CHAPTER 5

GROUND WATER FLOW MODEL

5.1 Theory of ground water flow

1) Darcy's Law

Henry Darcy, a French hydraulic engineer, who has investigated the flow of the water through horizontal beds of sand to be use for water filtration (Figure.5.1). The experiment can be written as the equation. It is Darcy's Law. (Freeze and Cherry, 1979) as follow:

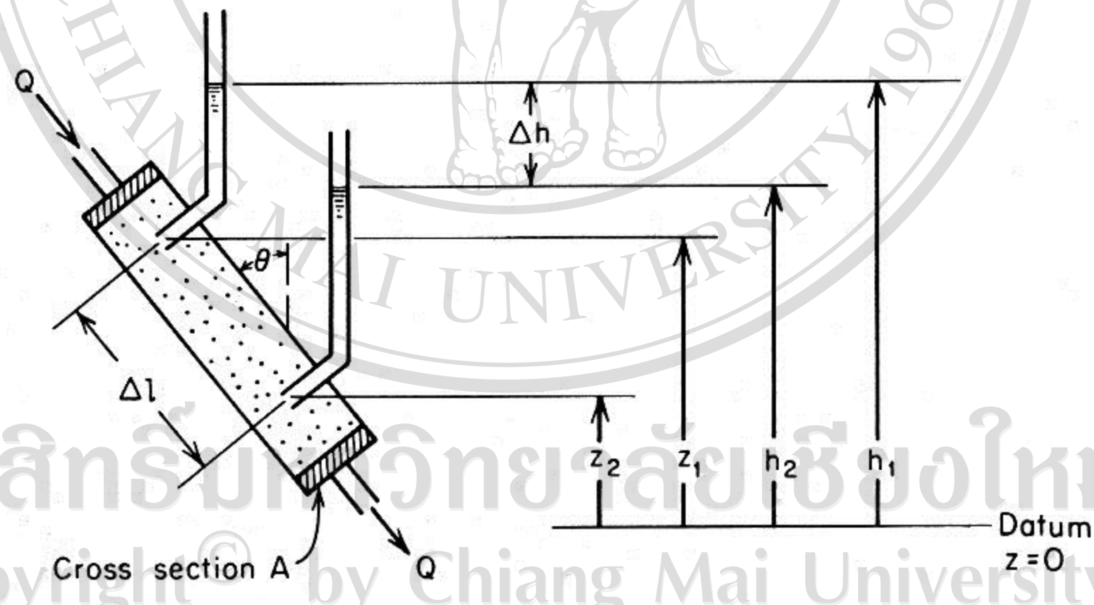


Figure 5.1 The experiment of Darcy.

$$q_x = \frac{Q}{A} = -K\frac{dh}{dl}$$

$$Q = -K\frac{dh}{dl}A = -KiA$$

Where,

Q is discharge [L^3/T]

q_x is Darcy velocity [L/T]

K is hydraulic conductivity [L/T]

dh/dl is hydraulic gradient

2) Groundwater flow

Darcy' law alone is not enough to describe groundwater flow. The general flow equation is formulated by combining the law of conservation of mass with a controlled volume of an aquifer. The governing equation for groundwater flow through a three-dimensional porous media, which is used in the following form for the steady state, as follow (Freeze and Cherry, 1979):

$$\frac{\partial}{\partial x}\left(-K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(-K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(-K_z\frac{\partial h}{\partial z}\right)=0$$

where,

K_x, K_y, K_z are values of hydraulic conductivity in x, y, z directions [L/T]

h is the potentiometric head [L]

5.2 Method of flow modeling set up

Groundwater flow model setup for both scales followed generic steps described in Figure 5.2. First, a conceptual model of the area was developed. Then, such conceptual model was converted to a mathematical flow model to simulate groundwater flow regime under both steady-state condition. The mathematical model is a finite-difference based program called MODFLOW which is a package in Visual MODFLOW® version 4.2 (Waterloo Hydrogeologic, Inc, 2006). Next, a model calibration was carried out in order to reproduce actual flow conditions by automatically adjusting model parameters. Lastly, the calibrated model was used to assessment of groundwater flow pattern in the study area.

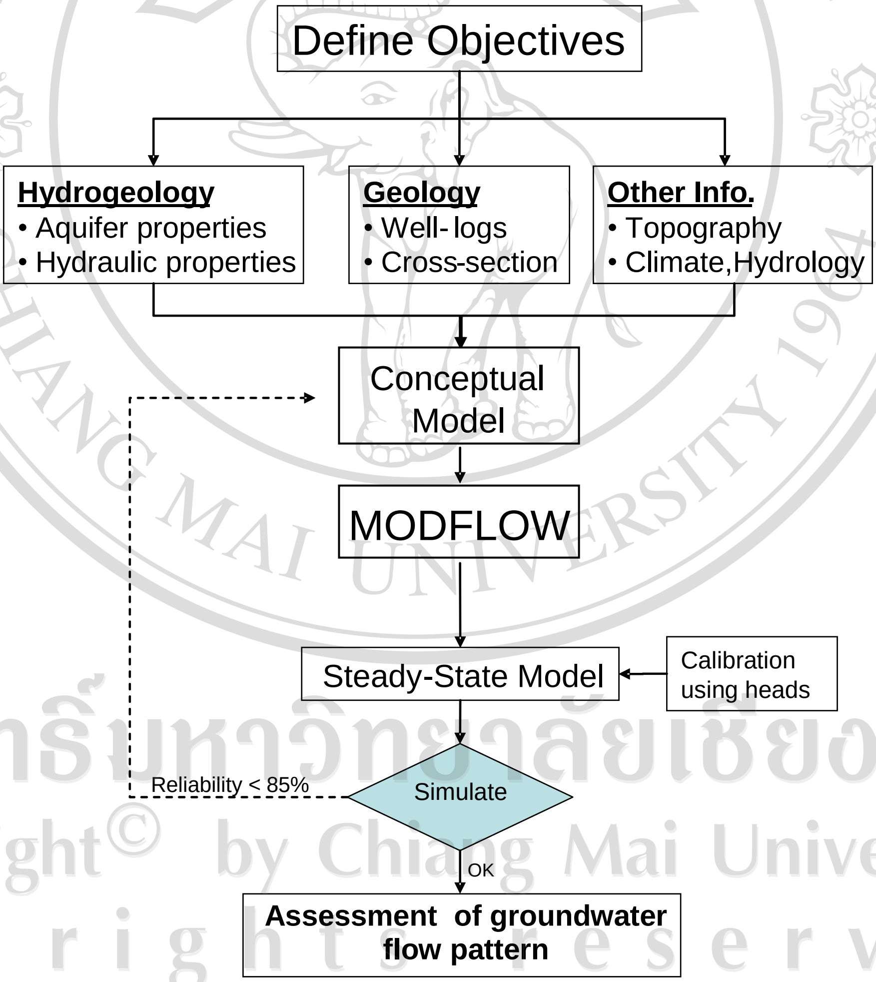


Figure 5.2 Model setup algorithms.

5.3 Conceptual model

A groundwater conceptual model is a qualitative representation of the groundwater flow and transport system based on available data. The purpose of the conceptual model is an idealized summary and integration of available data, such as geology, hydrogeology, and hydrology for the study area, into a coherent representation of the flow system to be modeled. This section describes the conceptual model of groundwater flow modeling of the study area. The conceptual model was documented using graphical representations and descriptive text before initiating model construction and calibration. Figure 5.3 is a pictorial conceptual model of the study area.

In this study, the conceptual model can be characterized into 3 aquifers. These are defined by hydrostritigraphic model (in chapter 4). All aquifer in the study area are either unconfined or semiconfined aquifers. They are mainly clay or sandy clay that have interbedded sand or gravel layers. The central part of the area is covered by thick sand and gravel beds that have interbedded clay layers. The thickness of sand and gravel layers were in the range of 1-25 meters, in some area this layer is not found.

Groundwater flow patterns and flow directions in the study area are described in Chapter 4. The groundwater flow directions in both shallow and deep aquifers were mainly toward the western and northwestern parts of the study area. The groundwater flows in from eastern part and flows out at western part. Consequently, the boundary is assigned to be a general head boundary.

In order to determine the recharge for the numerical model, the coefficient permeability of the soil map (DMR, 2000) was merged with the aquifer type map (DMR, 2000). These were divided into four recharge areas. The recharge was 1 to 8 percent of the annual rainfall, or about 10 to 80 millimeters per year.

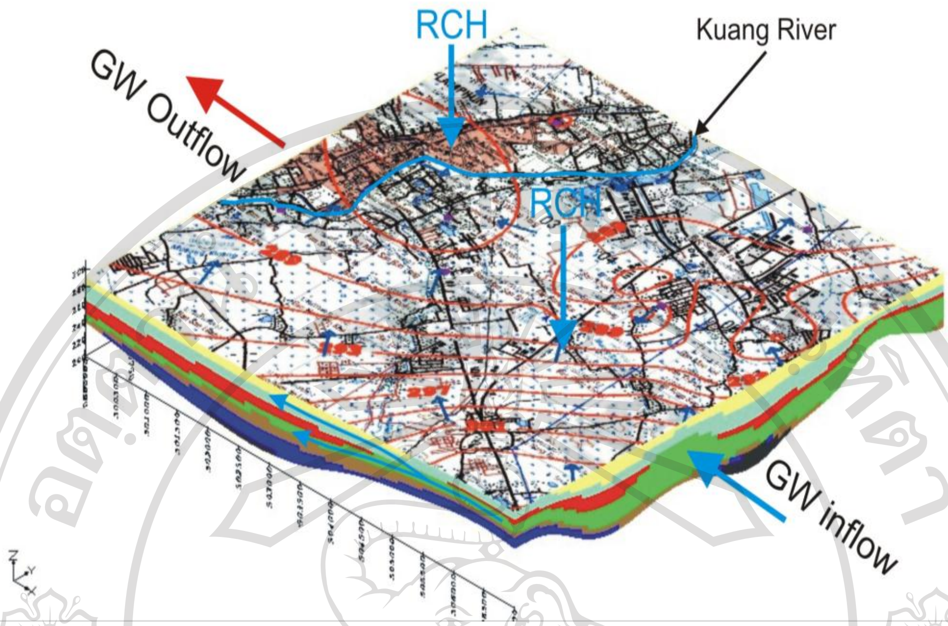


Figure 5.3 Pictorial conceptual model of the study area.

5.4 Model Design and Construction

Designation and construction of a groundwater flow model are a processes of transforming the conceptual model into a mathematical form that can be used to simulate hydraulic heads. The required result is an interactive model with features to represent the hydrogeologic framework, hydraulic properties, hydraulic process, and boundary conditions as designed in the conceptualization stage. The model design and construction involve the design of a model grid and layer and model parameter. Each node or element of the grid or mesh requires the assignment of a value for each hydrogeologic framework property and aquifer hydraulic parameter. Mathematical model was used a finite-difference based program called MODFLOW which is a package in Visual MODFLOW® version 4.2 (Waterloo Hydrogeologic, Inc, 2006).

5.4.1 Model Grids and Layers

The spatial area is divided into grids and the hydraulic parameters of these grids control the flow through the cells of the numerical model domain. They are defined in this study in terms of finite differences using MODFLOW. Finite differences divide an aquifer into a rectangular grid of nodes that define the corners of the centers of model cells. Model layers are used in models to represent the different hydrostratigraphic units, which are geologic units with similar aquifer properties. The three-dimensional numerical model of the study area covers 49 square kilometers. The model domain in MODFLOW exceeds the study area defined in the conceptual model. The lateral extent of the model corresponds to natural physical and hydrologic boundaries. The model has 14 layers, consist of 70 rows and 70 columns with uniform mesh size of 100 × 100 meters. All layer types are assigned as unconfined/semi confined.

The elevation data for the top layer 1, the outcrop of layer 2, and layer 3 were interpolated from a digital elevation model (DEM). The top elevation data of part of layer 2 to layer 14 were interpolated from available borehole drilling data. The bottom of layer 14 was assigned an elevation of 200 meters below mean sea level. This depth is based on the drilling data from chapter 3. The finite difference grids and model layers of the study area are shown in Figure 5.4.

5.4.2 Model Parameters

Hydraulic parameters were analyzed from eleven pumping test data and six slug test data that were carried out by Department of Groundwater Resources in 2007. These data were analyzed by WTAQ (Barlow and Moench, 1999) and UCODE (Poeter and Hill, 1998) programs. The hydraulic properties, including both horizontal and vertical hydraulic conductivity, Kh and Kv, and storage parameters, S (-) of each hydrogeologic unit were specified for input to the groundwater model. Hydraulic conductivity, K, controls the rate of water flow through a unit thickness of an aquifer at a given hydraulic gradient. Storage coefficient, S, determine the change in a water table that will occur in response to change in the volume of water stored in the aquifer. The horizontal hydraulic conductivity of the aquifer I, aquifer II, and aquifer III ranges from 2.6 to 11.5, 0.049 to 6.9, and 1.1 to 9.7 meters per day, respectively. The specific yield and storage coefficients of these three aquifer units range from 5.75 $\times10^{-7}$ to 2.45×10^{-3}, 8.76×10^{-4} to 1.63×10^{-3}, and 1.72×10^{-3} to 6.79×10^{-3}, respectively.

This study divided the area into seven zones using hydraulic conductivity. The distribution of hydraulic conductivity values in the steady- state model of layer 10 is shown in Figure 5.5 for the example and distribution of hydraulic conductivity of all layers are shown Appendix D.

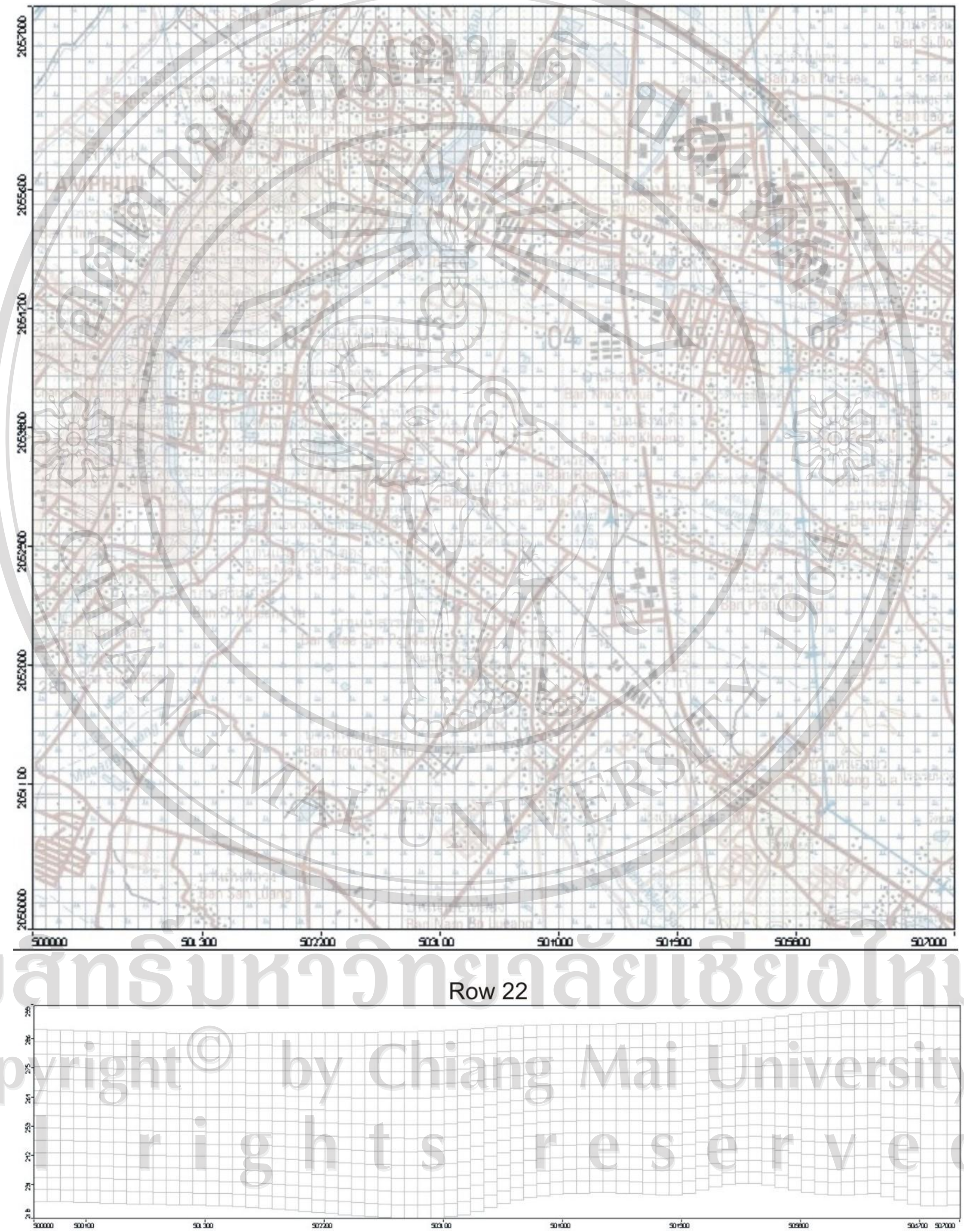
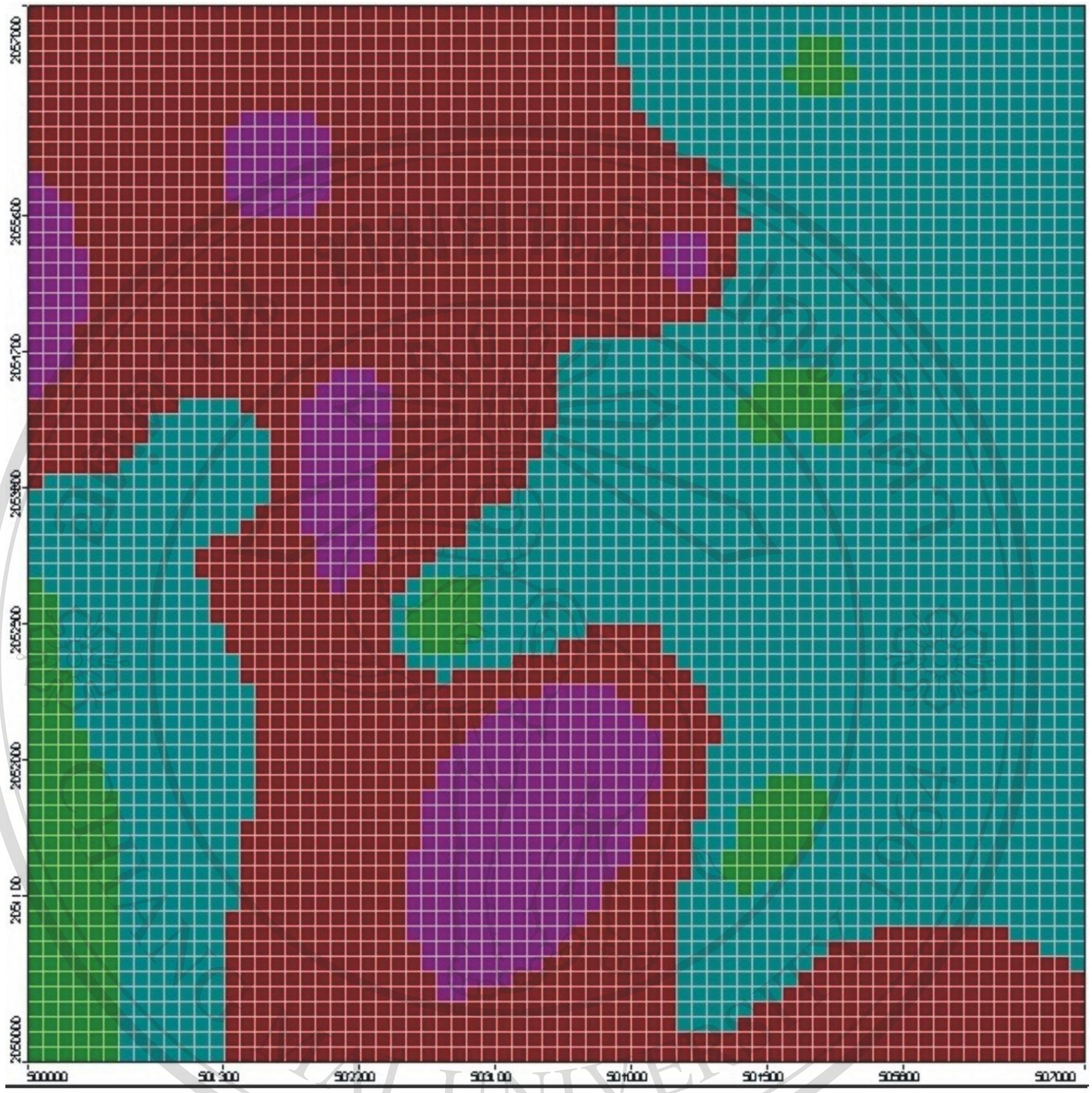


Figure 5.4 The finite difference grids and model layers of the this study area.



Conductivity

	Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]
	1	0.1	0.1	0.01
	2	2.6	2.6	0.26
	3	0.1	0.1	0.01
	4	3	3	0.3
	5	0.1	0.1	0.1
	6	4	4	0.04
	7	1.16E-6	1.16E-6	1.16E-7

Figure 5.5 Distribution of hydraulic conductivity of layer 10 in the steady-state model for the example.

5.4.3 Boundary Conditions

5.4.3.1 Simulating Boundaries

The conceptual model explained that the groundwater can flows in from eastern part and out at western part. This boundary is assigned to be a general head boundary (GHB), the purpose of using this boundary condition is to avoid unnecessarily extending the model domain outward to meet the element influencing the head in the model. As a result, the GHB condition is usually assigned along the outside edges of the model domain. This scenario is illustrated in the following Figure 5.6.

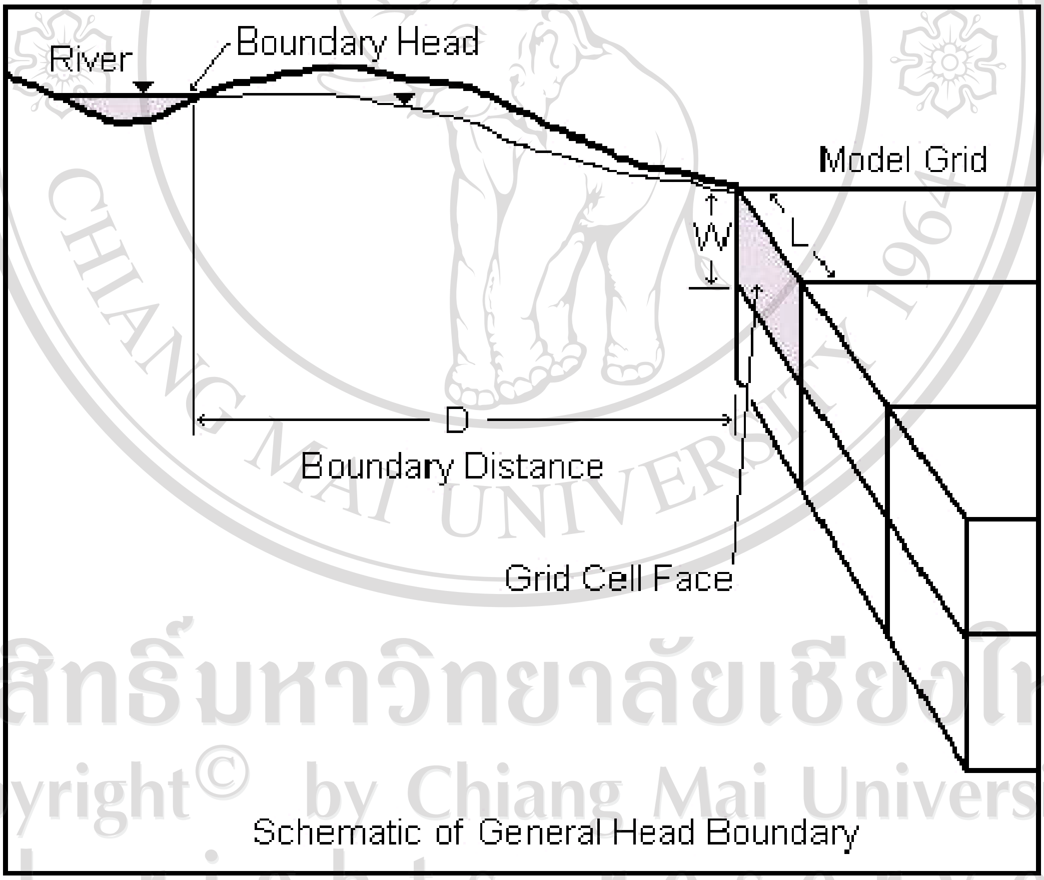


Figure 5.6 Schematic of General Head Boundary.

The conductance value may be physically based; representing the conductance associated with an aquifer between the model area and a large lake, or may be obtained through model calibration. The Conductance value (C) for the scenarios illustrated in the preceding figure may be calculated using the following formula:

$$C = \frac{(L \times W) \times K}{D}$$

Where,

(L×W) is the surface area of the grid cell face exchanging flow with the external source/sink

K is the average hydraulic conductivity of the aquifer material separating the external source/sink from the model grid

D is the distance from the external source/sink to the model grid

5.4.3.2 Recharge Rates

By applying initial recharge rates to the model, it was divided into four zones according to the hydrogeologic characteristics of each aquifer as described in the conceptual model. The coefficient permeability of the soil map (DMR, 2000) was merged with the aquifer type map (DMR, 2000), that used determined recharge zone (Figure 5.7). The recharge rate of zone 1, 2, 3, and 4 were 45, 10, 70, and 80 millimeters per year, respectively. These rates were 1 to 8 percents of the annual rainfall. The recharge rate estimates for the model are summarized in Table 5.1. These changed later when the model was calibrated. The recharge distribution in the steady-state model is shown in Figure 5.8.

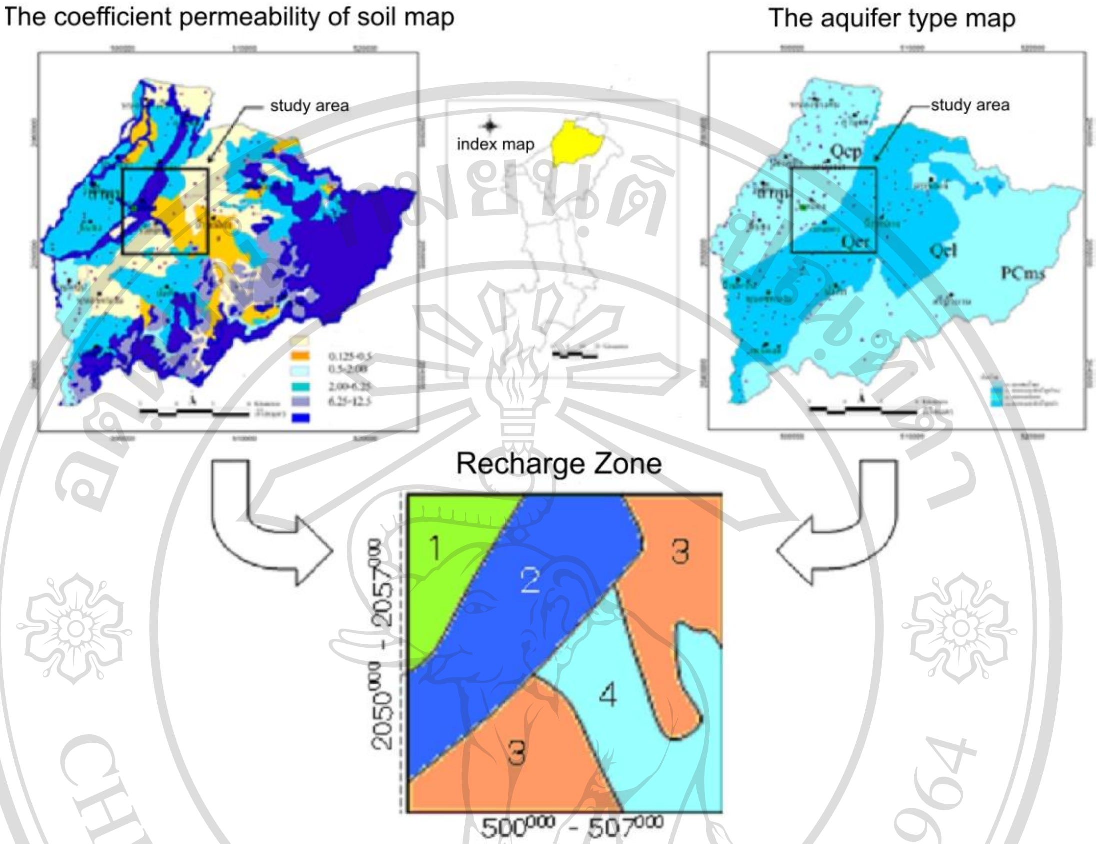


Figure 5.7 The recharge zone of the study area.

Table 5.1 Recharge rate estimates for the steady-state model.

Zone	Recharge rates (millimeters per year)	Percentage of annual rainfall
1	45	4.5
2	10	1
3	70	7
4	80	8

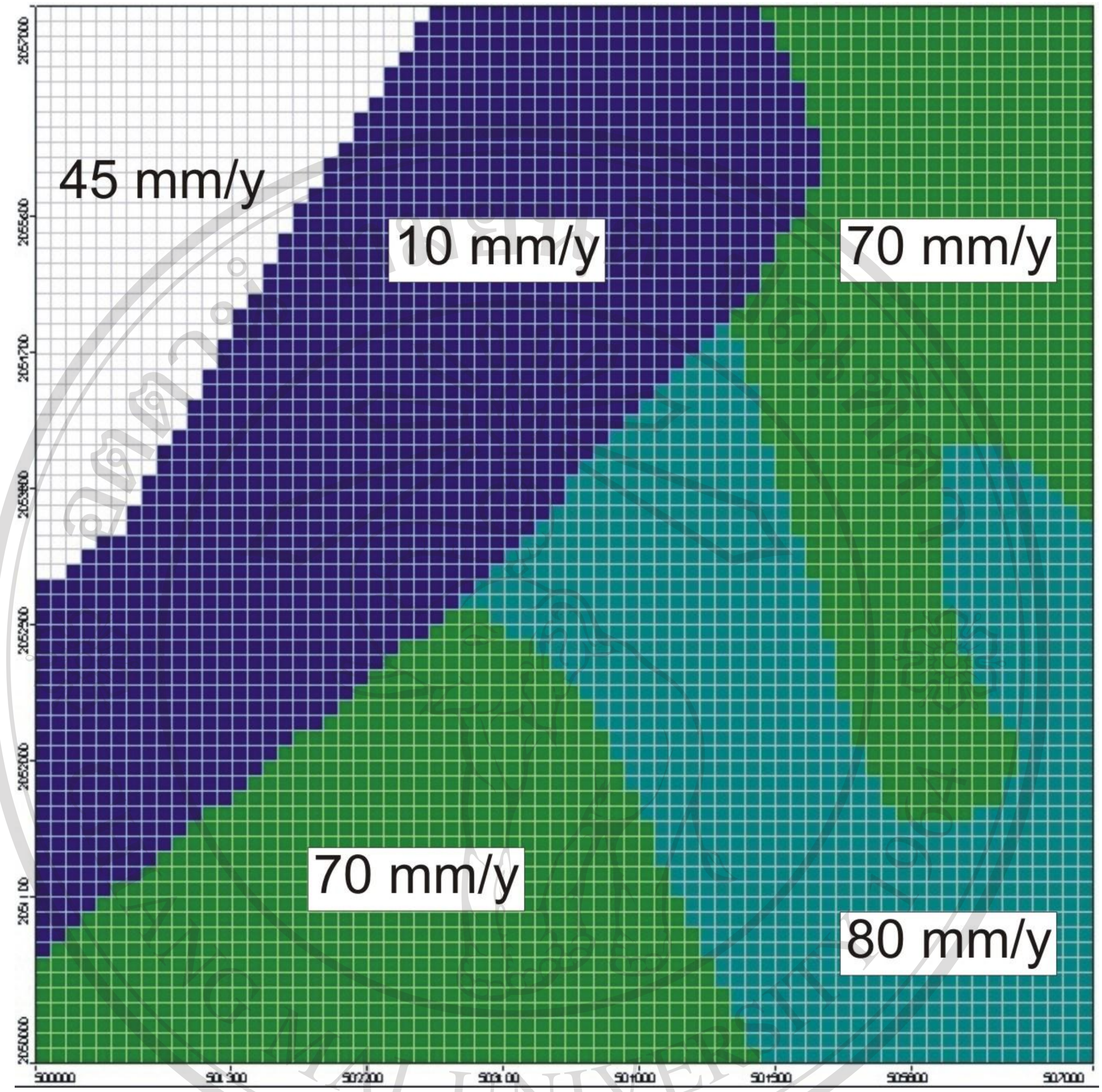


Figure 5.8 Recharge distribution of the steady-state model.

5.4.3.3 River

The river package simulates the flow between an aquifer and a surface water body. This package was used to represent rivers and streams in the model. The river package, which was one alternative, allows streams to gain and lose water. Data requirements for river package are include river stage elevation, river bottom elevation, and known streambed conductance. Stream bed conductance includes river parameters such as length, width, and bed thickness, and hydraulic conductivity of the streambed sediments. Stream bed conductance is determined by the following equation:

$$CRIV = \frac{KLW}{M}$$

Where,

CRIV = streambed conductance (m2/day)

K = hydraulic conductivity of stream bed material (m/day)

L = stream length (m)

W = stream width (m)

M = thickness of stream bed layer (m)

The Mae Kaung River was set as a river package by digitizing. The dimension of the Wang River is 30 meters in width and 6 meters in depth. The stream length of study area is 9,900 meters. The average thickness of stream bed layer is 5 meters. The hydraulic conductivity of these riverbeds ranges from 0.03 to 0.078 meter per day. The river package for the model is shown in Figure 5.9.

5.5 Model calibrations

Calibration is a process by which the independent variables of parameters and fluxes of model are adjusted within realistic limits to produce the best match between simulated and measured groundwater level monitoring data. The process involved refining the hydrogeologic framework, hydraulic properties, and boundary conditions of the model to achieve the desired degree of correspondence between the model simulations and observations of the groundwater flow system. Calibration is a necessary, but not sufficient, condition that must be done to have a degree of confidence in a model's predictions, as it shows that a model simulation can reproduce system behavior under a certain set of conditions. The acceptability of a calibration can be considered when calculating the approximate water balance, iteration residual, qualitative measures, and quantitative measures (Schaffner and others, 1999; Mace and others, 2000; Middlemis, 2000).

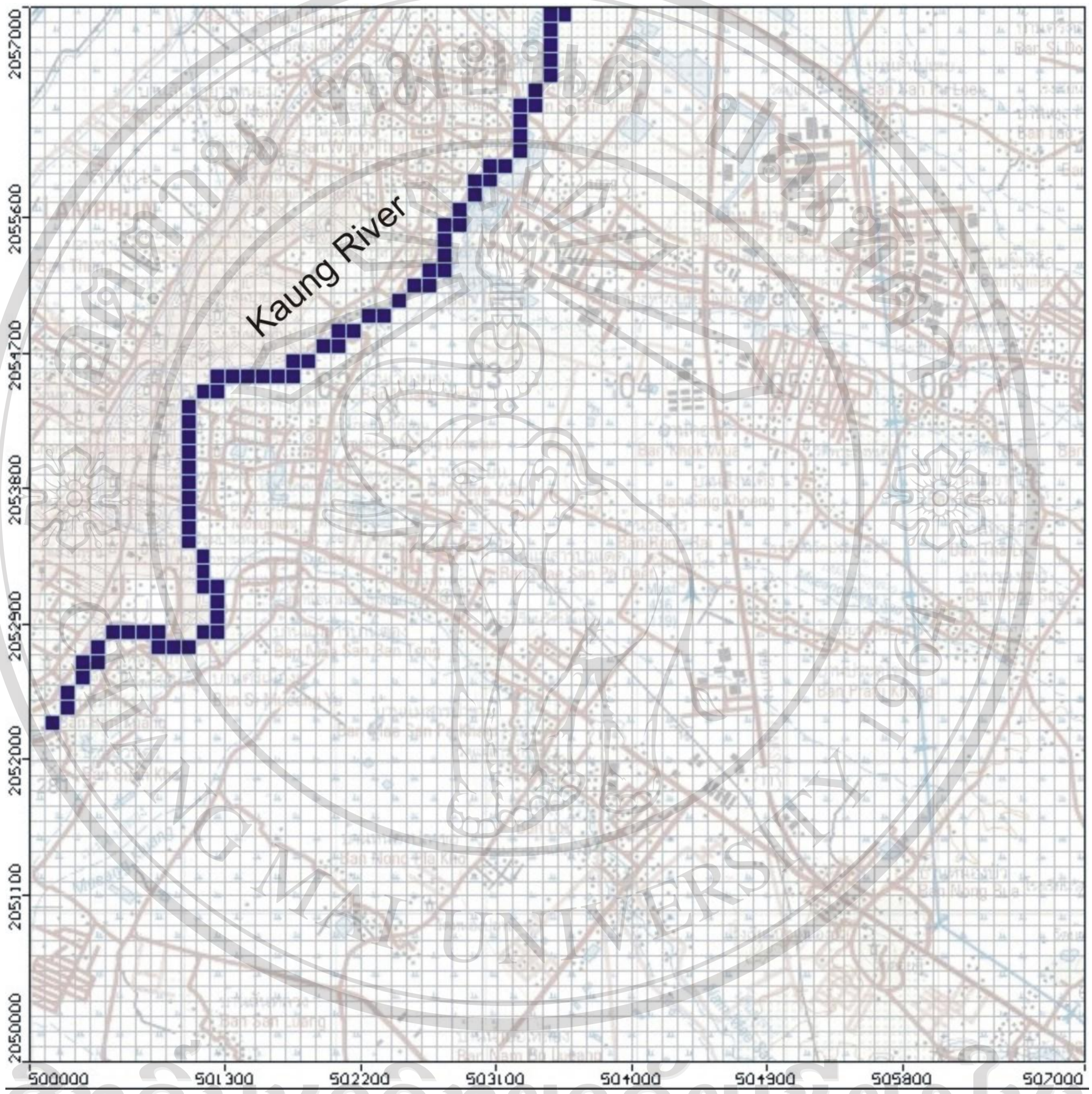


Figure 5.9 River package for the steady-state model.

5.5.1 Steady-State Simulations

Steady-state modeling is simulated under equilibrium conditions, such as representing the long term average hydrologic balance, and/or conditions where aquifer storage changes are not significant (Anderson and Woessner, 1992). The model is also used to investigate recharge rates, hydraulic properties, boundary conditions, and sensitivity analysis of the different parameters of the model results. This study assembled the input data sets, constructed the framework of the model, and calibrated the steady-state simulation. The initial parameters setup of the model included the distribution of aquifer parameters, such as hydraulic conductivity and the boundary conditions with field measured head as initial heads for steady-state simulations model.

The steady-state simulation was set to calibrate the groundwater conditions of January, 2010, using that month's complete data set. This calibration was done both quantitatively and qualitatively. The quantitative calibration included mathematical and graphical comparison between measured head and simulated head, calculation of statistics regarding residuals, and comparison of simulated and measured components of the water balance. The qualitative calibration was a comparison of groundwater flow patterns. Groundwater heads from 49 observation wells were selected especial located in this model area (49 wells selected from 67 measured groundwater level wells in chapter 4), these were used as calibration target and then the model was modified to simulate the groundwater heads. The simulated heads were matched against the measured head distribution and errors were compared by normalized root mean square percentage. Two techniques were utilized to reduce errors. First is a trial and error calibration and the second uses sensitivity analysis. First, the study adjusted the different model parameters to determine which parameters had the most effect on simulated water head. This process has determined that the model was most sensitive to recharge rate, hydraulic conductivity of aquifers, and hydraulic conductivity of river bed material. After reviewing previous studies of the recharge estimation and the range of hydraulic conductivity values from each of three aquifers and river bed material, this study decided to fix the range of recharge rates to that from evaluation of recharge and the range of hydraulic conductivity values from pumping tests according to the distribution of the hydrogeologic characteristics in the study area.

The recharge rate and hydraulic conductivity values from model calibration agree with the values that were estimated.

In this study, the simulated and observed heads agree with the satisfactory accuracy of the estimatation. Mathematical and graphical scatter diagrams comparing simulated heads with observed heads obtained from the steady-state model are shown in Figure 5.10. The normalized root mean square between simulated head and observed head is approximately 12.27 percent. Figure 5.11 showed comparison of groundwater flow pattern between simulated head and observed head of shallow aquifer. Groundwater flow pattern are similar. In the eastern part of study area, the groundwater flow directions in both simulated model and shallow aquifer are toward the northwest. In the central and western part of study area, groundwater flow of simulated model direct toward the west but the groundwater flow of shallow aquifer was toward northwest. Differences between simulated head and observed head were between 1 to 5 meters. The high head difference (3 to 5 meters) are confined to the southwest part and low head difference (1 to 2 meters) are founded in central and northeast parts of the study area. Figure 5.12 showed comparison of groundwater flow pattern between simulated head and observed head of shallow aquifer. Groundwater flow pattern are rather difference. The groundwater flow directions of simulated model are toward the west but the deep aquifer directing toward northwest. The differences between simulated head and observed head were between 1 to 14 meters. The highest head difference (14 meters) is confined to the north and northwest part. The result showed that the distribution and density of observation wells are mainly effecting the very important to used simulated head. The higher the distribution and density of monitoring wells result in lower the head difference value.

The results of the calibrated model indicate that the horizontal and vertical hydraulic conductivities of the aquifer I unit (zone1 and zone 2) range between 1.0 to 4.5 meters per day. For the aquifer II unit (zone3 and zone 4) these conductivities range from 1.5 to 4.5 meters per day and for the aquifer III unit (zone 5, 6, and zone 7) conductivities range from 1.5 to 4.5 meters per day. The recharge value of the steady-state calibration model ranges between 10 to 70 millimeters per year, which is approximately 1 to 7 percents of the annual rainfall.

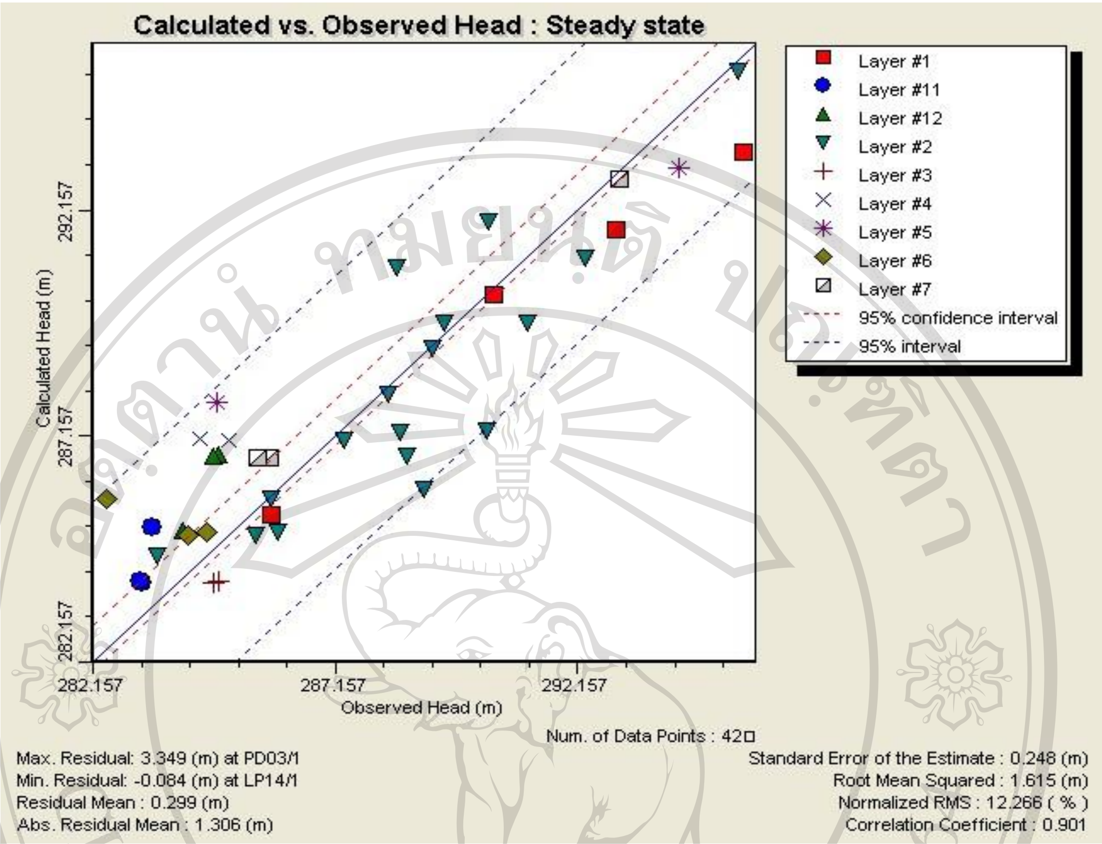


Figure 5.10 Mathematical and graphical scatter diagram comparing simulated heads and observed heads of the steady-state model.

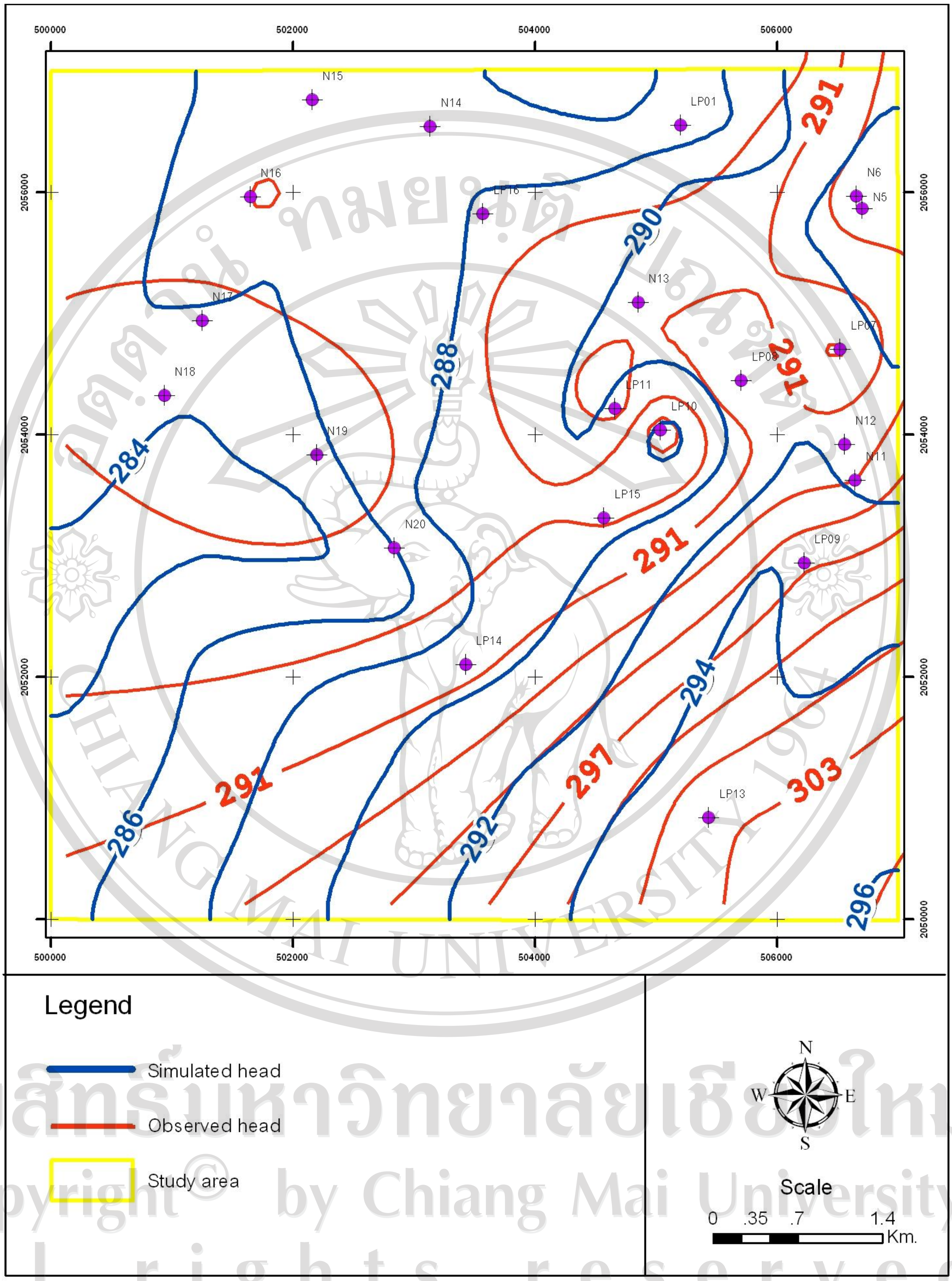


Figure 5.11 Comparison of groundwater flow between simulated and observed heads of shallow aquifer for the steady-state simulation.

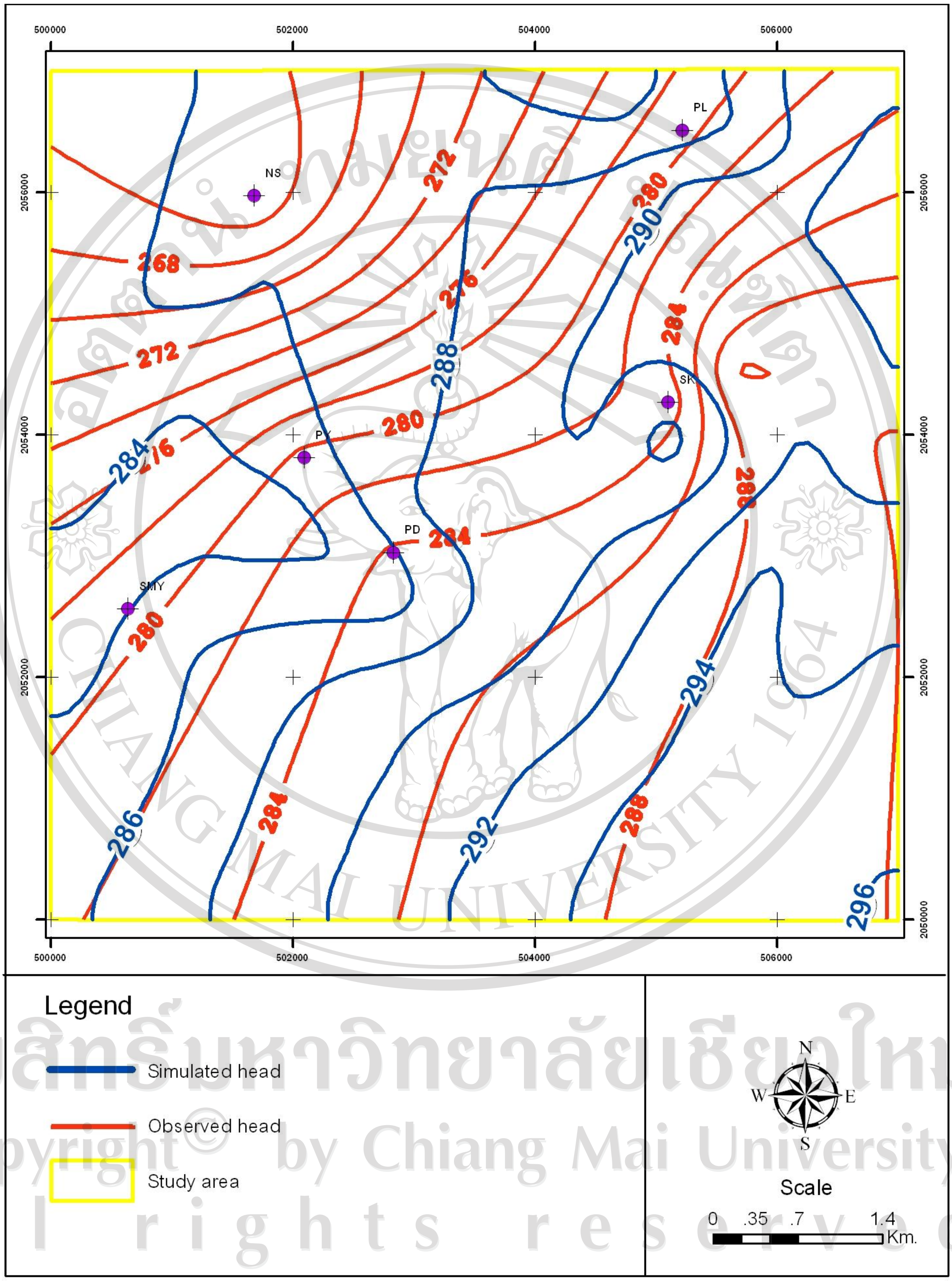


Figure 5.12 Comparison of groundwater flow between simulated and observed heads of deep aquifer for the steady-state simulation.

5.5.2 Sensitivity Analysis

The sensitivity analysis is a procedure for quantifying the impact on an aquifer's simulated response due to an incremental variation in a model parameter or a model stress. The purpose is to identify the varying model input parameters over a reasonable range of model parameter value uncertainty and observing the relative change in model response. Sensitivity analyses are also beneficial in determining the direction of future data collection activities (Fabritz and others, 1998; Dawes and others, 2000; Mandle, 2000).

In this study, the sensitivity analysis is done by decreasing and increasing of the different parameters by timing the recharge rates, horizontal hydraulic conductivity, and vertical hydraulic conductivity of aquifers with the multipliers 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, and 1.3. The estimated parameters value is changed by 10 % at each step. The results show that the horizontal hydraulic conductivity parameter is the most sensitive parameter while the least sensitive parameter is recharge parameter. Figure 5.13 shows the normalized root mean square from the sensitivity analysis.

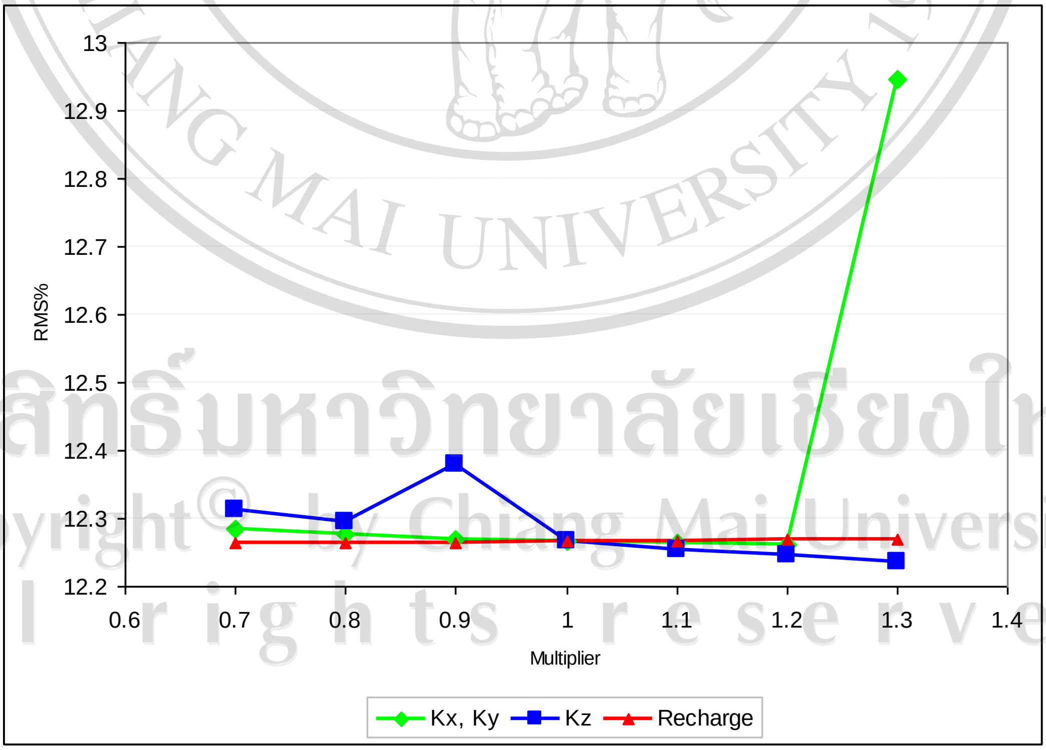


Figure 5.13 The normalized root mean square from the sensitivity analysis.

Figure 5.14 shows the sensitivity analysis between streambed conductance of river parameter and conductance value of general head boundary (GBH) parameter. The estimated parameters value is changed by decreasing and increasing 10, 50, 100, 500, and 1000 times, respectively. The results show that the general head boundary parameter is more sensitive than river parameter.

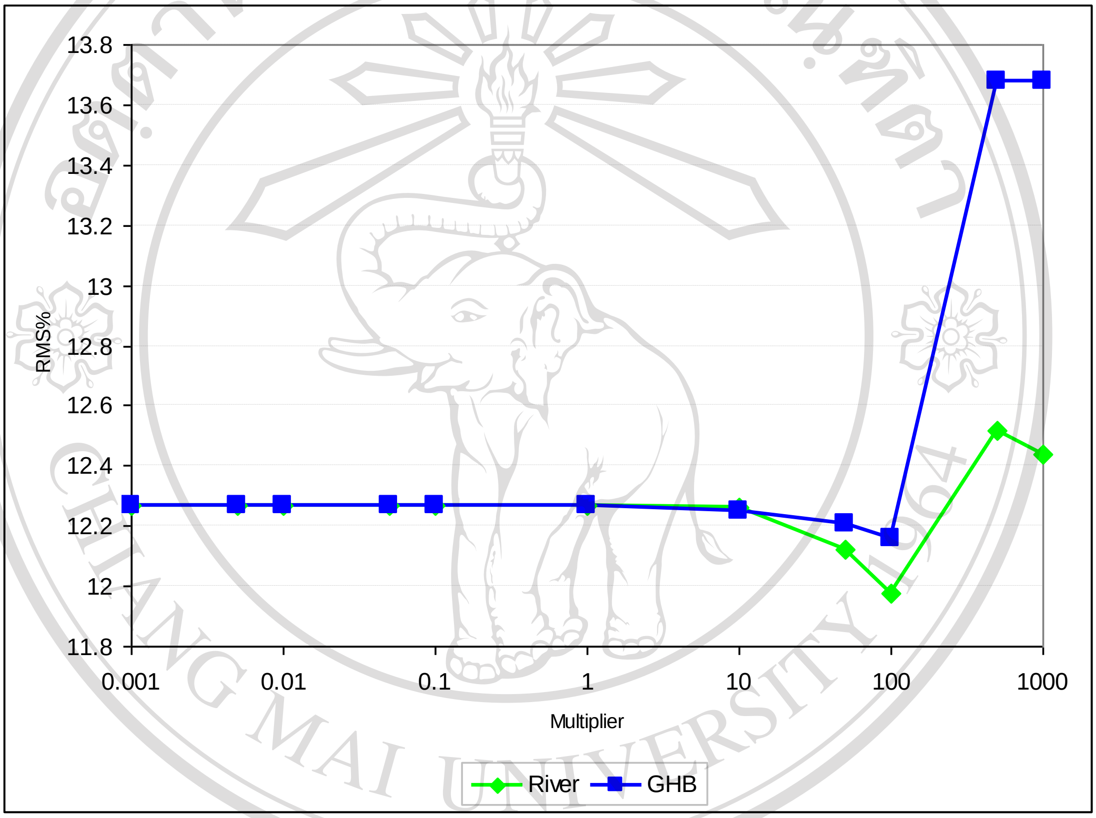


Figure 5.14 The sensitivity analysis between river parameter and GBH parameter.