CHAPTER 3

MODEL DEVELOPMENT

3.1 Methodology

This section describes the methods used for setting up a comprehensive groundwater flow model. The modeling procedures start from compiling all necessary data, developing a conceptual model, translating a conceptual model to finite-difference based numerical model, applying boundary conditions, executing and calibrating the model based on automatic parameter estimation method, and executing the Monte Carlo simulation for evaluating the model uncertainty. The flow model of the Bang Pakong river basin developed in this study is regional in nature because of the study area covers an area as wide as 8,614 square kilometers. The study has several landuse types ranging from forest and agriculture to urban.

The hydrogeological conditions of the area were defined based on the lithologic log data from over 3,000 wells and their distribution is shown in Figure 2-9 in Charter 2. Spatial model parameters and spatio-temporal fluxes such as rivers, wells, and reservoirs were acquired and processed in GIS environment and used as inputs for the regional numerical groundwater flow model. The mathematical modeling was based on the finite difference solution of the MODFLOW-2000 program (McDonald and Harbaugh, 1988; Harbaugh et. al., 2000) which is available in user-friendly software packages: GMS® 7.1, Visual MODFLOW® 4.2, and Processing MODFLOW™ 8.

Based on the knowledge of the described hydrogeological system, a steady-state mathematical model of the multi-aquifer system was developed based on the modification and corrections of the previous studies (DGR, 2006). In this study, major improvements from the model developed by DGR (2006) were layer elevation corrections and input of additional data that had been reviewed and updated in present day. The steady state model, simulating the average behavior in the period of 2006 to 2009, was validated and calibrated using a computer program PEST (Doherty, 1994) with the automated parameter estimation algorithm. After the steady-state flow model has been calibrated, prediction of model uncertainty in terms of groundwater potential will be evaluated using the Monte Carlo technique based on the parameter randomization method.

This study work can be achieved using several methods described below. A flow chart containing the groundwater modeling process used in this study that it is shown in Figure 3-1.

3.2 Data Collection and Processing

Data reviewing and data analysis are necessary in order to reconstruct and recheck a hydrogeological system from previously collected and interpreted data. This study used data from several sources such as geologic map, topographic map, drilling logs, resistivity surveys, measuring water level, pumping test data, and etc. Data were interpolated inside every active grid-block of this model. The kriging method was used to interpolate values of parameter such as the top and bottom elevations of the aquifers and hydraulic properties of the aquifers.

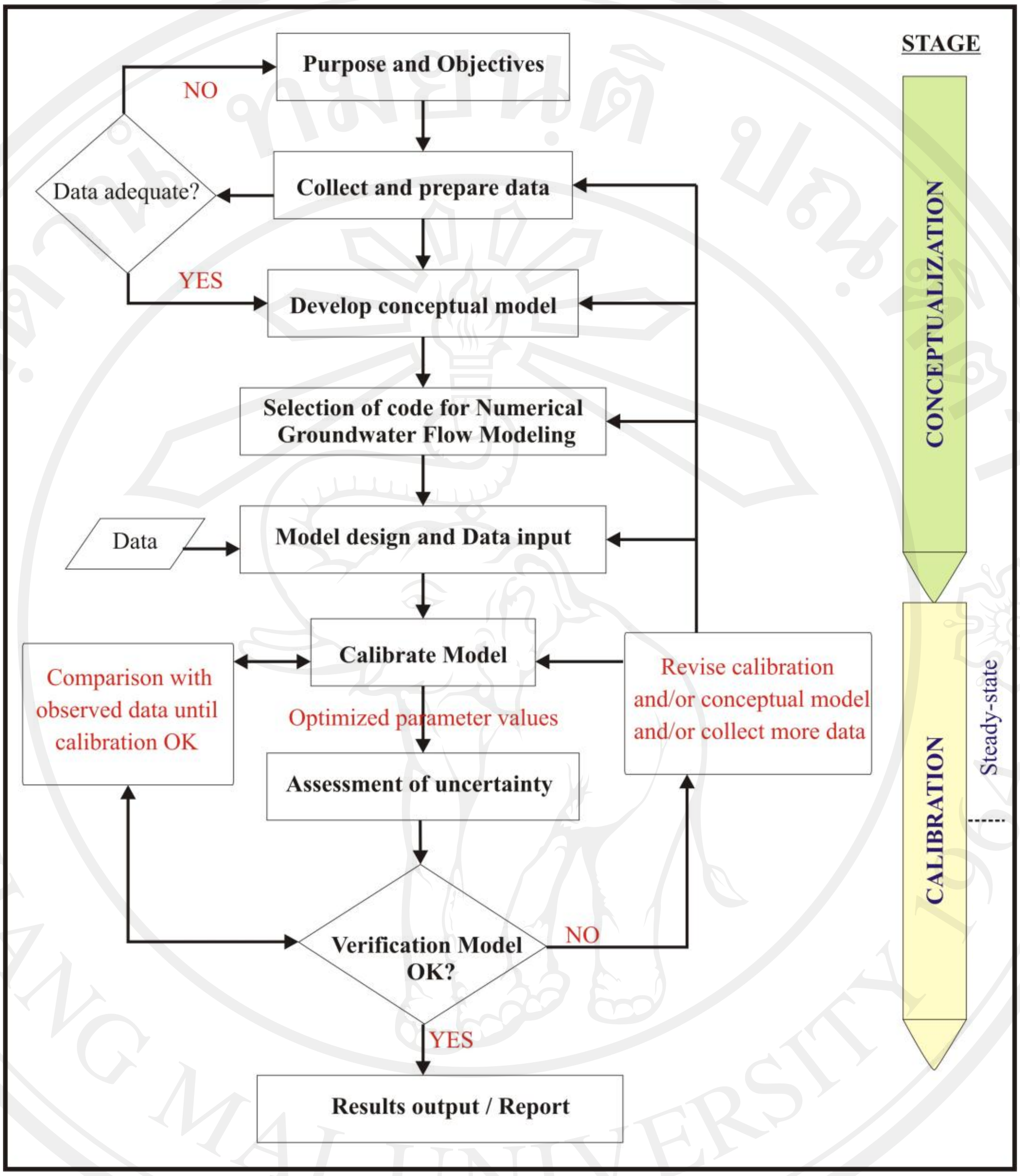


Figure 3-1 Flowchart showing steps for evaluation of the groundwater modeling process in this study (Modified from Ashraf, 2008).

For this study, the first step in the modeling protocol is to establish a conceptual model that represents a real groundwater system. The data requirements for a regional groundwater flow model in the study area such as hydrogeological framework and hydrologic stress data. The hydrogeologic framework data describes the physical system and parameters that do not change with time. The stress data described the dynamic hydrologic stresses on the system. All these diversified data were assembled and analyzed when formulating the conceptual model.

The development of a sufficient understanding on which to base decisions or make predictions often requires consideration of a multitude of data of different types and with levels of uncertainty (Middlemis et al., 2000). The data for the development of numerical groundwater flow model of this study area were obtained from several sources, such as previous studied i.e. all part of database gathered by Department of Groundwater Resources in "Explored and Assessed Groundwater Resource Potential of the Bang Pakong River Basin Project" (DGR, 2006), Department of Water Resources, measured field work data, and etc. are listed in Table 3-1.

3.3 Conceptual Model Development

This section describes the steps used to construction the conceptual model for the groundwater flow modeling simulation. The purpose of building a conceptual model is to visualize an integration of all applicable data, such as hydrogeology and hydrologic stresses representing the groundwater system. Normally, conceptual model will determine the dimensions of the numerical model and design of the grid. There are three steps for building a conceptual model of groundwater flow system: (1) defining hydrostratigraphic units; (2) preparing a water budget; (3) defining the flow system. The conceptual model from previous studied of DGR (2006), built from 14 lines of cross-section from more than 50 wells representing the complex multi-aquifers system in this area was reviewed. Next, the hydrostratigraphic system is rechecked. Then, the elevation of ground surface and top of wells are corrected and was reconstructed a hydrostratigraphic system. The data requirements for reconstruct a conceptual model are listed in Table 3-1. Figure 3-2 shows pictorial conceptual model of this study

3.3.1 Defining the Model Domain

The first step in formulating defined the area of interest such as identify the boundary conditions, type of aquifers, and hydraulic properties that there affect to groundwater flow in or groundwater flow out for this system. Numerical models require boundary conditions, such that the head or flux must be specified along the boundaries of system.

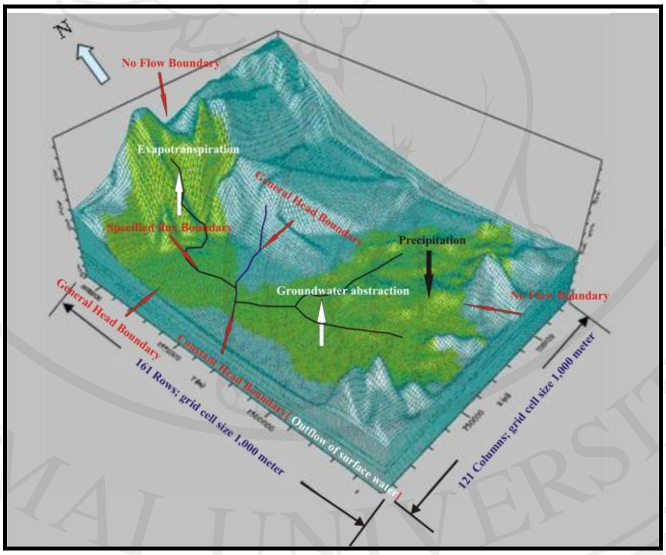


Figure 3-2 Pictorial conceptual model of this study area.

For this step, reconstruction of geologic information including hydrogeologic map, profile maps from 14 cross-sections, E-loggings data, geophysics data and lithologic logs from previous studied of DGR (2006) were combined with information on hydrogeologic properties to define hydrostratigraphic units for the conceptual model. In regional flow systems, aquifers and confining beds in this area are defined

Table 3-1 Summary of necessary model data and material requirements and sources (Modified from DGR, 2006).

Material/Data	Data Sources	Period/Times (year)	Description/Detail/Remark
I. Maps			
- Topographic Map	Royal Thai Survey Department	2005	- Showing surface water bodies, drainage features, and water divides. - Raster map: Map scale 1:50,000 (L7018)
- Base Map	Royal Thai Survey Department & Department of Groundwater Resources	2005 2005-2006	- GIS data: Vector map; consists of rivers, streams, roads, villages, Contours, location points of Tambon-Amphoe-Province, borders of Tambon- Amphoe-Province
- Land use Map - Soil Map	Land Development Department	2000	- GIS data: Vector map consists of land use type, soil type, properties of permeability of soil
- Geologic Map	Department of Mineral resources &	2002	- GIS data: Vector & Raster map - Extent and thickness of geologic units, lithologic logs, cross-sections.
- Hydrogeologic Map	Department of Groundwater Resources	2006	- GIS data: Vector & Raster map - Extent and thickness of aquifer units, groundwater potential, groundwater quality such as TDS, Cl, Hardness, and etc., wells location , wells history such as depth, drilled, owner, and etc., lithologic logs, cross-sections.
II. Data Compilation			
- Run off data - Rainfall data - Evapotranspiration data - Climatological data	Royal Irrigation Department & Thai Meteorological Department & Department of Water Resources & Reports of previous work	1977-2006	- Digital report data form all of measure stations cover the study area - Usually daily, monthly, yearly, average, mean, min, max data are often reported.
- Groundwater level	Department of Groundwater Resources	2006	- Documentation data: Water table and potentiometric data for all

Table 3-1 (Continued)

Material/Data	Data Sources	Period/Times (year)	Description/Detail/Remark
monitoring data		2009-2010	aquifers cover the study area. - Field work measurement of water table and potentiometric for all aquifers in 179 wells on 3 times.
- Hydraulic parameters	Department of Groundwater Resources & Reports of previous work	2006	- Documentation data
- Groundwater Pumpage	Department of Groundwater Resources & Reports of previous work	2006	- Documentation data & Estimated data
- Hydrogeologic cross sections 14 lines	Department of Groundwater Resources & Reports of previous work	2006	- Digital data : Showing the vertical extent and boundaries of the aquifers system
<u>Software Program</u>			
- Aquaveo GMS® v. 7.1	Department of Geology, Faculty of Science, Chiang Mai University		Program code (Upgraded license)
- Visual MODFLOW® v. 4.2			Program code
- ArcView GIS® v. 3.3			Program code
- Processing Modflow™ v. 8.0.31			Program code (Upgraded license)
-SURFER® 8.0			Program code

using the concept of the hydrostratigraphic units and understanding of the depositional history help reconstruct the environment of the deposition. In this case, the hydrostratigraphic units comprise geologic units of similar hydrogeologic properties. Moreover, several geologic formations were combined into a same hydrostratigraphic unit and some geologic formations may not be subdivided into aquifers and confining units, it is due to relatively large study area, the flow model is considered to be regional in nature.

As a result, the aquifer system in the study area can be grouped into ten hydrogeologic units as shown in Figure 3-3. Lithologic descriptions and 14 cross-sections indicates that the Quaternary deposits, which are unconsolidated and semi-consolidated, occur at various depths and locations within the study area. They are mainly thick sand or gravel beds that are inter-bedded with clay layers. The central part of the study area is covered by these units, especially the area along the main rivers. The thickness of the Quaternary sediment varies up to 100 meters. In the lowlands, the Quaternary aquifers (Q_{fd}, Q_{yt}, Q_{ot}) consist of several water-bearing beds and confining beds. The water-bearing units are frequently separated with silts, and clays. Then these units link a few discontinuous aquifers occurring in the uplands. These layers do not constitute a continuous aquifer, yet they are hydrodynamically linked. This is the case for the Quaternary sediments which are missing in some parts of the basin and it is not possible to define them separately on a regional scale. Therefore, in this study, the several water-bearing beds and confining beds are combined together in one layer for each unit. The Quaternary deposits are underlain by Precambrian to Triassic consolidated rocks. The thickness of these units vary up to 50 meters. The edge of basin is covered by these units. Aquifers in the basin margins are unconfined aquifers, semi-confined aquifers, and confined aquifers that based on depth and confining bed covering top layer. However, in some areas, clay lenses or confining bed occur occasionally in the top layer. It can be caused an aquifer to become either a semi-confined aquifer or confined aquifer.

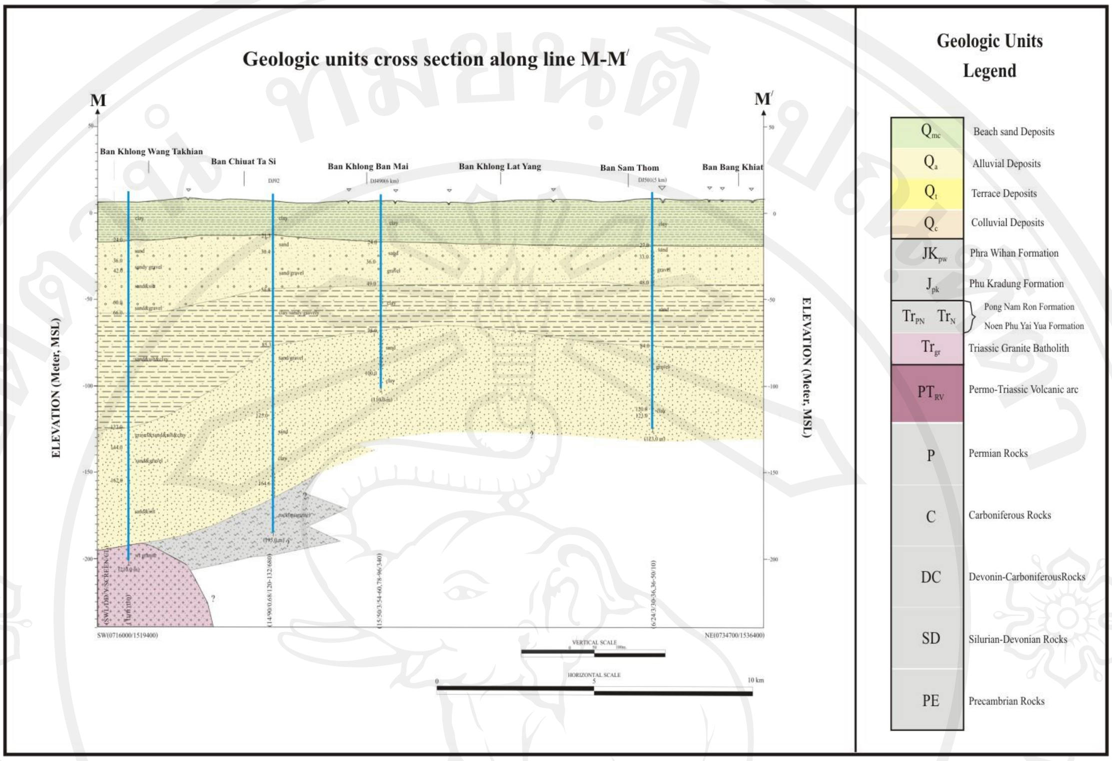
Hydraulic properties include horizontal hydraulic conductivities (K_x and K_y) and vertical hydraulic conductivity (K_z), specific storage (S_s), and specific yield (S_y). These parameters were estimated from 102 pumping tests and other observed secondary data as electrical resistivity and groundwater heads changes in previous study of DGR (2006).

3.3.2 Preparing a Water Budget

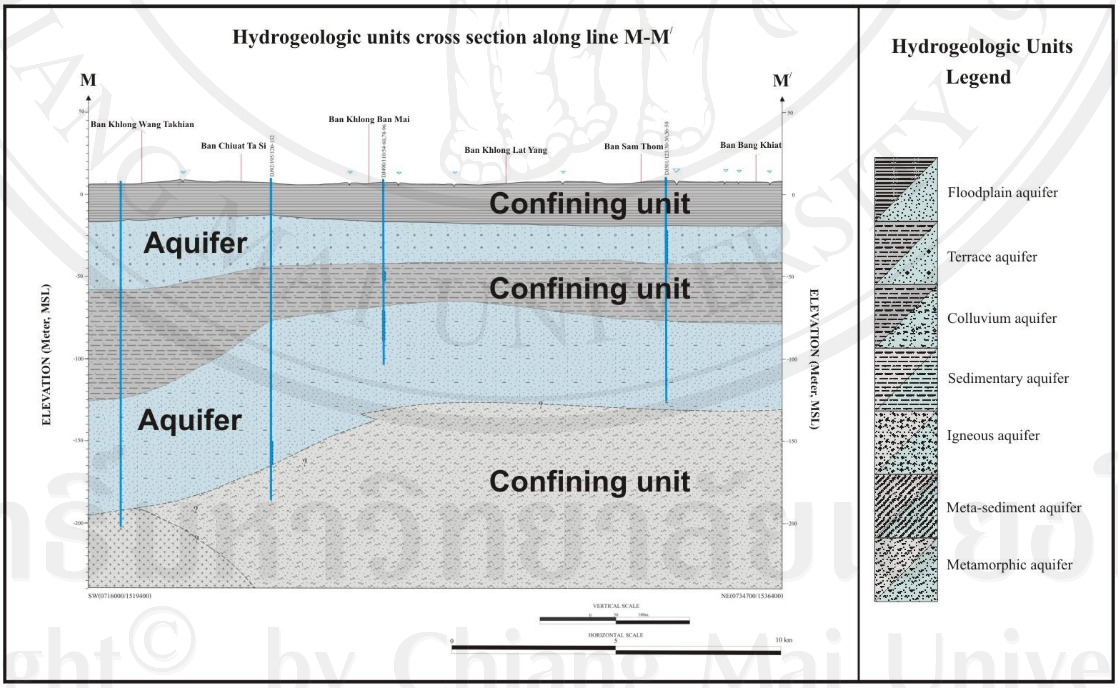
A water budget of the basin was prepared from the previous study of DGR (2006). Accuracy of groundwater recharge estimation is important for management of groundwater system. The water budget is considered all water flow into the basin, percolated or stored within the basin and flow out of the basin. Groundwater recharge estimation in this study was obtained from the water budget approach. It is based on a simple of the law of mass conservation. The system is recharged mainly by infiltration of precipitation. The hydrologic budget method estimated groundwater recharge of 7.82 percent of the annual rainfall or approximately 104.3 millimeters per year. The resulting average annual and monthly groundwater recharge from the period 1977 to 2006, that is shown in Table 3-2. Groundwater recharge occurs mainly in the rainy season. The recharge is due to rainfall but also partially to irrigation. Groundwater recharge is limited to only four months period from July to October.

Parameter zonation technique was used to group a set of the same recharge rate value of groundwater. There are eight zones that have been delineated. All of zones are based on the known hydrologic conditions, estimation of the subsurface material characteristics, simplified landuse. The first and second zones are mountain ranges and highlands which comprise bed rock formations and weathered rocks. These zones are in higher elevation than the other zones. The peripheral the basin normally have variable sediment patterns, such as gravel, sand, silt, clay, lateral soil, rock fragments, and rocks. Usually, these areas are the forest and barren hills with a deep slope and they collected a large amount of rainfall that subsequently percolates though the permeable deposits in central part of the basin. The third, fourth, and fifth zones are terrace deposits and colluvial units which have been used for agriculture; scrub areas and grasslands. These sediments include unconsolidated and semi-consolidated clay, sand, gravel, silt, lateritic. There are considered to be the localized recharge areas to Quaternary formations. The slope in these zones is moderate slope with have slopes greater than 2 percent. Therefore, in the margins that receives runoff influx from mountain areas. The sixth, seventh, and eighth zones are the alluvial deposits, which comprise the meandering belt sand, fluvial clay, alluvial fan and clay units. These units are composed of gravel, sand, silt, clay. The areas are relatively flat, with gentle slopes. Usually, these areas are used for growing rice and wetlands. From lithologic data, silty and clayey strata generally cover the aquifers in the area. Direct groundwater recharge from precipitation and evapotranspiration is quite moderate to high.

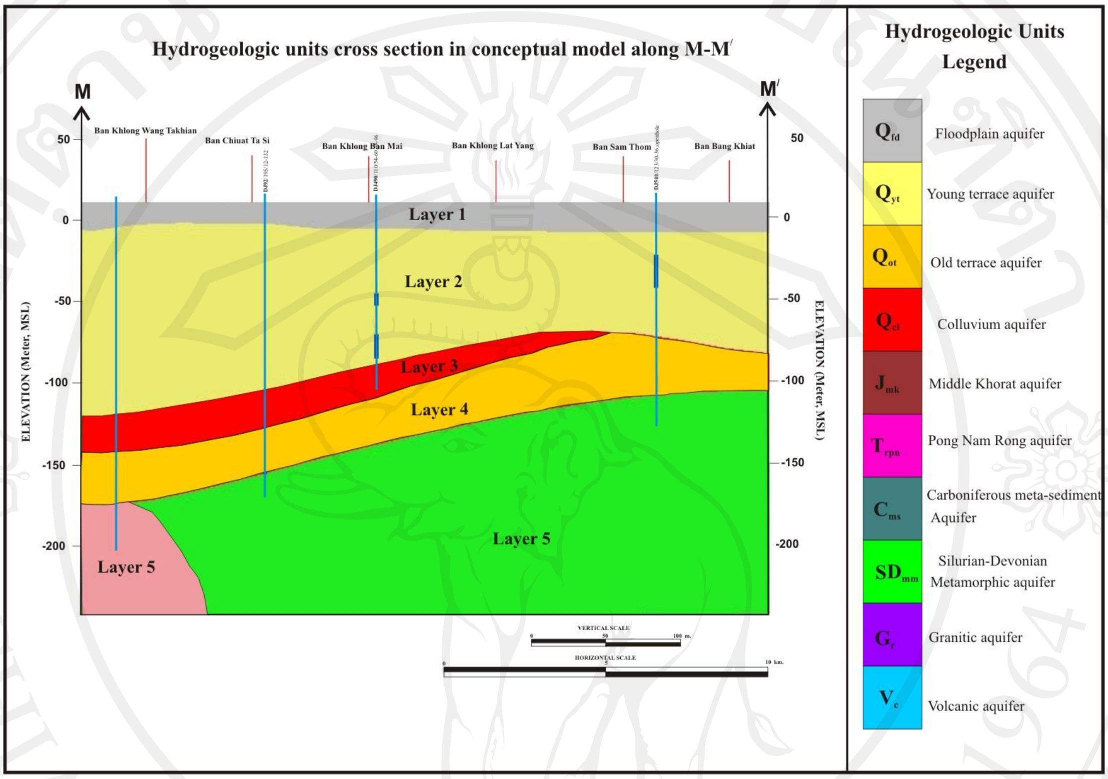
Evapotranspiration zonation of the study area can be divided into five zones based on geologic characteristics, soil types and landuse. The first, second and third zones are an alluvial fan that is mainly flat. There are commonly used for horticultural, paddy field, agriculture, irrigation, and urban area. The value is much



(a) Geologic units in hydrogeologic framework.



(b) Hydrogeologic units in hydrogeologic framework.



(c) Hydrogeologic units in regional conceptual model.

Figure 3-3 Simplified of hydrostratigraphic units into a conceptual model.

higher than other zones. The fourth zone is a terrace deposits in the rolling hills. The area is use mainly for scrub and agriculture areas. The value of ET in the fourth is lower than that in the paddy filed area. The fifth zone is mountain ranges that is mainly highland. It is covered with forest, though it is also partly a grassland and rangeland. The evapotranspiration is lower than other zones in this area. The average annual approximately evapotranspiration values for each zone were calculated as 1.97×10^{-4} to 3.80×10^{-6} meters per day, respectively, using an extinction depth varies between 0 to 2 meters based on type of crops and land covers (Doorenbos and Pruitt, 1977).

Table 3-2 Annual groundwater recharge (mm/yr) with the hydrologic budget approach used in the model (DGR, 2006).

Month	P_i * (mm)	E_{tp} * (mm)	P_i-E_{tp} (mm)	S	ΔS	Eta* (mm)	Out (mm)	Runoff (mm)	Recharge (mm/yr)
Jan.	8.00	80.77	-72.77	25.00		8.00		3.22	
Feb.	19.20	79.67	-60.47	25.00		19.20		2.13	
Mar.	40.20	128.96	-88.76	25.00		40.20		1.58	
Apr.	80.60	130.16	-49.56	25.00		80.60		2.23	
May	154.40	123.93	30.47	55.47	30.47	123.93		7.37	
Jun.	156.60	99.20	57.40	90.00	34.53	99.20	22.87	26.43	
Jul.	182.20	98.50	83.70	90.00		98.50	83.70	51.32	32.28
Aug.	227.80	95.95	131.85	90.00		95.95	131.85	89.33	42.52
Sep.	264.50	88.94	175.56	90.00		88.94	175.56	121.10	54.46
Oct.	165.40	93.82	71.58	90.00		93.42	71.58	93.09	
Nov.	30.90	203.28	-72.38	25.00	-65.00	95.90		17.87	
Dec.	4.40	98.81	-94.41	25.00		4.40		5.39	
Total	**1,334.20**	**1,221.97**	**112.23**	**-**	**-**	**848.63**	**485.57**	**381.27**	**104.30**

*Remark: *; Pi = Precipitation; E_{tp} = Evapotranspiration; Eta = Average of Evapotranspiration*

Groundwater abstraction for domestics used, irrigation, industrial, and agriculture are calculated and estimated using the data from field investigation and data from Department of Groundwater Resources: DGR (2006). The total estimation of groundwater abstraction based on 2006 was about 43,670 cubic meters per day.

3.4 Converting a Conceptual Model to a Numerical Model

The next step for this study is to convert a conceptual model into a numerical model. This step consists of four steps as described below;

3.4.1 Selecting Modeling Code

Based on the hydrological system of the study area, the three-dimensional model (3D) was developed to represent groundwater flow of the Bang Pakong multi-aquifer system. Full three-dimensional models have essentially the arrays requirements which it must be specified for each layer of the model (Figure 3-4).

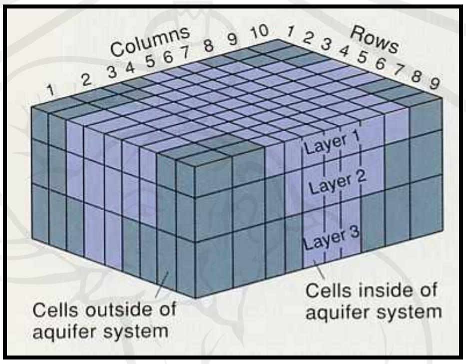


Figure 3-4 Three-dimensional finite difference grid used in MODFLOW (Anderson and Woessner, 2002).

After reviewing different programs that have been used to simulate aquifer dynamics, the groundwater simulation model developed by the United States Geological Survey (USGS) has been chosen using the finite difference solution MODFLOW-2000 (Harbaugh, et. al., 2000), in the software package GMS® 7.1 (Aquaveo, LLC., 2010), Visual MODFLOW® 4.2 interface (Guigure and Franz, 2006), and Processing MODFLOW™ 8 (Chiang, W.H., 2012) in this study. MODFLOW-2000 also has several packages for solving different and variety types of boundary conditions. It includes several modules such as wells (WEL), rivers (RIV), leakage from reservoir and outside aquifers (GHB), evapotranspiration (EVT), and recharge from rainfall (RCH). An additional simulation module is the zone budget package that allows the determination of flow to or from any section of the model.

This package is be used to evaluate the volumetric flow through a cell using Layer Property Flow package (LPF). The chosen packages for this study are listed and briefly described in Table 3-3.

Table 3-3 List of packages are chosen for use in this study.

No.	Packages	Descriptions-Adjustable parameters
1	LPF	Layer Property Flow Package-All layer types
2	RIV	River Package-Conductance of RIV cells
3	WEL	Well Package-Pumping rate of WEL cells
4	GHB	General Head Boundary Package-Conductance of GHB cells
5	EVT	Evapotranspiration Package-Maximum EVT rate
6	RCH	Recharge Package-Recharge flux
7	GMG	Geometric Multigrid Solver Package-To calculate the hydraulic heads in each cell

3.4.2 Model Setup

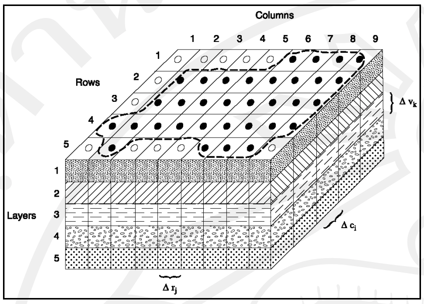
This step involves the design of the grid size and number of layer, modeling environment, model features representing boundary conditions and stress-inducing processes such as pumping, model parameterization, and time stepping. They also involve the initial assignment of the time-variant data and time-constant parameters to the model. Table 3-4 shows the detail of model setup.

(1) Model Grid and Layer

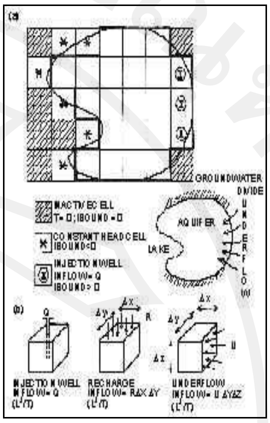
In finite difference (MODFLOW), an aquifer system is divided into a set of blocks by a grid. The grid block is designated, by rows, columns, and layers, and each block is commonly called a "cell". Nodes are labeled using an (i, j, k ≈ col, row, lay) indexing convention, to refer to the position within a row, column, and layer. Nodes may be regularly spaced so that Δx, Δy, and Δz are all constants but not necessarily equal to each other (Figure 3-5). It is assumed that hydrogeologic properties within each block are homogeneous, or uniform. 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. The discrete process ultimately results in a system of simulation linear algebraic equations.

This step, the uniform grid cell size of 1,000 x 1,000 meters is built to cover all this study area which has 162 rows and 121 columns. In the vertical, the aquifers were modeled using 6 horizontal layers of varying thickness. The total three dimensional finite difference block-centered grids consist of 116,886 block grids (121, 161, 6). Each layer type is assigned as confined/unconfined (i.e., convertible) is based on a characteristic of hydraulic properties.

For the top layer, the elevation values were interpolated from a digitized topographic map using SURFER® 8.0 (Golden Software, 1999). The elevation values of each layer of the aquifers were interpolated to generate the layer surface using the kriging interpolation method from available borehole drilling data. The bottom of layer 6 was assigned an elevation of 300 meters below mean sea level. The top and bottom of each layer is based on the topographic map and drilling data. Then the total model grids, layers and designated active cells designs for this model are shown in Figure 3-6.



(a)



(b)

Figure 3-5 Block-centered finite difference grid, (a) Schematic diagram of a full three-dimensional block-centered model, and (b) Example of two-dimensional finite difference grids with no-flow boundaries are designated at the mountain range and along the streamlines (Anderson and Woessner, 2002).

(2) Assigning Model Parameters and Modeling Environment

After the grids and layers are constructed, the next step is to define the hydrogeologic properties, sets up modeling environment, and assigns all of model parameters to model grid (see Table 3-4). The data for the development of numerical groundwater flow model can be categorized into time constant (i.e., aquifer thickness, hydraulic parameters, and etc) and time variant data (i.e., hydro-meteorological, water level, recharge rate, and etc.).

Table 3-4 Summary of the model setup used in this study.

Model setup	Description/Meaning/Unit
1) Scale of model	
- width of model (UTM-E)	705,000 - 826,000 meters
- length of model (UTM-N)	1,449,000 – 1,610,000 meters
- top and bottom of model (msl.)	-300 to + 1,100 meters (msl.)
2) Model grid and layer	
- grid cell size (West-East)	1,000 meters
- grid cell size (North-South)	1,000 meters
- number of column	121 columns
- number of row	161 rows
- total of grid cell	116,886 grid cells
3) Layer setting	
- number of layer	6 layers
- number of hydrogeologic unit	10 units
- thickness of layer	variable
- layer type	confined/unconfined/variable
4) Units	
- length, thickness of layer	meters
- time	day
- hydraulic conductivity	m/day
- pumping rate	m^3/day
- recharge rate	m/day
5) Time options	
- start date for run model	1 May 2009
- steady-state simulation time period	Average within 1 year of measurement
6) Number of Groundwater wells	
- Pumping well	521 locations (total ≈ 43,670 m^3/day)
- Observation well	179 wells

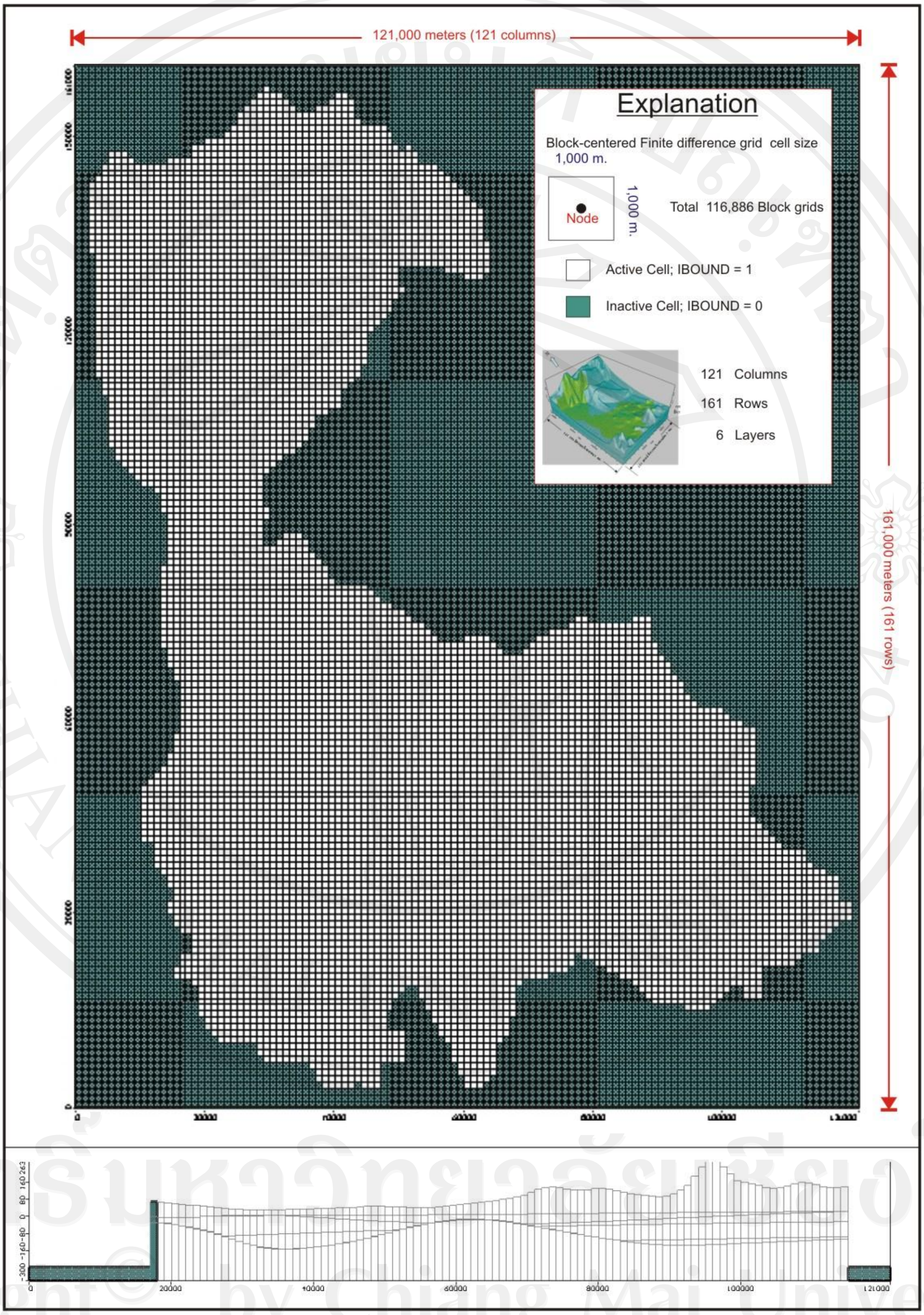


Figure 3-6 The uniform finite difference grids and IBOUND design of the model.

(3) Transferring Model Data to Model Grid

Because of this model is a regional scale covering large area, parameter zonation technique is used to group the same values of parameters into zones. In this study, there are three parameters using this technique; hydraulic properties of aquifer, recharge rates, and evapotranspiration rates as described below;

➢ **Hydraulic conductivity**: Hydraulic property parameters were compiled from analyses of pumping test data of 249 groundwater wells (DGR, 2006). The geometric average of horizontal hydraulic conductivity (K_x = K_y) for all tested wells corresponded to each hydrogeologic unit was input into the model. The vertical anisotropy (K_z/K_x) was initially specified as 1.0.

This study divided hydraulic conductivity parameter into ten zones based on the hydrostratigraphic units. Table 3-5 shows the hydraulic properties for each unit. The distribution of hydraulic conductivity values in the steady-state model of each aquifer layer is show in Figure 3.7.

➢ **Recharge Components**: The surface-water percolates to aquifer mainly occurs from rainfall, canal seepage, reservoir, dam, and induced recharge through irrigation system return. This study area is recharged mainly by infiltration of precipitation. The focus of this study, the average annual recharge is calculated using hydrologic budget approach foe the last three decades. The recharge rate is influenced by hydrologic properties of soils, land use, and the subsurface lithologic set up. It is difficult to introduce precise distribution of recharge over the area due to complex distribution of various types of soils and land use in the area. However, equal distribution of the recharges from various sources, on a regional scale, generally gives the results within practical limits (Thangarajan, 2004). The recharge area can be divided into eight zones. Figure3-8 described the value of yearly average recharge rate for each zone and shown spatial distribution of recharge zones in the model.

- **Evapotranspiration (ET)**: The effect of plant transpiration of water and direct evaporation removing water from saturated groundwater regime depends upon the depth of water table from the ground surface and depth of root based on type of crops. The ET is maximum when water table is within ground surface to two foots below the natural surface level but it decreases exponentially with increase in depth to water table. This study estimated evapotranspiration rate using recalculated data from previous studied from DGR (2006). ET area can be divided into five zones as shown in Figure 3-9. The data required for EVT package consist of an ET elevation, an ET extinction depth, and maximum ET rate.

Table 3-5 The hydraulic conductivities for each unit were used in the model, based on a results of pumping test data (DGR, 2006).

Hydrogeologic unit	**Hydrogeologic unit symbol**	**Horizontal hydraulic conductivity (K_x= K_y), m/day**
Floodplain aquifer	Q_{fd}	1.6023
Young terrace aquifer	Q_{yt}	0.6347
Old terrace aquifer	Q_{ot}	0.6347
Colluvium aquifer	Q_{cl}	0.3303
Middle Korat aquifer	J_{mk}	1.7819
Pong Nam Rong aquifer	T_{rpn}	0.7352
Carboniferous meta-Sediment aquifer	C_{ms}	0.1767
Silurian-Devonian Metamorphic aquifer	SD_{mm}	0.7352
Granitic aquifer	G_r	0.3134
Volcanic aquifer	V_c	0.9961

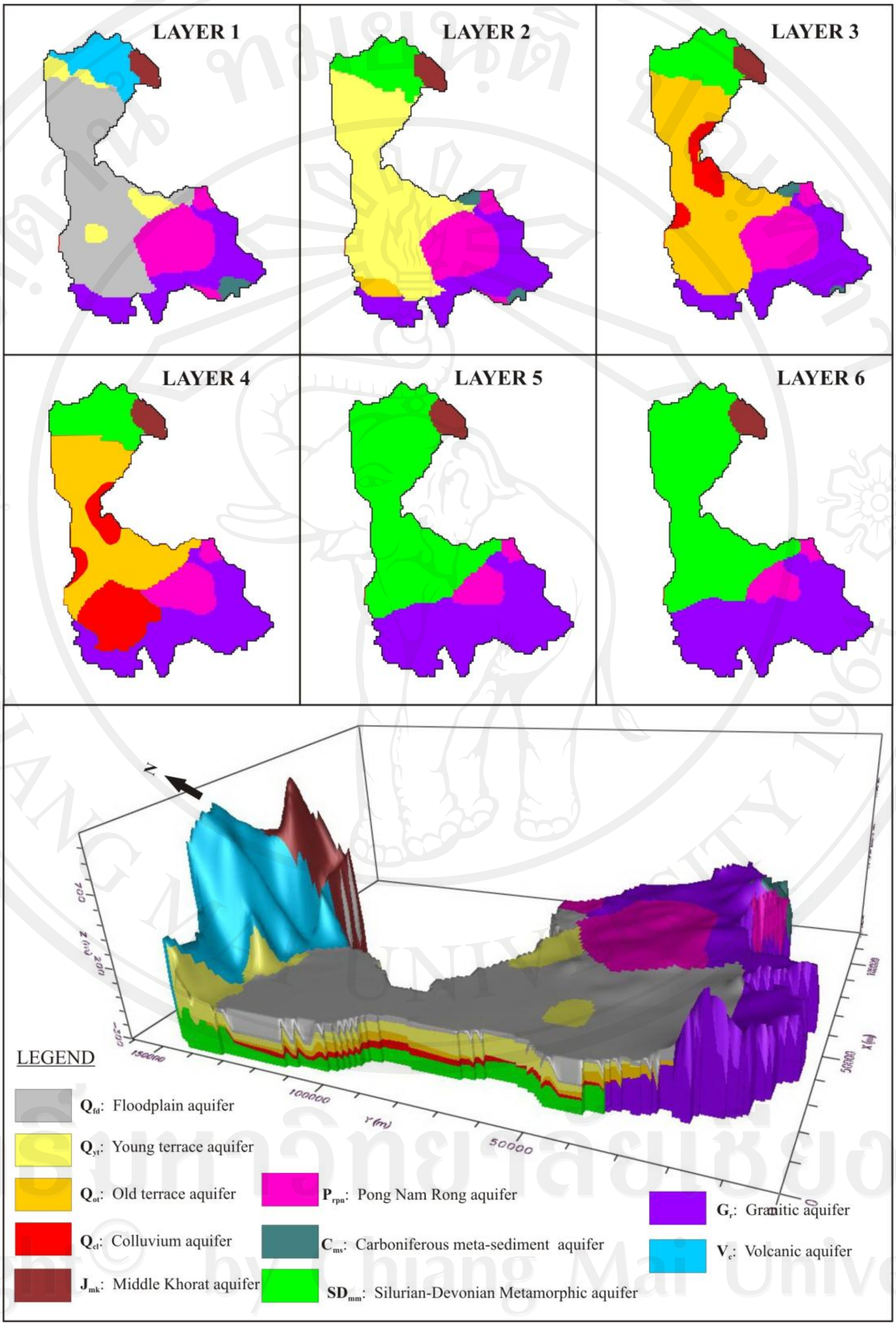
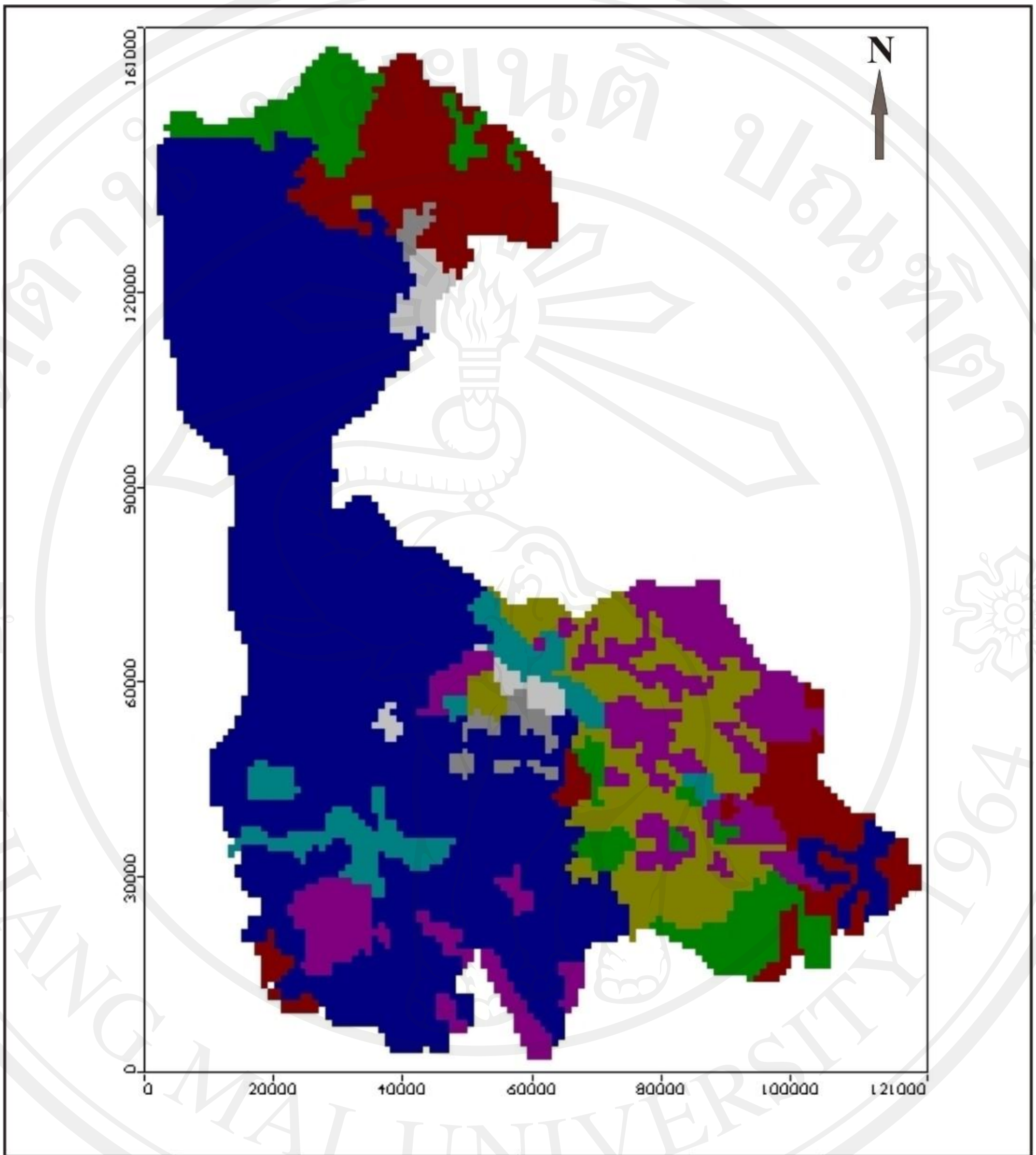
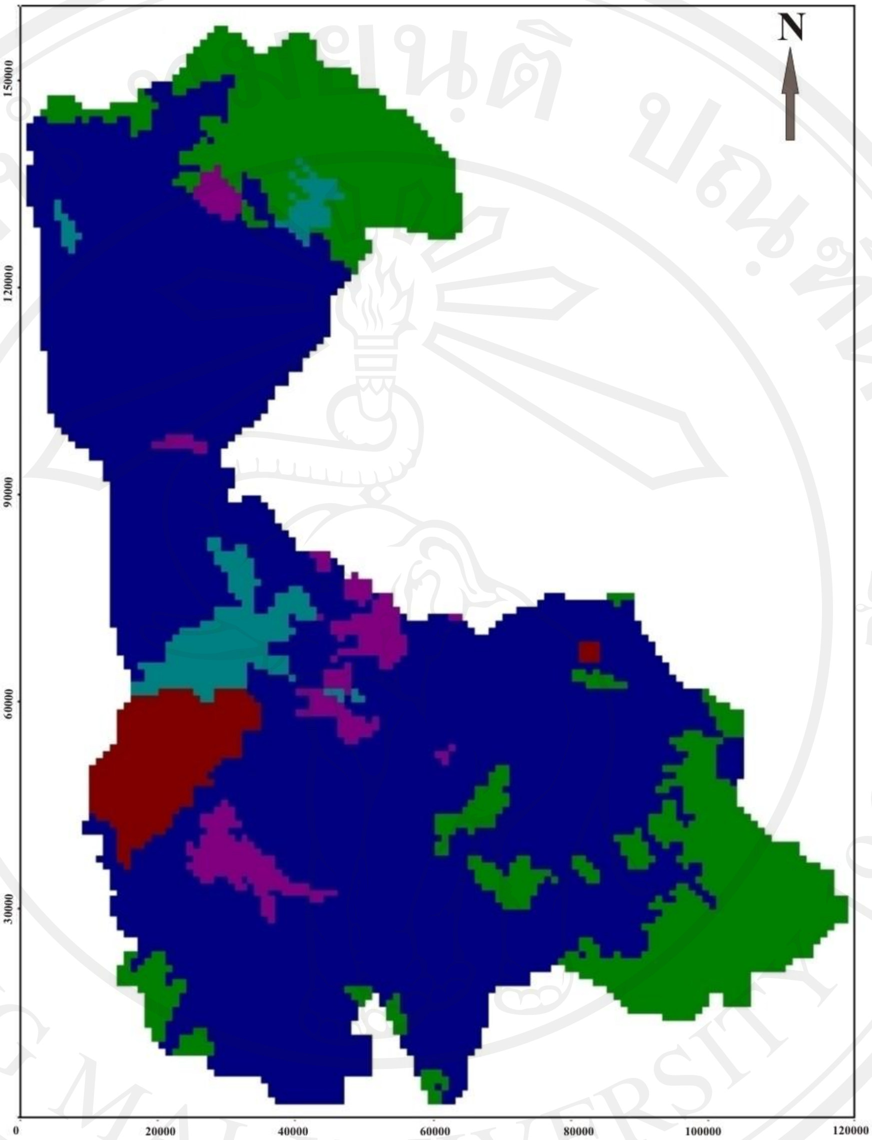


Figure 3-7 Spatial distribution of the hydrogeological parameters (K) in the six layers of the constructed model.



Zone Name	Symbol	Recharge rate (m/d)	Zone Name	Symbol	Recharge rate (m/d)
Zone-1		9.38×10^{-5}	Zone-5		2.83×10^{-5}
Zone-2		8.35×10^{-5}	Zone-6		2.14×10^{-5}
Zone-3		1.76×10^{-5}	Zone-7		5.52×10^{-8}
Zone-4		8.40×10^{-5}	Zone-8		9.07×10^{-6}

Figure 3-8 Map of groundwater recharge (m/d) estimated with the water budget approach (1977-2006), illustrating the spatial distribution of the recharge zone using in this model.



Zone Name	Symbol	ET Extinction Depth, (m)	ET rate (m/d)	ET Surface (m)
Zone 1		0.00	7.22×10^{-5}	Surface Elevation
Zone 2		0.00	3.80×10^{-6}	Surface Elevation
Zone 3		1.00	1.97×10^{-4}	Surface Elevation
Zone 4		1.50	1.00×10^{-5}	Surface Elevation
Zone 5		2.00	1.00×10^{-5}	Surface Elevation

Figure 3-9 Map of Evapotranspiration rate (m/d), illustrating the spatial distribution of the Evapotranspiration zone using in this model.

- **Groundwater Abstraction from Wells**: The main source groundwater discharge is through pumping from public and private groundwater wells. Groundwater is mainly used for irrigation, domestic use, and agricultural purpose. The mostly location of groundwater abstraction are located in the south and north of area as shown in Figure 3-10. The estimation total of groundwater abstraction is 43,670 cubic-meters per day (DGR, 2006). Transferring each pumping well to the grid in the numerical model must be defined using the Well Package, WEL. In this step, it is typically defined a set of selected cells can be specified as wells using the Point Sources/Sinks command in the MODFLOW menu. Wells are specified by assigning a well name, coordinate, pumping rate, and screen elevation. Sometimes the pumping wells are located in the same cell, then, they were summed up to obtain total pumping rating of one representative well.

- **River and Distributaries**: The other sources of groundwater discharge and recharge that affected GW flow in the basin are seepage from surface-water such as canals, distributaries, and main rivers. All the main rivers from north to south in this study area are defined by the special river boundary condition using River Package, RIV Package. A set of selected cells can be specified as river cells using the Point Sources/Sinks command in the MODFLOW menu. It is typically defined as arcs. This condition, on the basis of the relation between the river stage and groundwater level, it simulates the interchange of the flow between river and aquifer. The corresponding of water levels are those of the main rivers and tributaries, which has been measured monthly at gage stations and estimated from the river cross-sections. The river distribution is shown in Figure 3-11. River bed elevation is constant but stage and conductance of riverbed may be varying with time.

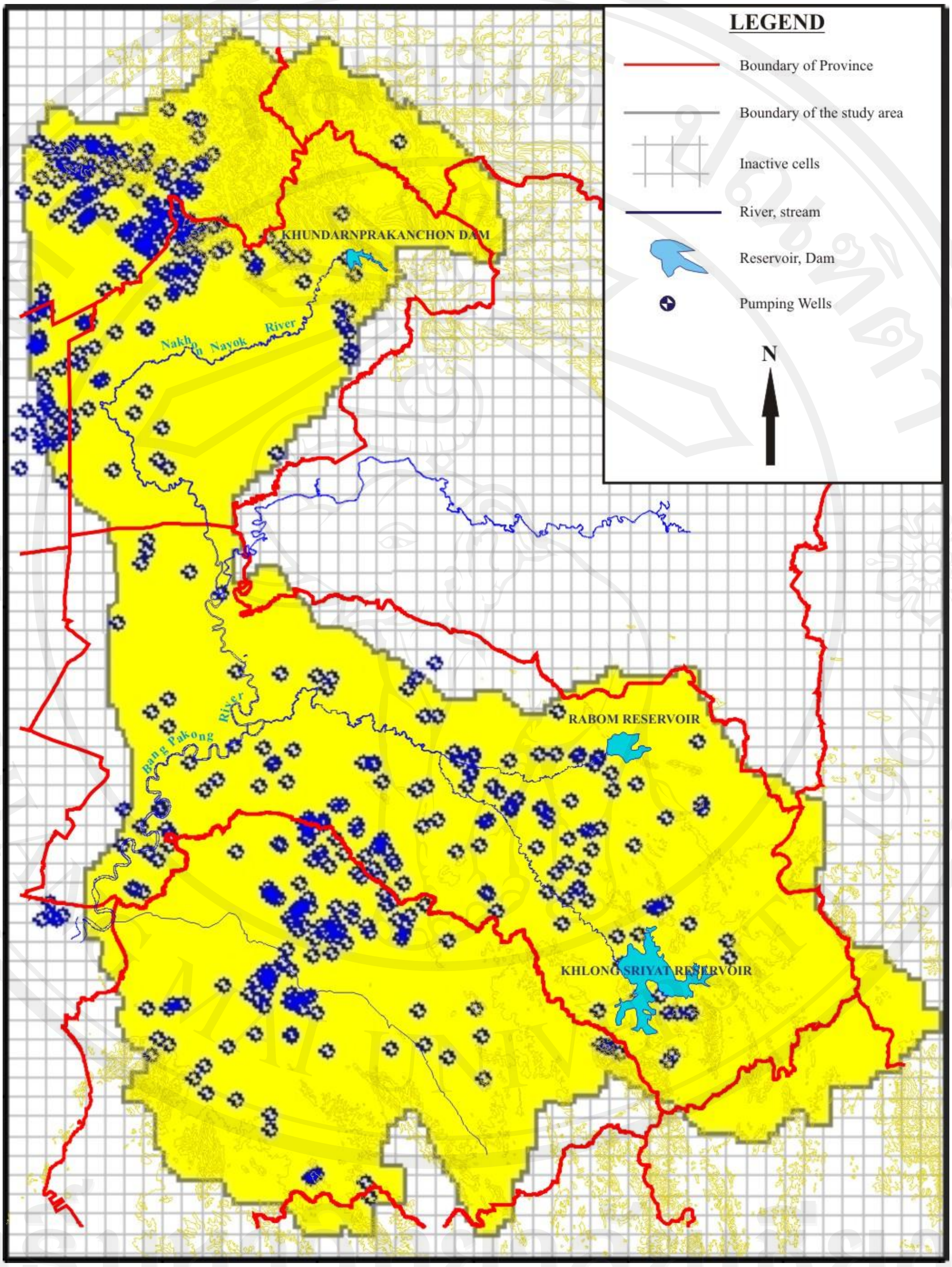


Figure 3-10 Map of the spatial distribution of pumping wells (m^3/d) estimated to use in this model.

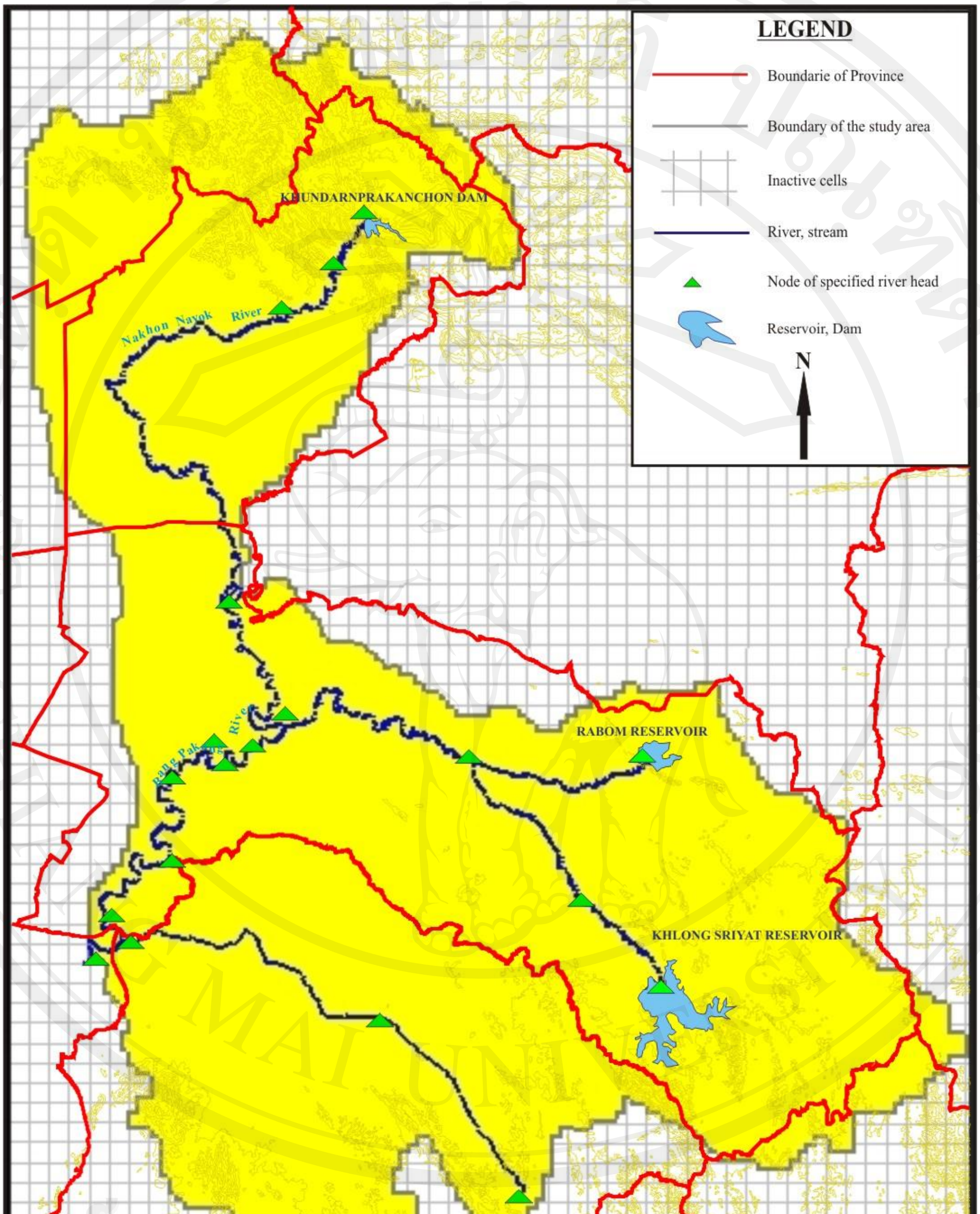


Figure 3-11 Location of main rivers and 19 point stations used for input data in the model.

3.5 Boundary Conditions

Applying correct boundary condition of this model is important for accurate simulation of the hydrogeological conditions. The boundary conditions can be separated into two conditions, physical or natural boundaries and hydraulic boundaries. The physical boundaries of groundwater flow systems are formed by the physical presence of impermeable body of rock or a large body of surface water. The hydraulic boundaries are imaginary boundaries that include specified head boundaries, specified flow boundaries, and head–dependent flow boundaries. Whenever possible the natural hydrogeologic boundaries of the system should be used as the boundaries of the model. In order to simulate boundary conditions, cells are grouped as constant-head cells and inactive (or no-flow) cells. Constant-head cells have a specified value through all time steps of the simulation. Inactive cells do not allow flow into or out of the cell.

3.5.1 Setting and Simulating Boundaries

In steady state simulations, the boundaries solely determine the flow pattern. Thus, the boundaries must be selected such that it can simulate realistic effect. The lateral boundary of the study area is divided into four types; such as no-flow boundary, constant-head boundary, specified–head/flux boundary, and general head boundary (for reservoirs). Figure 3-12 shows the lateral boundary condition for constructing the conceptual model in this study area. In the north, south, and southeast boundaries, they are surrounded by mountain ranges and highland of rock formation. They are formed by the surface water divide. It is quite clear that these boundaries are defined no-flow boundaries. In the east and west boundaries, they are influenced by groundwater flow and seepage from outside. They do not fully correspond to the aquifer groundwater divide. In the west, area is flat and continuous to Chao Phraya Central Plain which groundwater can be exchanged. Similarly, in the east, this area is flat and connects to the Prachinburi river basin where water can be exchanged. The amount of water flow into the study area depends on hydraulic gradient and cross sectional area of the aquifer. By applying the general head boundary, it allows groundwater flow through the boundaries. The general head boundary can be set by assuming other piezometric wells outside the area. However, some part of the edge of model along the western part forms coastline, a constant head boundary was used to approximate the freshwater flowing through the boundary line. A specified head (Dirichlet condition) is simulated by head at the relevant boundary nodes equal to head of Bang Pakong river from the nearest gage station measurement.

The lower boundary condition of the model corresponds to the basis of the rock formation. A null flux (Neumann condition) is imposed in every point because the underlying by Precambrian to Jurassic rock formation. A prescribed impervious boundary is chosen. The upper boundary conditions of the model corresponds to represent of fluxes, volume of water are placed into the block or extracted from the block using wells, recharge rate or leakage from rivers and distributaries on the profile model. The setting and simulating of the boundary conditions are summarized in Table 3-6.

3.5.2 Initial Conditions

Initial conditions refer to the initial value of parameters at the beginning of the simulation. For the steady-state simulations, the values of the head distribution, boundary condition, and parameters in the system are assigned to all active cells in model (see Table 3.7). Initial head should be higher than the elevation of the cell bottom and are consistent with the steady-state model boundary conditions and parameters. When the model calibration under steady-state condition was completed, the resulting will become a new set of the initial conditions for a subsequent transient simulation. Initial heads in transient should closely resemble the head distribution derived from field data. Although initial head is not required for steady-state simulation, it is assigned to the model for efficient-computation for iterative solver purpose.

3.6 Steady-State Model Execution and Calibration

The model execution for this study can be divided into four major steps: (1) developing a model for steady-state simulations; (2) calibrating a model parameters (3) estimating a probability or risk that a certain outcome will occur; and (4) developing a model for transient –state simulations.

Steady-state simulations were carried out to calculate the three dimensional flow fields (i.e., head distribution) over the entire model domain. It is used to recheck and adjust the conceptual model whether it represents of reality system. The simulated heads were compared with hydraulic heads measured from 179 observation wells during 2009. The locations of observation wells for groundwater level monitoring are depicted in Figure 3-13. Model calibration is preformed using PEST, a well-known external model calibrator PEST, to automatically adjust model parameters based on modified Gauss-Newton scheme.

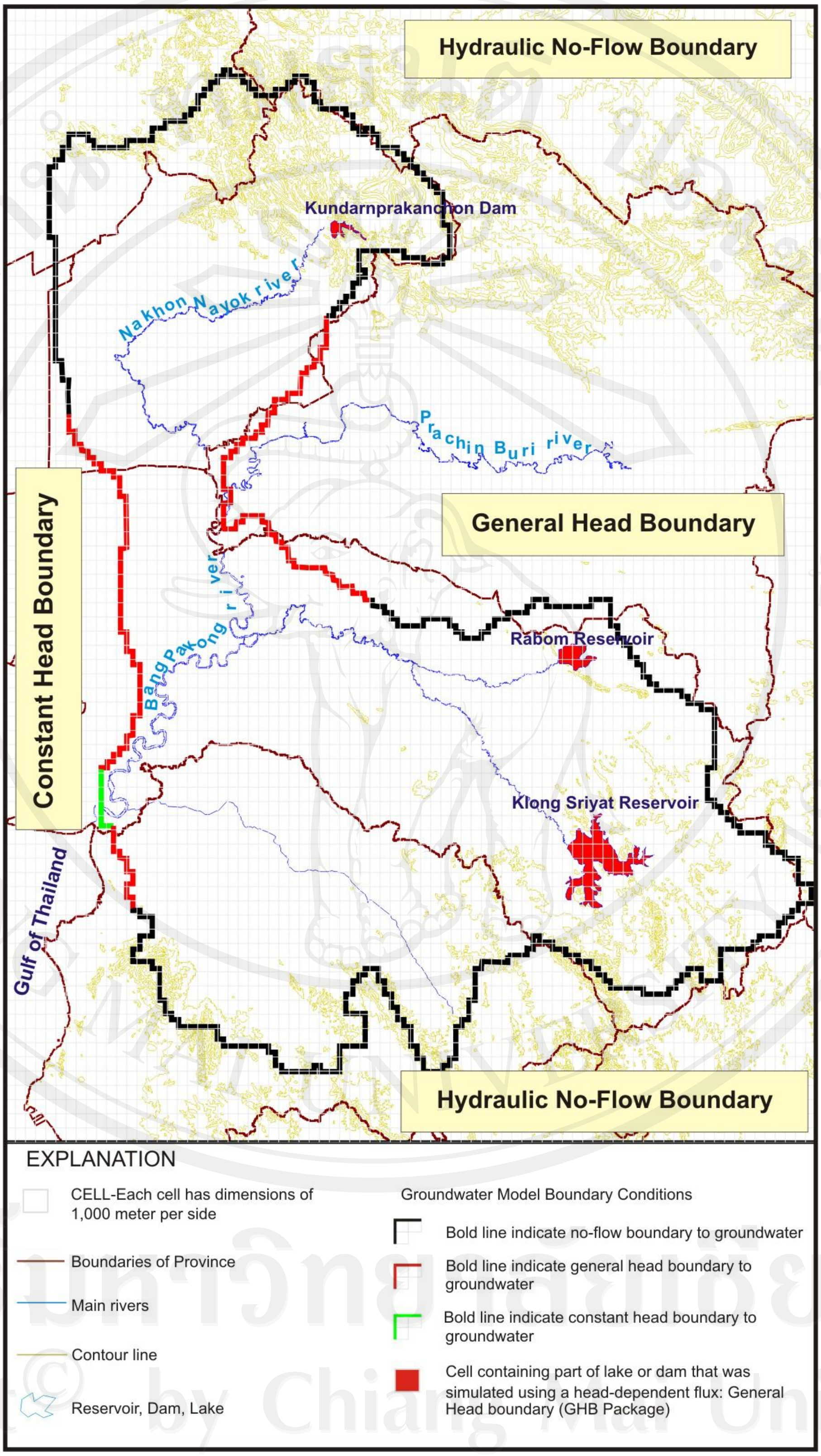


Figure 3-12 Lateral boundaries condition of the groundwater system used in this model.

Table 3-6 Summary of the boundary conditions used in the model.

Area	Description/Detail	Boundary Conditions (BC)
Northern and Southern part	Mountain ranges, bedrock outcrops and Water divides	No flow boundary: specified flow (Neumann condition)
Eastern part	Groundwater divide expanded continuous to Chao Phraya Central Plain	General head boundary: head-dependent flux (Cauchy condition)
Western part	Groundwater divide expanded continuous to Prachin Buri river basin	General head boundary: head-dependent flux (Cauchy condition)
Western part along the coastline	The saltwater/freshwater interface	Constant head boundary: Specified head (Dirichlet condition)
Inside part	Large water bodies: - *Tha Dan Dam* - *Sri Yat Reservoir* - *Klong Rabom Reservoir*	General head boundary: head-dependent flux (Cauchy condition)
The lower boundary of model	Bedrock underlying the modeled system	No flow boundary: specified flow (Neumann condition)
The upper boundary of the model	- Recharge /Infiltration rate - Rivers and Distributaries	- Specified flow boundary (Neumann condition) - head-dependent flux (Cauchy condition)

3.6.1 Model Execution

The steady-state simulation performed in the first stage of groundwater flow modeling. This is traditional approach to investigate the long-term system behavior of a groundwater-dominated watershed. The steady-state modeling refers to the arrival of a condition in the groundwater regime when hydraulic heads are no longer changing and the magnitude and direction of the flow velocity becomes constant with time (Freeze and Cherry, 1979). It is simulated under equilibrium conditions where no change in aquifer storage is observed. Steady-state simulation was carried out to describe the three-dimensional flow field or head distribution over the entire modeling domain. All of hydraulic heads data used in model calibration is average values with in 1 year measurement in 2009.

After reviewing and adjusting initial data set of parameter values and boundary conditions that is used of the DGR previous studied (2006), this study decided to constraint the range of recharge rate, the range of hydraulic conductivity values from pumping test, and conductance of riverbed material. The initial set of all parameter values from previous studied (DGR, 2006) where the previously developed model was adjusted using trial and error method. Once the model was successfully executed and the reasonable head distribution is obtained, it is appropriated to proceed to the next step; a model calibration step.

3.6.2 Model Calibration

The model calibration procedure used in this study is automated estimation parameter. During calibration, the model parameters are varied in a systematic, iterative manner and model simulated heads are compared with field observed head to identify the set of model parameters and features. The system parameters were

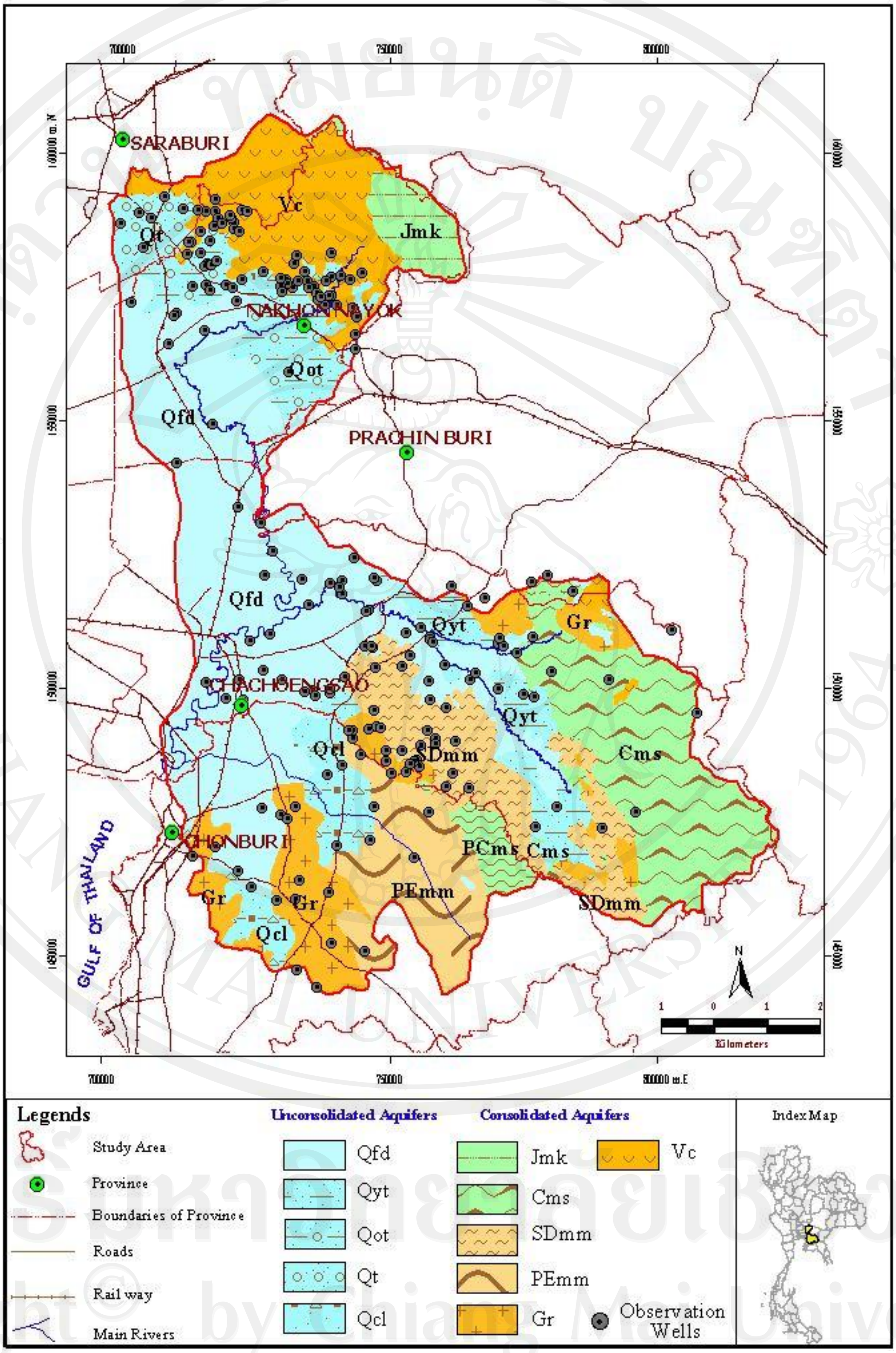


Figure 3-13 Location of observation wells for groundwater level monitoring.

calibrated in order to achieve the best fit between the numerical solution and the historical data. The following steps involved in setting up for developing a calibration simulation of this study using (1) Create a parameter set list and (2) Set parameter estimation options as described this document below. It actually searches a parameter set for which the sum of squared deviations between model-calculated and observed values at the observation wells is reduced to a minimum. The calibrated simulations are stopped until the model-generated heads fit the heads of observation values as close as possible. The parameter estimation was based on observation of hydraulic head from 179 observation wells measure in 2009 (see Appendix A).

In this study, it required 35 parameters that have been delineated to calibrate the steady-state model as shown in Table 3-7. During execution PEST, the parameter values are adjusted according to the control setting as shown in Table 3-8. When the optimization process is completed and one of the termination criteria have been met, PEST then writes some information concerning the optimized parameter set to its run record file.

Table 3-7 List of the initial parameters value used in steady-state and parameter estimation with PEST for this study.

No.	Parameter name	Description	Package name	Parameter values
1	HK-1	Horizontal hydraulic properties: Floodplain aquifer unit (Q_{fd})	LPF	1.6023
2	HK-2	Horizontal hydraulic properties: Young terrace aquifer unit (Q_{yt})	LPF	0.6347

Table 3-7 (Continued)

No.	Parameter name	Description	Package name	Parameter values
4	HK-4	Horizontal hydraulic properties: Old terrace aquifer unit (Q_{ot})	LPF	0.6347
5	HK-5	Horizontal hydraulic properties: Colluvium aquifer unit (Q_{cl})	LPF	0.3303
6	HK-6	Horizontal hydraulic properties: Silurian-Devonian metamorphic aquifer unit (SD_{mm})	LPF	0.7352
7	HK-7	Horizontal hydraulic properties: Middle Korat aquifer unit (J_{mk})	LPF	1.7819
8	HK-8	Horizontal hydraulic properties: Carboniferous meta-sediment aquifer unit (C_{ms})	LPF	0.1767
9	HK-9	Horizontal hydraulic properties: Pong Nam Rong aquifer unit (Tr_{pn})	LPF	0.7352
10	HK-10	Horizontal hydraulic properties: Granitic aquifer unit (G_r)	LPF	0.3134
11	HK-11	Horizontal hydraulic properties: Volcanic aquifer unit (V_c)	LPF	0.9961
12	VK-26, VANI-12	Vertical hydraulic properties Vertical anisotropy	LPF	1.00 1.00
13	RCH-18	Recharge rate: Zone-1	RCH	9.38E-05
14	RCH-19	Recharge rate: Zone-2	RCH	8.35E-05
15	RCH-20	Recharge rate: Zone-3	RCH	1.76E-05
16	RCH-21	Recharge rate: Zone-4	RCH	8.40E-05
17	RCH-22	Recharge rate: Zone-5	RCH	2.83E-05
18	RCH-23	Recharge rate: Zone-6	RCH	2.14E-05

Table 3-7 (Continued)

No.	Parameter name	Description	Package name	Parameter values
19	RCH-24	Recharge rate: Zone-7	RCH	5.52E-08
20	RCH-25	Recharge rate: Zone-8	RCH	9.07E-06
21	EVT-13	Evapotranspiration rate: Zone-1	EVT	7.22E-05
22	EVT-14	Evapotranspiration rate: Zone-2	EVT	3.80E-06
23	EVT-15	Evapotranspiration rate: Zone-3	EVT	1.97E-04
24	EVT-16	Evapotranspiration rate: Zone-4	EVT	1.00E-5
25	EVT-17	Evapotranspiration rate: Zone-5	EVT	1.00E-5
26	RIV-32	Nakhon Nayok river, Conductance of RIV cells	RIV	10000
27	RIV-33	Bang Pakong river, Conductance of RIV cells	RIV	10000
28	RIV-34	Luang canal, Conductance of RIV cells	RIV	10000
29	RIV-35	Sri Yat canal, Conductance of RIV cells	RIV	10000
30	RIV-36	Rabom canal, Conductance of RIV cells	RIV	10000
31	GHB-27	General head boundary, Tha Dan Dam	GHB	10000
32	GHB-28	General head boundary, Khlong Rabom reservoir	GHB	10000
33	GHB -29	General head boundary, Sri Yat reservoir	GHB	10000
34	GHB -30	General head boundary, flow into or out of Prachin Buri river basin	GHB	1000
35	GHB -31	General head boundary, Coastline	GHB	1000

Table 3-8 Initial control settings used in parameter estimation (PEST) for steady-state calibration.

Parameter estimation options	**Value**
Initial lambda	10.00
Lambda adjustment factor	2.00
Sufficient new/old Phi ratio per optimization iteration	0.30
Limiting relative Phi reduction between lambdas	1.00E-02
Maximum trial lambdas per iterations	8
Maximum number of optimization iterations	25
PEST error tolerance (using Euclidean L2 integral NRMS)	0.10E-02

3.7 Uncertainty Analysis of Groundwater Budget Using Monte Carlo Technique

After the model was successfully calibrated, a groundwater budget can be calculated based on the hydraulic heads obtained from the simulation and the boundary conditions. However, the values of groundwater budget obtained from a single model run simply and indicate the total amount of water flowing into or flowing out of the groundwater system without showing a possible range (e.g., 95% confidence interval). Further analysis is required to analyze water budget's uncertainty in the basin.

The uncertainty in groundwater budget calculation may arise from the uncertainty of the model's parameter values. This uncertainty can be viewed as incomplete information in model simulation and, of course, could be reduced by additional sampling and data analysis. For example, if parameter field is known exactly at every point, the uncertainty is zero, but the spatial variability in parameter field still exists (Delhomme, 1979). In describing any groundwater system using mathematical model, the uncertainty in specifying a parameter may depend on spatial variability of the zonal hydraulic conductivities, zonal recharge values, hydraulic conductance in other boundaries.

The uncertainty analysis in the groundwater modeling of the Bang Pakong river basin in this study was evaluated using Stochastic Modeling tools (more specifically, Monte Carlo option) in GMS® where parameters (after calibration) were treated as normally distributed random functions as shown in Equation (3-1). Note that a normal distribution of a parameter x can be defined as:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \qquad (3\text{-}1)$$

where σ is the standard deviation, μ is the mean, and x is the value being sampled. The above equation can be used for both native and log-transformed parameters.

The approach of evaluating model uncertainty is to generate multiple sets (in the order of tens to thousands sets) of parameter values and input into the model. The resulting groundwater budgets will be recorded and analyzed for their uncertainty envelop. Random sampling, the most widely used approach for generating multiple random model simulations, was used to generate a set of parameter values. To set up the random sampling, it is needed to specify the mean and standard deviation for each parameter. Then, a number of sets or realizations or model runs can be specified. The mean values of the parameter are the optimized values obtained from model calibration process. The standard deviation, on the other hand, can be calculated from a specified value of coefficient of variation (*CV*) where

$$CV = \frac{s}{\bar{x}} \tag{3-2}$$

The coefficient of variation is a statistical parameter that can be used to indicate the distribution of a parameter around the mean. If the value of *CV* is high, the parameter is considered highly uncertain. In geostatistics, the coefficient of variation has been widely used to investigate spatial variability of soil hydraulic properties, natural recharge, etc. (Agyare, 2004; Johnston et al., 2009). Studies have also suggested that the hydraulic conductivity having a *CV* value as high as 1.0 (or 100%) can be considered as highly uncertain (or highly heterogeneous). In this study, a range of CV value of 1.0 was picked indicating that a high uncertainty of the model is being evaluated. Once the value of mean and standard deviation were obtained, multiple sets of Monte Carlo simulations can be conducted.

However, the question of how many model runs is suitable or sufficient for evaluating uncertainty may arise. To answer this question, a number of datasets were chosen as 50, 100, 250, 500, 750, 1000 and 1500 (to evaluate the most suitable number of model runs). The average water budget or each set were plotted against the number of model runs (i.e., realizations). Groundwater budget was expected to fluctuate early and smooth out when the number of model runs increases. The number of model runs at the point where average groundwater budget stabilizes should be the answer of above question. Lastly, the statistical analyses of water budget can be performed. The results of this section will be presented in Chapter 4.