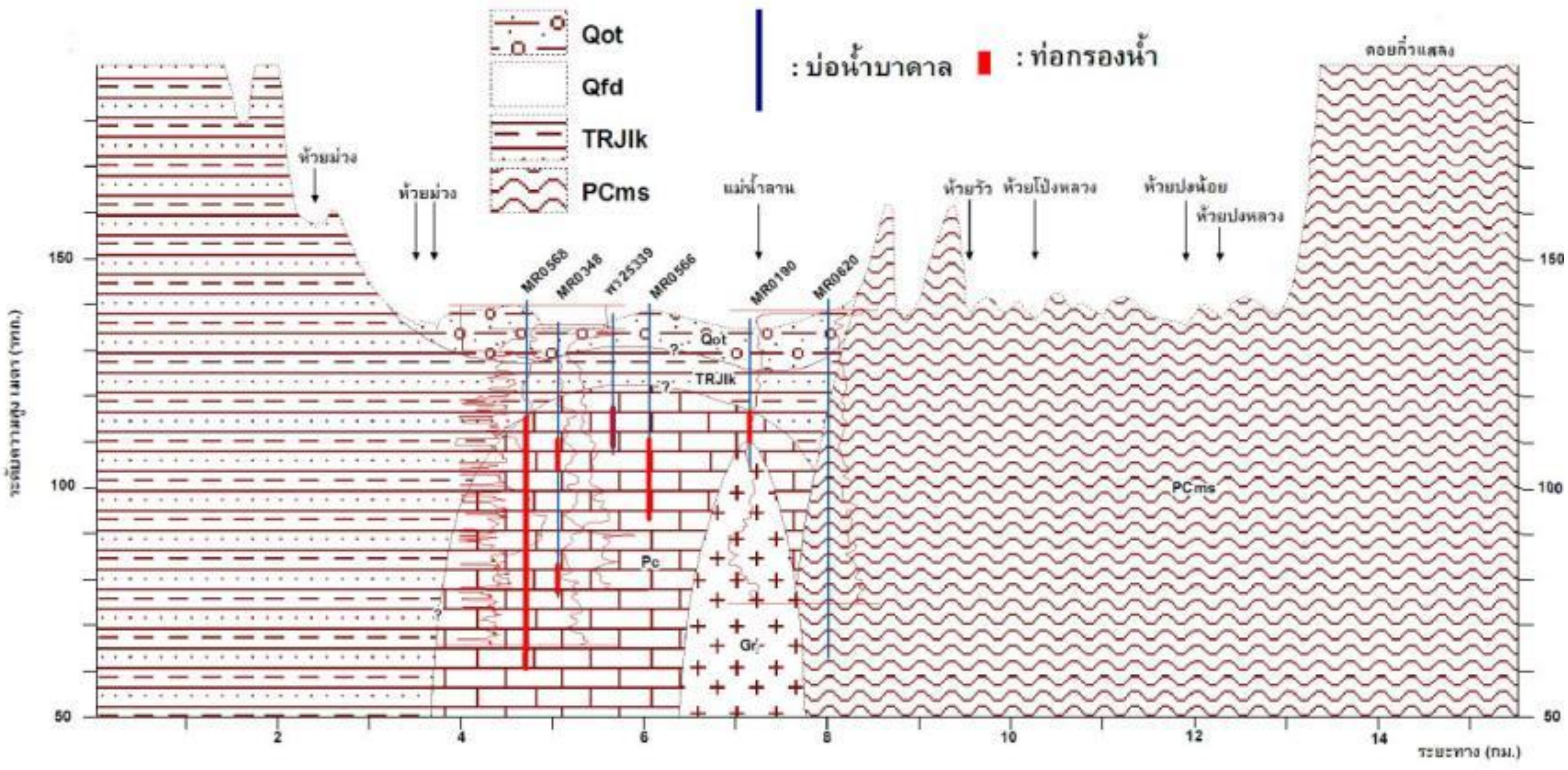
Geologic cross section line 1 (DGR, 2010).



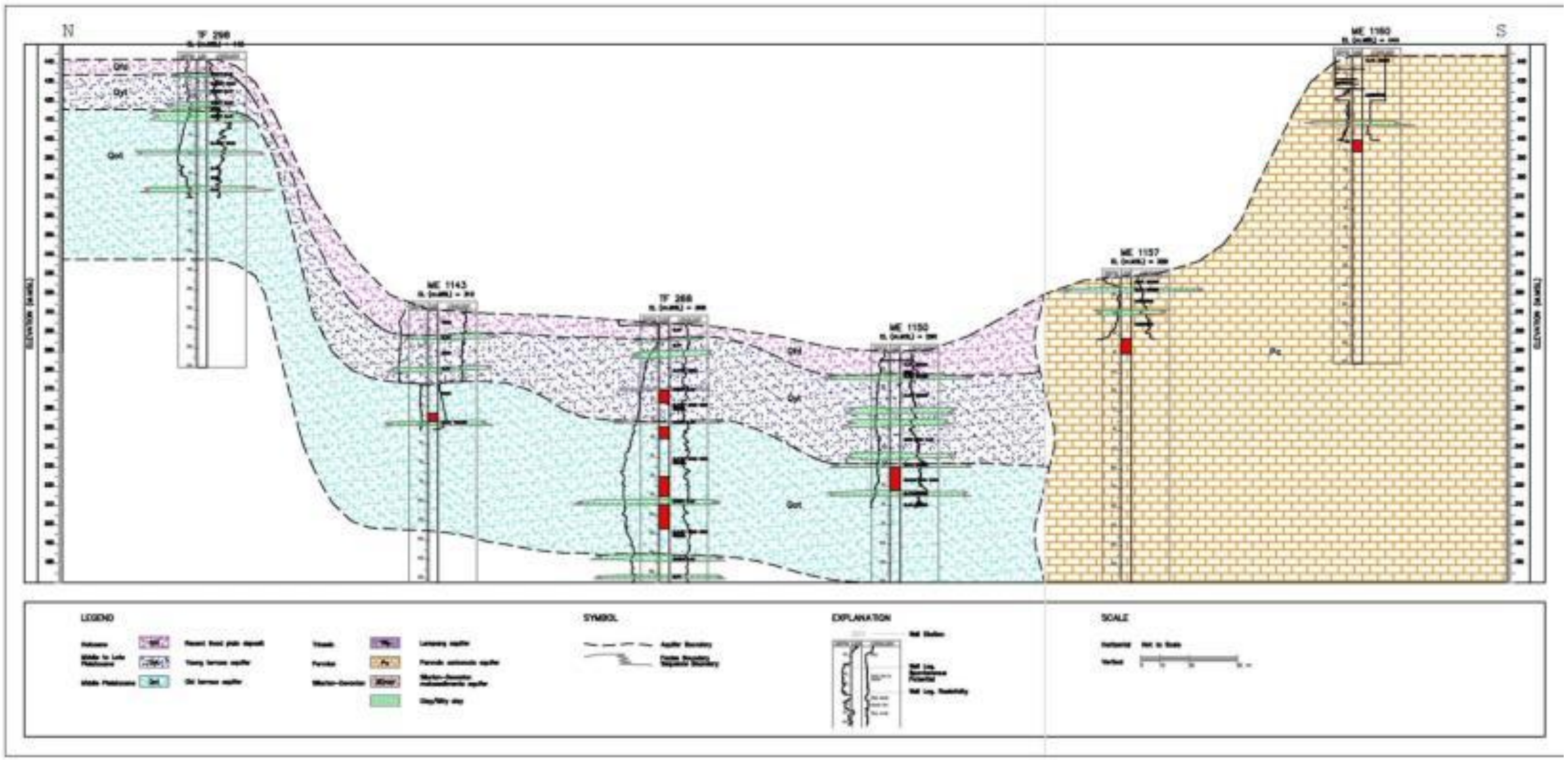
Geologic cross section line 2 (DGR, 2010).



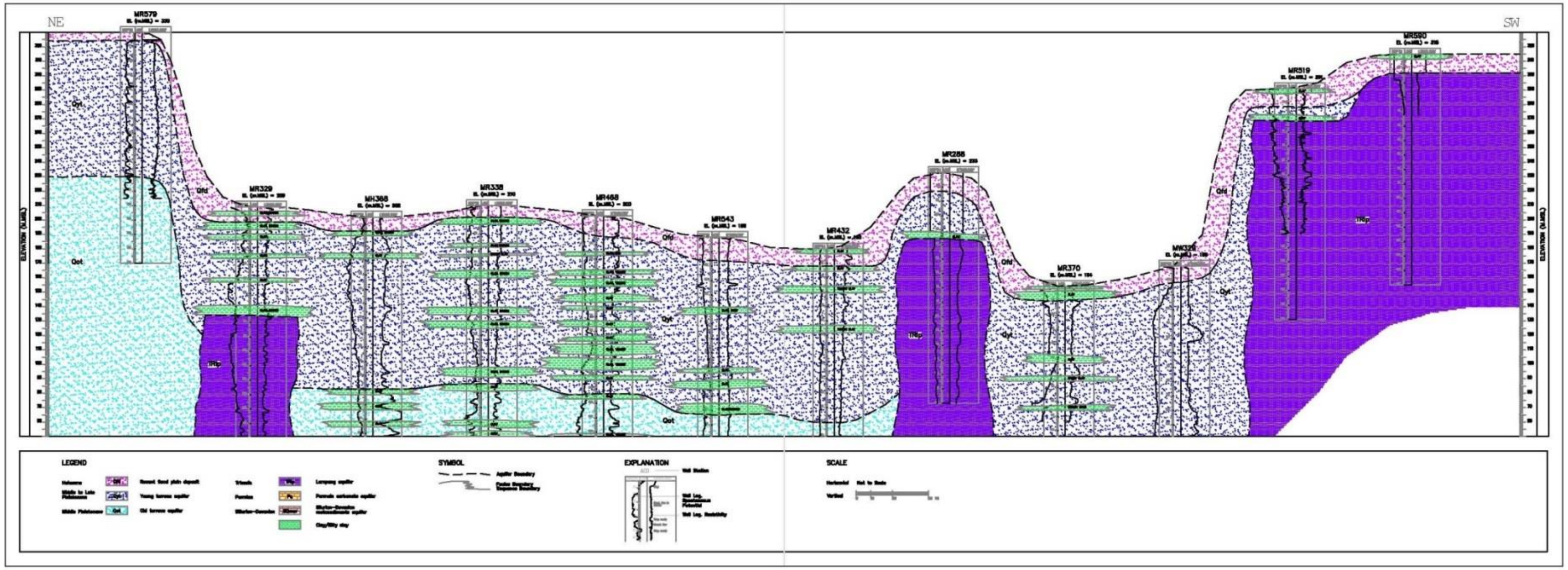
Geologic cross section line 3 (DGR, 2010).



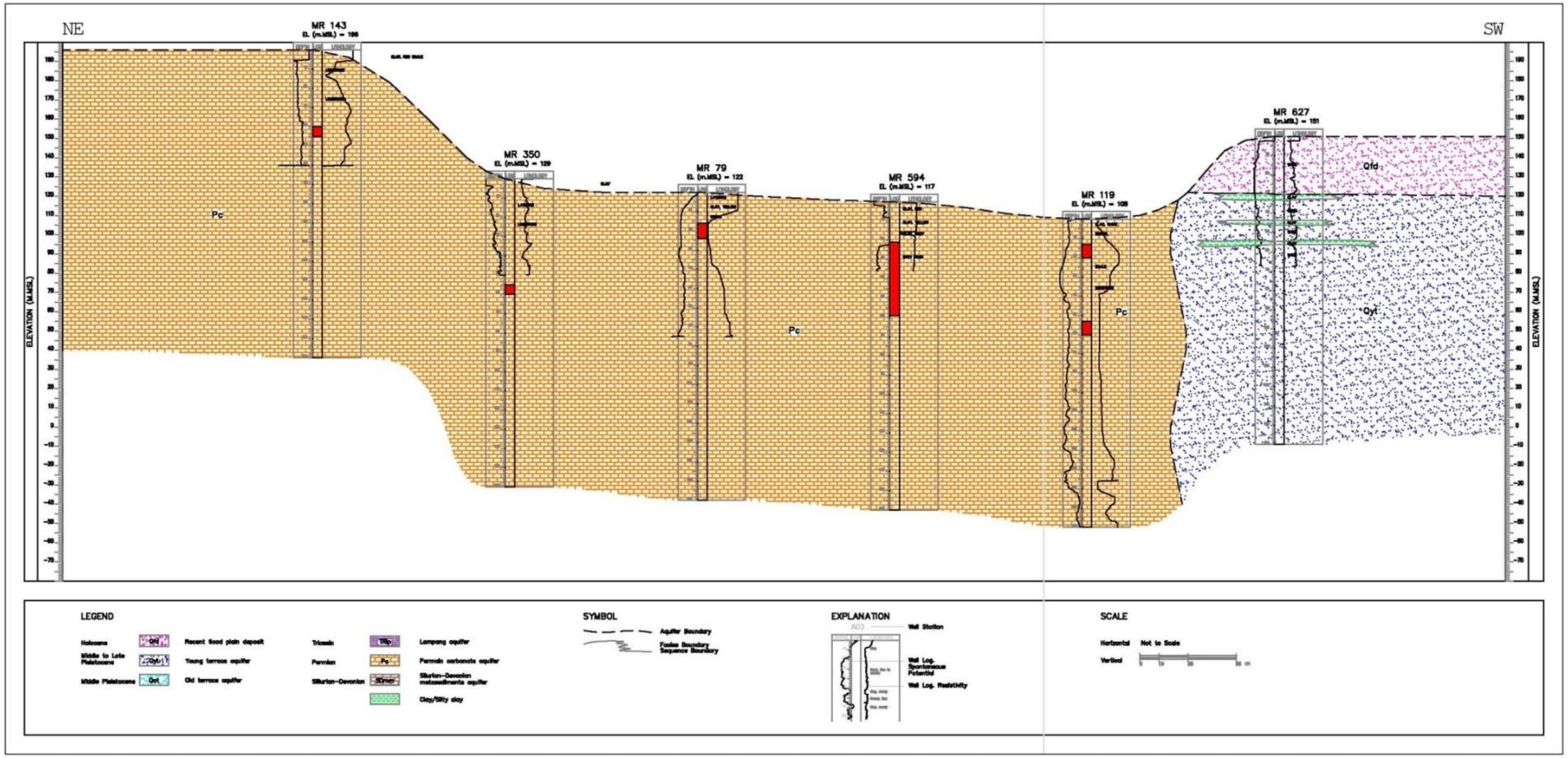
Geologic cross section line 4 (DGR, 2010).



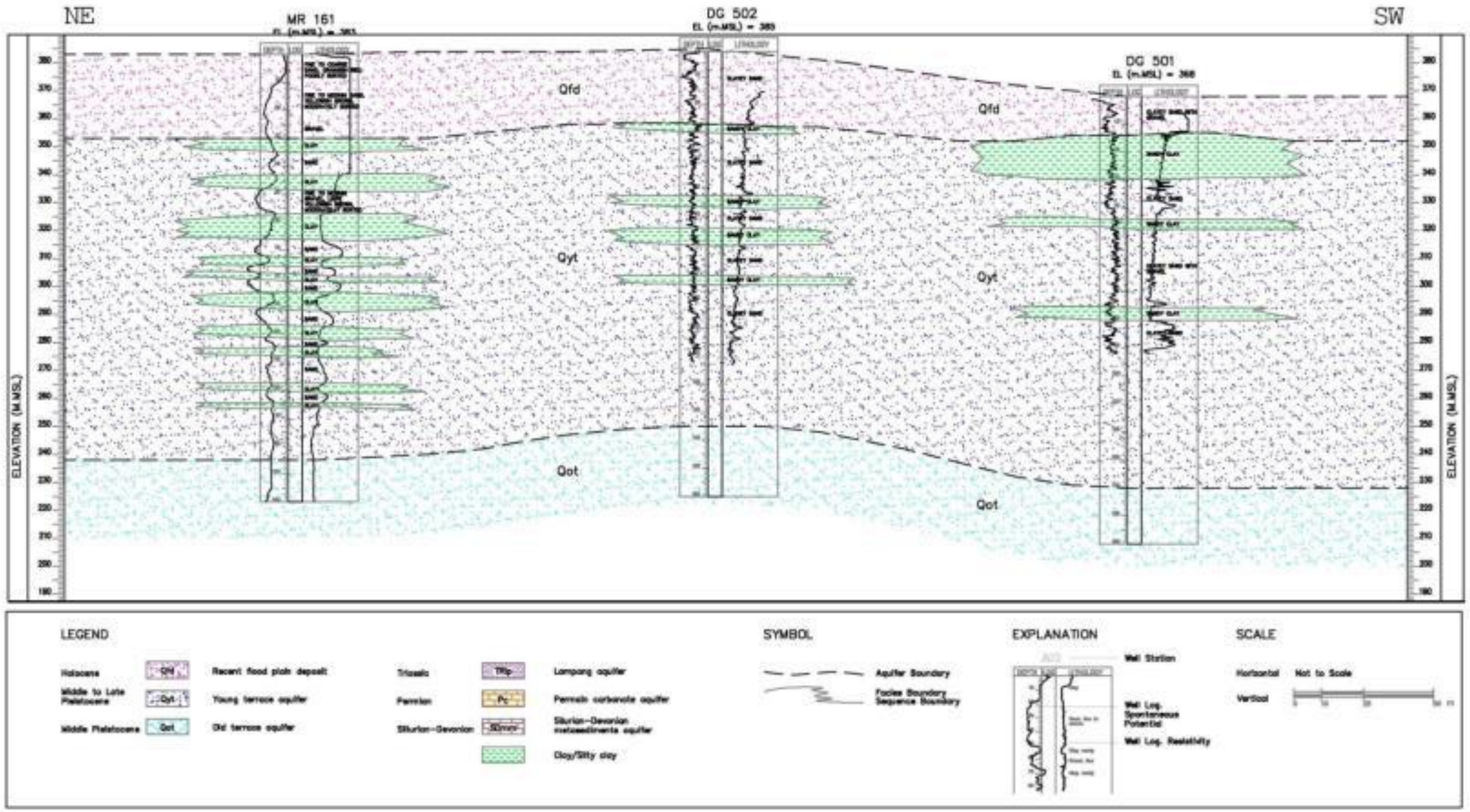
Geologic cross section line 5 (NTRC, 2013).



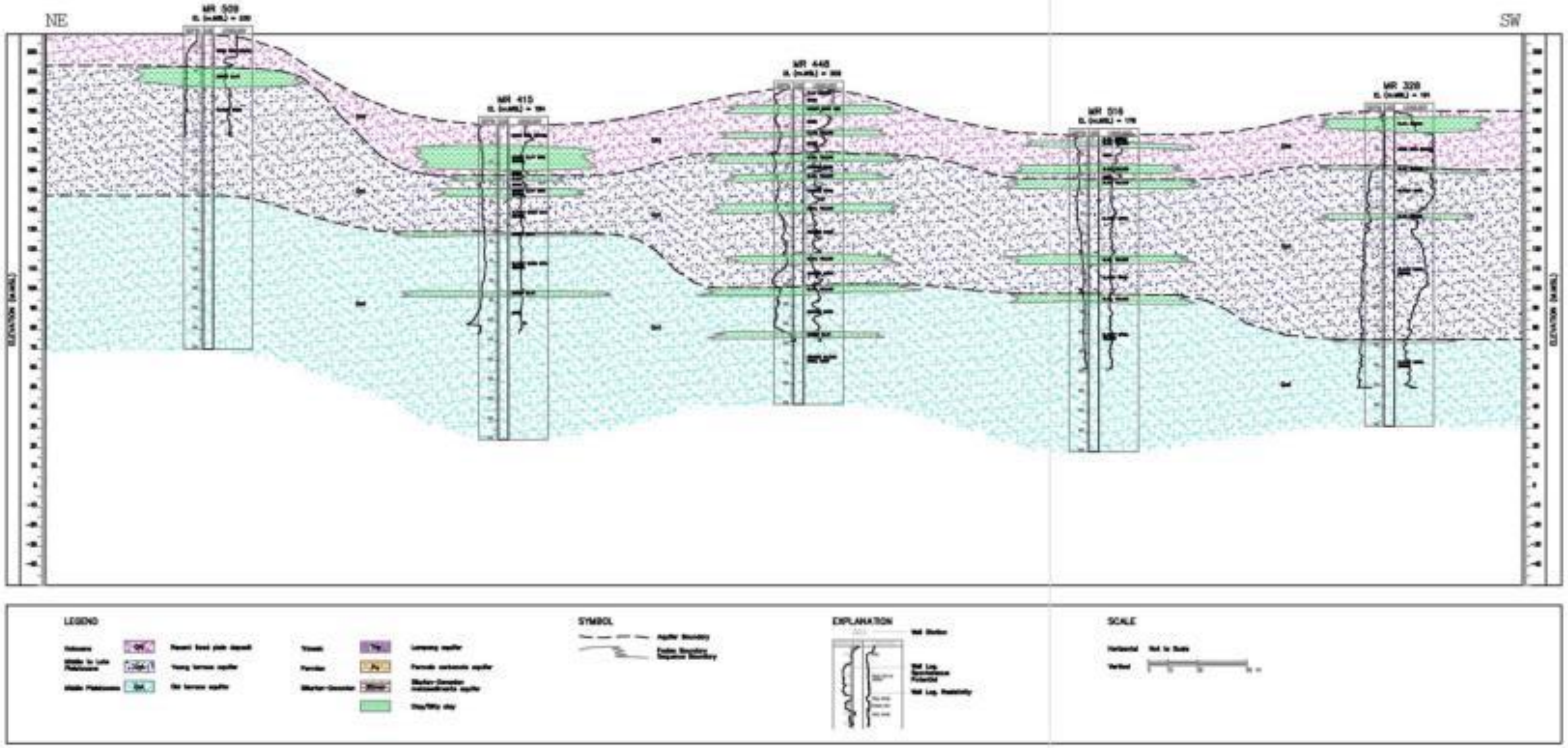
Geologic cross section line 6 (NTRC, 2013).



Geologic cross section line 7 (NTRC, 2013).



Geologic cross section in the Quaternary floodplain depositted (NTRC, 2013).



Geologic cross section in the Quaternary floodplain depositted (NTRC, 2013).

APPENDIX D

Groundwater wells database

from the Department of Groundwater Resource in 2011

Groundwater well database in Changwat Phrae (DGR, 2011)

X_E	Y_N	MUBAN_NO	TUMBOL	AMPUR	LOCATION	WELL_NO	WELL_DEEP	WL_NORMAL	WELL_LEVEL	USAGE_VOL
586968	1996458	2	ปากกาง	ลอง	วัดบุญยืน	MR351	10.00	7.00	Qot	
558736	1971104	7	แม่พุง	วังชิ้น	ทางเข้าโรงเรียนป่าคา	MR360	102.00	13.10	Qyt	10.00
610311	1977741	2	ห้วยไร่	เด่นชัย	ประปาหมู่บ้าน	MR460	105.00	6.50	PCms	
582719	1995680	9	บ่อเหล็กลอง	ลอง	หอ	MR529	105.00	9.20	Qfd	15.00
571557	1987841	10	แม่ป้าก	วังชิ้น	โรงเรียนแม่ยางใต้	MR604	108.00	1.50	Qfd	3.00
627688	2045764	11	เตาปูน	สอง	อนามัย ม.11	MR580	114.00	5.80	Qot	
612026	1988091	8	เด่นชัย	เด่นชัย	โรงเรียนเด่นทัพชัย	MW66	120.00	3.00	Qfd	
630695	2023709	2	แม่ยางตาล	ร้องกวาง	โรงเรียนหนองเจริญ	MW336	126.00	10.00	Qot	10.00
585051	2005240	2	ห้วยอ้อ	ลอง	โรงเรียนแม่จองไป	MR444	144.00	4.20	TRJlk	
569676	1983456	8	ทุ่งแล้ง	ลอง	ที่สาธารณะ	MR281	150.00	6.80	TRJlk	
607160	1987617	2	ไทรย้อย	เด่นชัย	ประปาหมู่บ้าน	MR321	18.00	4.00	Qfd	
643875	2030801	10	ร้องกวาง	ร้องกวาง	นานชม	PW15958	18.15	5.75	TRJlk	
582245	1997329	6	หัวทุ่ง	ลอง	หน้าบ้านนายชาติ แก้ว	PW2164	18.80	3.20	TRJlk	
615244	1990143	6	แม่จั๊วะ	เด่นชัย	วัดบ้านแพะร่องหิน	MR276	180.00	7.80	Qfd	2.00
632767	2022686	6	แม่ยางตาล	ร้องกวาง	แม่ยางกาด	PW2621	19.80	7.80	Qfd	5.00
626221	2047119	8	เตาปูน	สอง	ศูนย์เด็กเล็ก	MR507	21.00	10.00	Qfd	
561871	1972191	8	แม่พุง	วังชิ้น	โรงเรียนปางไฮ	MR127	21.00	3.10	TRJlk	10.00
627079	2021980	4	หนองม่วงไข่	หนองม่วงไข่	ประปา	MH369	21.00	7.80	Qfd	10.00
594911	1981300	8	ไทรย้อย	เด่นชัย	นายรัตน์ คำโฮ 138/1	PW5178	21.26	10.00	Vc	

Groundwater well database in Changwat Phrae (DGR, 2011)

X_E	Y_N	MUBAN_NO	TUMBOL	AMPUR	LOCATION	WELL_NO	WELL_DEEP	WL_NORMAL	WELL_LEVEL	USAGE_VOL
589075	1998143	12	ห้วยอ้อ	ลอง	วัดแม่ลานใต้	MR190	24.00	1.00	Qfd	
651907	2029463	4	ไผ่โทน	ร้องกวาง	บ้านนายเล็ง	MR578	24.00	5.14	TRJlk	1.00
609449	1991287	2	ปงป่าหวาย	เด่นชัย	โรงเรียนบ้านสวนหลวง	PW10099	24.18	5.20	Qfd	
563770	1984534	7	แม่เกิ๋ง	วังชิ้น	โรงเรียนบ้านค้างใจ	MR465	26.00	5.65	Qyt	3.00
584776	1997702	2	หัวทุ่ง	ลอง	โรงเรียนไผ่ล้อม (ถังล	MR347	27.00	1.30	Qfd	5.00
562779	1977746	10	แม่พุง	วังชิ้น	โรงเรียนบ้านแม่พุง	MR84	27.00	6.00	TRJlk	2.00
588166	1998782	6	ห้วยอ้อ	ลอง	โรงเรียนลองวิทยา	MR88	30.00	1.00	Qot	
594911	1981300	8	ไทรย้อย	เด่นชัย	ประปาหมู่บ้าน	MR274	30.00	12.00	Vc	30.00
600460	2008118	7	ต้าผามอก	ลอง	สวนหินมหาราช	PW20033	30.22	6.74	PCms	
611815	1993045	1	ปงป่าหวาย	เด่นชัย	49 ชูชาติ	PW10098	30.30	5.40	Qfd	10.00
611436	1979102	3	ห้วยไร่	เด่นชัย	ประปาหมู่บ้าน	PW12037	30.50	6.70	PCms	10.00
582245	1997329	6	หัวทุ่ง	ลอง	ประปาหมู่บ้าน	PW13906	30.60	3.50	TRJlk	
625942	2050178	4	เตาปูน	สอง	โรงเรียนนาไร่เดียว	PW2762	31.00	7.10	Qot	
597638	1998785	7	บ้านปิน	ลอง	หลัง38/3	MR600	35.00	0.70	Vc	10.00
587269	2007532	1	ห้วยอ้อ	ลอง	โรงเก็บบอล	MR309	36.00	1.00	TRJlk	
598601	1982021	6	ไทรย้อย	เด่นชัย	9 หมู่ 6	MR165	36.00	18.00	Vc	
574103	1990322	7	บ่อเหล็กลอง	ลอง	หน้าเรือนเกษตร	MR483	38.00	3.00	TRJlk	1.00
624828	2042408	6	บ้านกลาง	สอง	หอประปา	MR413	39.00	1.75	Qfd	30.00
580390	1987954	11	ทุ่งแล้ง	ลอง	วัดปากจอก	MR595	39.00	5.10	Qfd	10.00

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X_E	Y_N	MUBAN_NO	TUMBOL	AMPUR	LOCATION	WELL_NO	WELL_DEEP	WL_NORMAL	WELL_LEVEL	USAGE_VOL
625942	2050178	4	เตาปูน	สอง	46/2 ม.4	MW129	39.00	7.00	Qot	
637159	2075840	2	สะเอียบ	สอง	โรงเรียนบ้านนาฝาย ห้อ	MR673	40.00	3.55	TRc	7.00
624405	2042110	7	บ้านกลาง	สอง	หอประปา	MR412	42.00	0.90	Qfd	
585263	1996064	7	ปากกาง	ลอง	ศูนย์สาธารณสุข	MR296	42.00	11.80	Qot	
583278	1997300	8	หัวทุ่ง	ลอง	ประปาหมู่บ้านหน้าซ.9	MR564	42.00	18.00	TRJlk	8.00
594345	1981059	4	ไทรย้อย	เด่นชัย	พร 23 (บ่อแก้ว)	MR166	42.00	8.00	Vc	2.00
624387	2019089	3	น้ำรัด	หนองม่วงไข่	ประปาหมู่บ้าน	MR634	44.00	7.15	Qfd	4.00
581265	1988572	3	ทุ่งแล้ง	ลอง	บ้านปากจอก	MR623	45.00	10.10	Qfd	10.00
590442	1968377	9	นาพูน	วังชิ้น	ข้างบ้านพักหน่วยป้องก	MR167	45.00	2.20	PCms	
554622	1969621	7	ป่าสัก	วังชิ้น	ศาลเจ้าพ่อเมืองดัง	MR628	45.00	27.00	TRJlk	
582245	1997329	6	หัวทุ่ง	ลอง	หน่วยป้องกันรักษาป่าท	MR563	45.00	3.30	TRJlk	
589827	1999418	14	ห้วยอ้อ	ลอง	นายเลิศ บ้านเลขที่ 1	MR302	48.00	21.35	Qot	10.00
609449	1991287	2	ปงป่าหวาย	เด่นชัย	วัดสวนหลวง	MR458	48.00	4.20	Qfd	45.00
624011	2020122	2	น้ำรัด	หนองม่วงไข่	ตำรวจชุมชน ต.น้ำรัด	MR635	48.00	4.25	Qfd	0.30
580390	1987954	11	ทุ่งแล้ง	ลอง	ข้างศาลาประชาคม	MR524	48.00	4.40	Qfd	
612691	1981839	6	ห้วยไร่	เด่นชัย	71/3 หมู่ 6	MR522	48.00	6.00	Qyt	2.00
581265	1988572	3	ทุ่งแล้ง	ลอง	โรงเรียนปากจอกวิทยา	MR525	48.00	6.80	Qfd	
572922	1982781	7	ทุ่งแล้ง	ลอง	หน้าบ้าน 44/3	MR572	48.00	8.00	Qyt	
572922	1982781	7	ทุ่งแล้ง	ลอง	โรงเรียนวังเลียง	MR494	50.00	10.00	Qyt	10.00

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X_E	Y_N	MUBAN_NO	TUMBOL	AMPUR	LOCATION	WELL_NO	WELL_DEEP	WL_NORMAL	WELL_LEVEL	USAGE_VOL
587033	1998628	13	ห้วยอ้อ	ลอง	ที่สาธารณะ	MR492	50.00	3.15	Qfd	
610332	1989442	3	เด่นชัย	เด่นชัย	140 หมู่ 3	MR463	51.00	11.00	Qfd	
586455	1997439	1	ปากกาง	ลอง	บ้านสวน64/3	MR561	51.00	47.00	Qot	5.00
580130	1988478	4	ทุ่งแล้ง	ลอง	วัดใหม่ปากจอก	MR565	54.00	11.10	Qfd	10.00
624236	2043647	10	บ้านกลาง	สอง	หอประปา	MR454	54.00	2.50	Qfd	20.00
643875	2030801	10	ร้องกวาง	ร้องกวาง	นายธนพล รางคำ 6 ม.10	MR577	54.00	6.20	TRJlk	
610332	1989442	3	เด่นชัย	เด่นชัย	146/3 หมู่ 3	MR637	54.00	9.00	Qfd	
580390	1987954	11	ทุ่งแล้ง	ลอง	ข้างศาลาประชาคม	MR552	54.00	9.80	Qfd	10.00
573425	1983967	6	ทุ่งแล้ง	ลอง	โรงเรียนผาจั๊บ	MR497	55.50	12.80	TRJlk	10.00
611413	1992357	5	ปงป่าหวาย	เด่นชัย	ศาลาเอนกประสงค์ หมู่	MR607	56.00	6.10	Qfd	
572601	1982423	12	ทุ่งแล้ง	ลอง	วัดทุ่งทอง	MR594	57.00	11.25	Qyt	5.00
611243	1983774	5	ห้วยไร่	เด่นชัย	วัดบ้านแม่พวก	MR638	57.00	5.70	Qyt	3.00
611413	1992357	5	ปงป่าหวาย	เด่นชัย	ศาลาโปร่งใจ	MR663	57.00	6.10	Qfd	1.00
586003	1995794	3	ปากกาง	ลอง	ศาลาเอนกประสงค์	MR643	57.00	9.10	Qot	
624389	2034048	5	ทุ่งน้าว	สอง	ที่อ่านหนังสือพิมพ์	MR557	60.00	1.50	Qfd	
558736	1971104	7	แม่พุง	วังชิ้น	หน้าวัดป่าคา	MR359	60.00	3.00	TRJlk	
599068	1985690	11	ไทรย้อย	เด่นชัย	120 หมู่ 11	MR642	60.00	5.00	Vc	10.00
622945	2039023	1	ห้วยหม้าย	สอง	ประปาหมู่ 1	MR368	60.00	6.00	Qfd	0.10
578650	1995645	4	บ่อเหล็กลอง	ลอง	หน้าบ้านนายเสมียน	MR606	60.00	8.20	Vc	1.00

Groundwater well database in Changwat Phrae (DGR, 2011)

X_E	Y_N	MUBAN_NO	TUMBOL	AMPUR	LOCATION	WELL_NO	WELL_DEEP	WL_NORMAL	WELL_LEVEL	USAGE_VOL
594345	1981059	4	ไทรย้อย	เด่นชัย	101 หมู่ 4	MR641	60.00	9.00	Vc	20.00
626440	2046614	7	เตาปูน	สอง	วัดอัมพวัน	PW20341	60.40	7.80	Qfd	
624777	2042936	3	บ้านกลาง	สอง	ซ.10/2	MR452	62.00	1.10	Qfd	
580136	1988032	9	ทุ่งแล้ง	ลอง	ข้างบ้านผู้ช่วย ม.9	MR526	63.00	3.30	Qfd	
611243	1983774	5	ห้วยไร่	เด่นชัย	โรงเรียนบ้านแม่พวก	MR523	63.00	6.50	Qyt	2.00
578650	1995645	4	บ่อเหล็กลอง	ลอง	ริมถนนสายปางเก่า	MR569	63.00	9.00	Vc	3.00
588166	1998782	6	ห้วยอ้อ	ลอง	โรงเรียนลองวิทยา	MR603	66.00	19.30	Qot	7.00
583094	1994164	9	ปากกาง	ลอง	ประปา	MR549	66.00	6.10	TRJlk	10.00
565609	1984488	6	แม่เกิ๋ง	วังชิ้น	โรงเรียนบ้านแม่สิน	MR466	68.00	6.60	TRJlk	2.00
627430	2043408	1	บ้านกลาง	สอง	วัดพระธาตุละออ	MH389	69.00	7.00	Qfd	6.00
588166	1998782	6	ห้วยอ้อ	ลอง	โรงเรียนจรูญลอง	MR191	72.00	4.10	Qfd	
563532	1977343	8	วังชิ้น	วังชิ้น	บ้านนายข้อ อนันชัย	MR605	75.00	3.40	TRJlk	
586968	1996458	2	ปากกาง	ลอง	สอ.ปากกาง	MR624	75.00	3.70	Qfd	
587269	2007532	1	ห้วยอ้อ	ลอง	นายบอล บ้านเลขที่ 57/	MR538	75.00	4.50	TRJlk	
627430	2043408	1	บ้านกลาง	สอง	หอประปาทรงลูกบอล	MR411	76.00	12.30	Qot	20.00
621589	2036601	6	ห้วยหม้าย	สอง	ศูนย์พัฒนา	PW2123	78.00	8.20	Qfd	
621280	2046733	9	บ้านกลาง	สอง	โรงเรียนบ้านวังหิน	MW34	84.00	3.40	Qfd	20.00
582279	1994638	3	บ่อเหล็กลอง	ลอง	ข้างหอกลางบ้าน	MR357	84.00	6.20	TRJlk	17.00
585263	1996064	7	ปากกาง	ลอง	บ้านนายจัน	MR548	87.00	6.50	Qot	

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X_E	Y_N	MUBAN_NO	TUMBOL	AMPUR	LOCATION	WELL_NO	WELL_DEEP	WL_NORMAL	WELL_LEVEL	USAGE_VOL
584776	1997702	2	หัวทุ่ง	ลอง	ประปาหมู่บ้าน	MR439	90.00	1.50	Qfd	
571123	1989932	1	แม่ป้าก	วังชิ้น	ที่สาธารณะ	MR534	90.00	7.00	Vc	
583610	1997464	3	หัวทุ่ง	ลอง	อาคารเอนกประสงค์ ม.3	MR491	92.00	2.30	TRJlk	10.00
626974	2054166	5	เตาปูน	สอง	นายดอน สมบุตร	MR672	93.00	7.90	PCms	10.00
583278	1997300	8	หัวทุ่ง	ลอง	โรงเรียนหัวทุ่ง	MR539	96.00	2.15	TRJlk	2.00
625051	2040399	6	บ้านหนุน	สอง	โรงเรียนสองพิทยาคม	MR36	96.00	4.85	Qot	2.00
625112	2040938	7	บ้านหนุน	สอง	ที่สาธารณะหมู่บ้าน	MR94	99.00	16.00	Qot	

VITA

Mr. Jaturon Kornkul was born in Bangkok, Thailand on February 1, 1987. In 2009 he received a Bachelor of Science degree in Geography with second class honors from Department of Geoinformatic, Faculty of Humanities and Social Sciences, Burapha University. After then he entered the Earth Sciences program, Department of Geology, Faculty of Science, Chulalongkorn University for a Master of Science degree study.