CHAPTER 5

GROUNDWATER MODELING

5.1. Groundwater Modeling

5.1.1. Modeling approach

The techniques of groundwater modeling are employed for a sub basin-wide groundwater management in order to come up with appropriate strategies for prevention of negative effect of groundwater abstraction. The Visual Modflow software version 3.1. is used to make simulation for 3-D groundwater flow in the research area.

After defining the purpose, the model is established based on accurate hydrogeological investigations and analyses. Appropriate boundary conditions and geohydrologic parameters are assigned to the model. Initial calibration for the model is carried out by steady-state simulation to understand the model behaviour. The assigned boundary conditions and the input parameters are checked and/or modified by comparing between computed piezometric heads and the observed piezometric heads.

After preparing the historical pumpage data from 1993 to 2003, the model is carefully calibrated by transient simulation. In the process, some earlier assumed parameters and boundary conditions are finally fixed. The historical calibration is carried out using the input pumpage data. The calibration continued until the computed piezometric heads agreed satisfactorily with the observed data.

These calibrated models can be used to predict future groundwater flow and piezometric heads based on future groundwater pumpage plan.

5.1.2. Conceptual model

Conceptual model is an illustration of the general condition of groundwater flow system and hydrogeological unit, in the block or cross section hydrogeology. The aim of conceptual model is to simplify of the problem and field data organizer, so the system can be analysed easily. Simplified the model is an important step because the detail reconstruction on hydrogeology system in the research area is impossible. Three steps to develop a conceptual model are (1) determining the hydrostratigraphic unit; (2) determining input and output factors of groundwater flow; (3) determining flow system

(Anderson & Woessner, 1992). Conceptual model of the research area is illustrated in Figure 5.1.

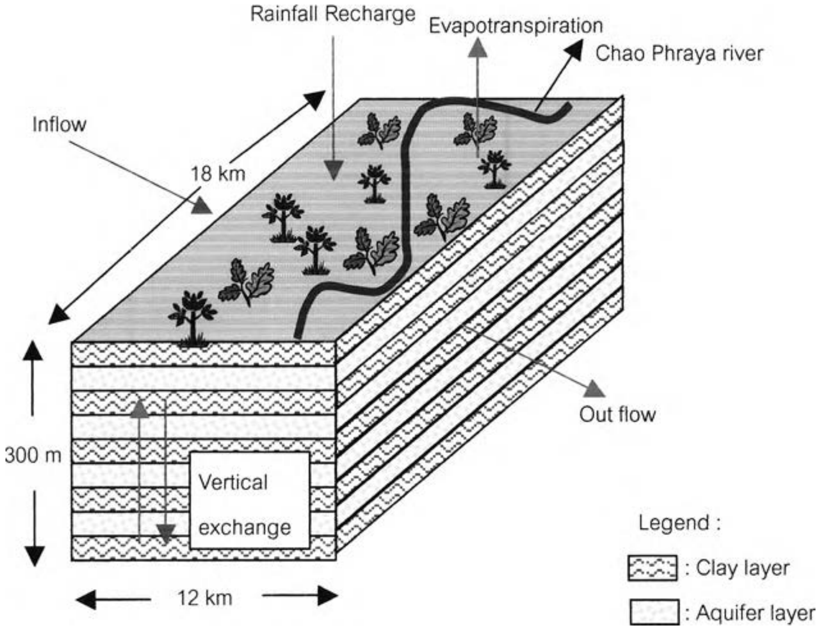


Figure 5.1. Conceptual model.

Four aquifers are presented in the conceptual model. The first aquifer is Bangkok aquifer located on the top of the model, and is confined by clay layers on top and bottom. It is considered as semi-confined aquifer. The second, third and fourth are Phra Padaeng aquifer, Nakhon Luang aquifer and Nonthaburi aquifer respectively. They are confined aquifers, as the clay layers on top and bottom boundaries as confining beds. The horizontal boundaries of each layer are defined using hydrogeological condition obtained from geological data and well log data. It is important to note that the attempt of grouping the hydrogeologic units together is made based not only on the lithologic and hydrogeological properties of aquifer but also their consistency with the already existed hydrogeologic maps of the research area.

5.1.3. Assumption of the model

It is understood that the numerical model has some limitations. The limitations are shown when generalization of the model is made. Therefore, some assumptions have to be made to accommodate this implication. Such assumptions are:

- The boundary of the model is determined based on the result from contouring the groundwater table data that available in the research area.
- Each layer of aquifer and clay are homogenous and isotropic.
- The recharge rate is assumed 10% from the total rainfall.
- Pumping rate is constant.
- Calibration is conducted based on the parameter values that still acceptable with the field condition.
- Interpolation and extrapolation from the field data are used for completing the input data for simulation.
- The value from the model simulation is relative and not absolute.

5.1.4. Model grid

Because of the study area is situated at the Lower Central Plain, it is necessary to consider the hydrogeological conditions of the Lower Central Plain in order to include the effect of regional groundwater flow in the model. The knowledge of regional hydrogeological conditions allows a better judgment in assigning boundary conditions along boundaries of research area. It is observed that the groundwater flow within the study area is affect by the groundwater flow outside the study area, especially along the northern and western boundaries. Therefore, in this study, the grid orientation is rotated around 20° in the clockwise direction to adjust with the boundary conditions. The model grid is constructed as shown in Figure 5.2.

The grid size in the study is fixed at 500 m x 500 m. The grid size is refined to 250 m x 250 m at Khong Phraya Bunlue. A total number of cells in each layer are 1209 (39 rows x 31 columns). The model area divided into 9 layers based on the hydrogeological classification. The total number of 3-D cell is 10,881. The structure of the 3-D model is presented in Figure 5.3., and Table 5.1. summaries the model grid construction. Map of surface elevation of each layer is attached in Appendix 1.

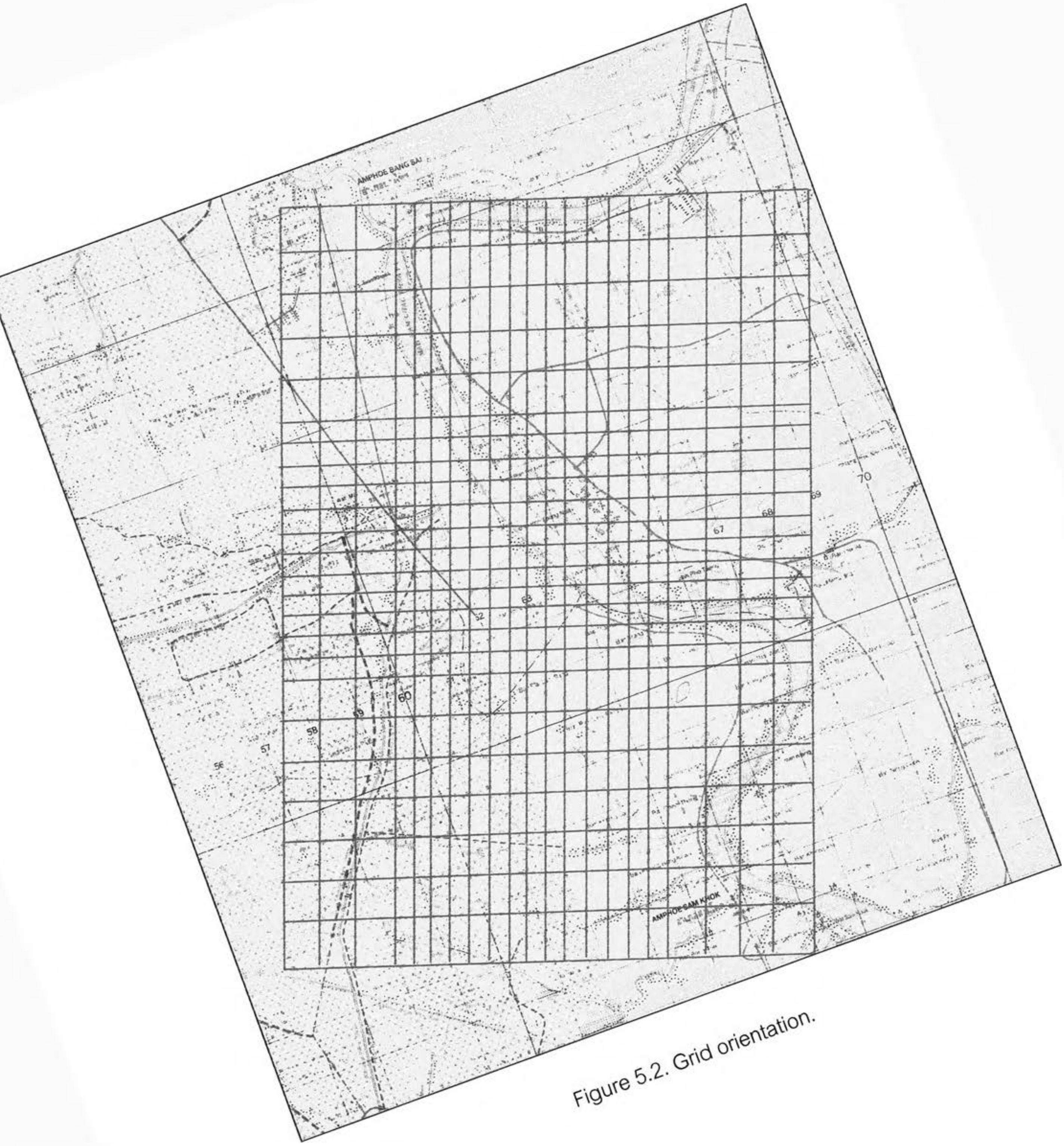


Figure 5.2. Grid orientation.

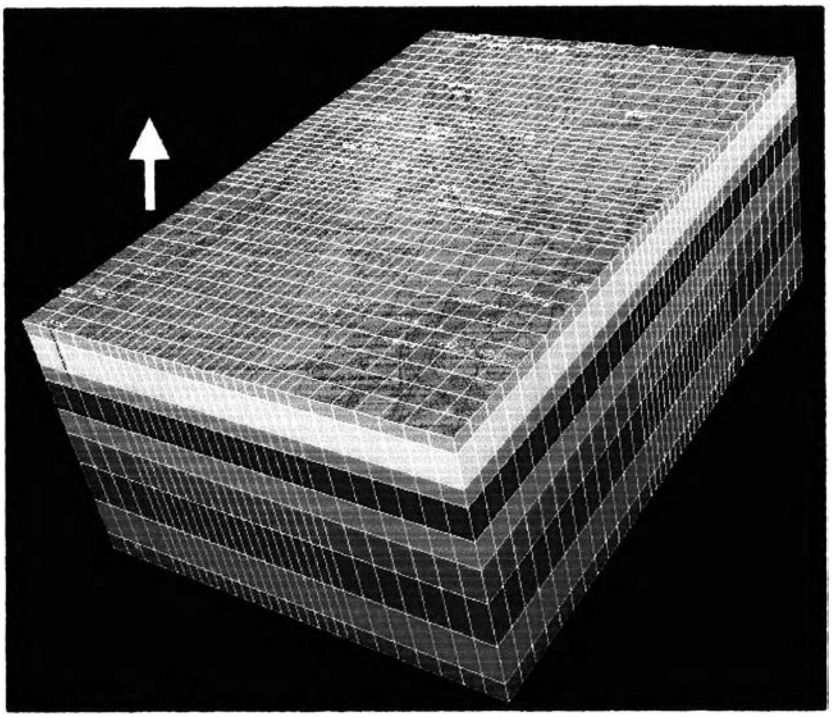


Figure 5.3. A 3-D model of the research area.

Table 5.1. The model grid construction.

Parameters	Amount	Width (meters)
Row	21	500
	18	250
Column	11	500
	20	250
Layer Number	**Minimum depth (meters below SWL)**	**Maximum depth (meters below SWL)**
1	3	28
2	40.4	68
3	46.9	85
4	71.3	149
5	109.2	150
6	160	223
7	175	250
8	250	297.2
9	300	300

Source: Primary Analysis, 2004

5.1.5. Flow boundary condition

Setting boundary conditions is the step in the model design that is most subject to serious error (Franke et al, 1987). Determining the flow boundary system is important in the planning of numerical model. Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. In the steady state condition, the boundary condition has a big effect for groundwater flow.

In this study, appropriate boundary conditions are specified for numerical calculation based on the hydrogeological information. From the original outset, the extent of each aquifer unit is defined based on the geological studies done in the previous stage. Since the physical boundaries do not exist in the research area, so hydraulic boundaries are applied for simulation. The hydrogeological boundaries in this model are no flow boundary, constant heads, recharge, evapotranspiration and river boundary. Table 5.2. presents the boundary conditions in the model.

Table 5.2. A summarized of boundary conditions.

Number	Boundary	Boundary condition
1	North-West	Constant head
2	South-East	Constant head
3	North-East	No flow
4	South-West	No flow
5	First layer	Recharge
6	First layer	Evapotranspiration
7	Chao Phraya river	River (constant flux)

Source: Primary Analysis, 2004

No flow boundaries in the model are located in the Northeast and Southwest. Based on the groundwater flow map (Figure 4.7.), the directions of groundwater flow in all aquifers are come from Northwest direction. Therefore, these are no inflow from the Northeast and Southwest directions since they are parallel to flow direction.

The constant head boundaries are located in the Northwest and Southeast of the model area. Because of the difficulties in measuring the groundwater table in the model boundaries, the groundwater table is extrapolated from monitoring wells. The details constant head in each aquifer are summarized in Table 5.3.

Table 5.3. Constant head values in the model.

Aquifer	North-West		South-East	
	Start (m. SWL)	Finish (m.SWL)	Start (m.SWL)	Finish (m.SWL)
Bangkok	-7	-8	-8	-9
Phra Padaeng	-14.5	-20	-20	-26
Nakhon Luang	-17	-22.5	-21.5	-24
Nonthaburi	-17	-27	-22.5	-25

Source : Groundwater flow map 1993 and 2003

Recharge into the model mainly come from rainfall infiltration and some part from the Chao Phraya river. It is very difficult to measure the rate of infiltration from the field. The assumption is made that only 10% from the rainfall infiltrates to the ground, and the rate of infiltration is the same for all areas. Refers to the rainfall data in the research area that available from 1993 until 2003, the infiltration rate is adjusted accordingly.

Evapotranspiration is calculated based on the data on the year 1994, since it is only data available. It uses as an input into the model and is not change for over the years.

Chao Phraya river is digitized and presented as river boundary in the model. River yield information from monitoring stations in Bang Sai and Muang stations are used to determine the river stage value. The width of river is 400 meters and constant along the study area, with depth of 4.5 meters based on the data from Irrigation Department. Providing these information the conductance of Chao Phraya river is determined at 323.875 m^3/day.

5.1.6. Hydrologic parameters

The parameters of aquifer consist of porosity, specific storage and hydraulic conductivity. Assumption is made that the aquifers and aquitards are homogenous and isotropic. The values of parameters are obtained from the analysis of pumping test data from the field and are inferred from the previous study. Because of the situation and condition on the site, the pumping test is only conducted at Nonthaburi aquifer. The hydraulic parameters of aquifers and aquitards used as an input to the model are summarized in Table 5.4.

Table 5.4. Input parameters for the initial model.

No.	Layer	Hydraulic conductivity (m/day)	Specific storage (1/m)	Source of Data
1	First layer	4.65×10^{-2}	6.75×10^{-3}	JICA
2	Bangkok aquifer	13.7	1×10^{-4}	JICA
3	Phra Padaeng clay	1.77×10^{-6}	2.12×10^{-4}	JICA
4	Phra Padaeng aquifer	17.8	1×10^{-4}	JICA & AIT
5	Nakhon Luang clay	9.01×10^{-7}	1.67×10^{-4}	JICA
6	Nakhon Luang aquifer	16.1	1×10^{-4}	JICA & AIT
7	Nonthaburi clay	7.29×10^{-7}	1.15×10^{-4}	JICA
8	Nonthaburi aquifer	22.72	1.29×10^{-4}	Field analysis
9	Sam Khok clay	3.33×10^{-7}	7.72×10^{-5}	JICA

Source : Compilation data, 2004

5.1.7. Steady state simulation

A steady state simulation is developed based on the data in the year 1993, as initial time. The groundwater levels of aquifers are determined from the water level observed in monitoring wells (see Figure 4.7). Based on the contouring of groundwater table, the flow direction and the initial boundary for modeling are determined.

For the calibration model, the monitoring wells located inside the research area are used. There are 6 monitoring wells within the research area, two monitoring wells for each aquifer. The detail information of monitoring wells is summarized in the Appendix 3.

5.1.8. Transient simulation

The transient simulation is carried out employing the result of groundwater level from the steady state simulation as initial condition. The calibration of the model is conducted using data from the year 1993 until 2003. The calibration is processed in consideration of rainfall data and groundwater level monitoring data. Due to the incomplete information of pumping rate and pumping schedule of groundwater wells located within the research area, therefore, the assumption is made that the information of the incomplete data wells are interpolated from the closest wells. And, they are assumed to have a constant pumping rate throughout the period of 1993 to 2003.

5.1.9. Model calibration

Model calibration is carried out in the steady state simulation and in transient simulation. The accuracy of calibration is determined by a comparison between observed values and calculated values in the model. The different between observed values and calculated values are calculated using statistical analysis. ARM (Absolute Residual Mean) and NRMS (Normalized Root Mean Square) are used to calculate the error of calculation.

ARM is a measure of the average absolute residual value defined by the equation :

$$\left|\bar{R}\right| = \frac{1}{n}\sum_{i=n}^{n}\left|R_i\right|$$

where is R_i is the calibration residual.

The ARM measures the average magnitude of the residuals and therefore provides a better indication of calibration than the residual mean.

NRMS is the root mean squared divided by the maximum difference in the observed head values and is expressed by the equation :

$$\mathrm{NRMS} = \frac{\sqrt{\frac{1}{n}\sum_{i=n}^{n} R_i^2}}{(X_{obs})_{\max} - (X_{obs})_{\min}}$$

The NRMS is expressed as a percentage and is a more representative measure of the fit than the standard root mean squared because it accounts for the scale of the potential range of data values.

Calibration target for steady state simulation is set within ARM and maximum error of estimation values less than 1 meter. Calibration for transient simulation is set within ARM less than or equal to 1.5 meter and NRMS less than 25%. The calibration is applied step by step starts from the upper layer of Phra Padaeng aquifer to the lower layer of Nonthaburi aquifer. This step minimizes the effect from upper layer aquifers.

Sixth monitoring wells with recorded data from 1993 to 2003 are used in the calibration process to match with the recharge data. The detail observed values from 1993 to 2003, on each monitoring well are attached in Appendix 3.

Phra Padaeng aquifer has two monitoring wells, which are PD 68 and PD 74. Nakhon Luang aquifer also has two monitoring wells, which are NL 12 and NL 78. And, Nonthaburi aquifer has two monitoring wells, which are NB 69 and NB 13. The details of well location and screen position are summarized in Table 5.5.

Table 5.5. Monitoring wells in the modeling area.

No.	Well Code	Easting	Northing	Screen Position (meters. below SWL)
1.	PD 68	665126	1569470	-91.5
2.	PD 74	663979	1562320	-110
3.	NL 12	665120	1569478	-145
4.	NL 78	663970	1562311	-160
5.	NB 69	665126	1569478	-225
6.	NB 13	663979	1562311	-186

Source : Groundwater Department Thailand, 2003

5.1.10. Calibration of Groundwater Flow Model in the Steady State Condition

The model is developed from the result of stratigraphic modeling with parameters input from pumping test analysis and from previous study, and is called base case model. The calibration process is carried out in the basecase model. The hydraulic conductivities of observed aquifers are varied, while other parameters remain constant. Note that, in short time the effect of the recharge from rainfall is not significant and can be neglected because all aquifers in the research area are confined aquifer. This can be reconfirmed from the result provided from monitoring wells in Phra Padaeng aquifer where there is no changed in groundwater level during the pumping carried out on Nonthaburi aquifer. The hydraulic conductivity is varied based on the value that still acceptable with field condition.

Method of calibration uses a trial and error method. Calibration process of hydraulic conductivity parameter is applied to for Phra Padaeng aquifer, Nakhon Luang aquifer and Nonthaburi aquifer, which are target aquifers. The hydraulic conductivity in each aquifer is scale down and up to 10 times the magnitude from the basecase value. The details of hydraulic conductivity for each calibration are summarized in Table 5.6.

Table 5.6. Groundwater flow models and its hydraulic conductivity parameter.

No.	Case Model	K (m/day) Phra Padaeng	K (m/day) Nakhon Luang	K (m/day) Nonthaburi
1	Basecase	17.8	16.1	27.22
		Phra Padaeng aquifer		
2	Model 1	1.78	16.1	27.22
3	Model 2	8.9	16.1	27.22
4	Model 3	12.46	16.1	27.22
5	Model 4	35.6	16.1	27.22
6	Model 5	89	16.1	27.22
7	Model 6	178	16.1	27.22
		Nakhon Luang aquifer		
8	Model 7	178	1.61	27.22
9	Model 8	178	8.05	27.22
10	Model 9	178	11.27	27.22
11	Model 10	178	32.2	27.22
12	Model 11	178	80.5	27.22
13	Model 12	178	161	27.22
		Nonthaburi aquifer		
14	Model 13	178	161	2.722
15	Model 14	178	161	13.61
16	Model 15	178	161	19.054
17	Model 16	178	161	54.44
18	Model 17	178	161	136.1
19	Model 18	178	161	272.2

Note : all parameters in other layer are the same as basecase model.

Actually, after running the basecase model with input values from the field and previous analysis yields an acceptable result, because the absolute error of estimation is less 1 meter for all layers. However, the variation of hydraulic conductivity value is still carried out in calibration process to find the best model and to understand the effect of hydraulic conductivity value variation.

The results of calibration of Phra Padaeng aquifer are showed in Figures 5.4 and 5.5. Based on the Figures, the best of model is obtained in model 6 with hydraulic conductivity of 178 m/day. The value of ARM is 0.785 meters, and NRMS is 36.067%. The maximum absolute error of estimation in this model is 0.876 meter.

Figures 5.6 and 5.7 illustrate the results of calibration simulation in the Nakhon Luang aquifer. From the Figures, they show that the best simulation could be obtained in model 12 with hydraulic conductivity of 161 m/day. The value of ARM is 0.764 meter, and NRMS is 179.382%. The maximum absolute error of estimation in this model is 0.868 meter.

The results of calibration of Nonthaburi aquifer are illustrated in Figures 5.8 and 5.9. From the Figures, the best simulation model is model 14 with hydraulic conductivity of 13.61 m/day. The value of ARM is 0.613 meter, and NRMS is 41.706%. The maximum absolute error of estimation in this model is 0.619 meter.

ARM and NRMS of the final model in the steady state simulation are 0.747 meter and 16.818 % respectively. The absolute maximum error is 0.912 meter.

The results of all layers show that by increasing the hydraulic conductivity value greater than the basecase value has a small effect on calibration results. Only the hydraulic conductivity that less than the basecase value has significant impact on calibration results. The calibration statistics converges sharply from models 1, 7 and 13, then they became stable or very small effect. This behavior is observed for all target aquifers. The results of groundwater modeling are presented in Appendix 4.

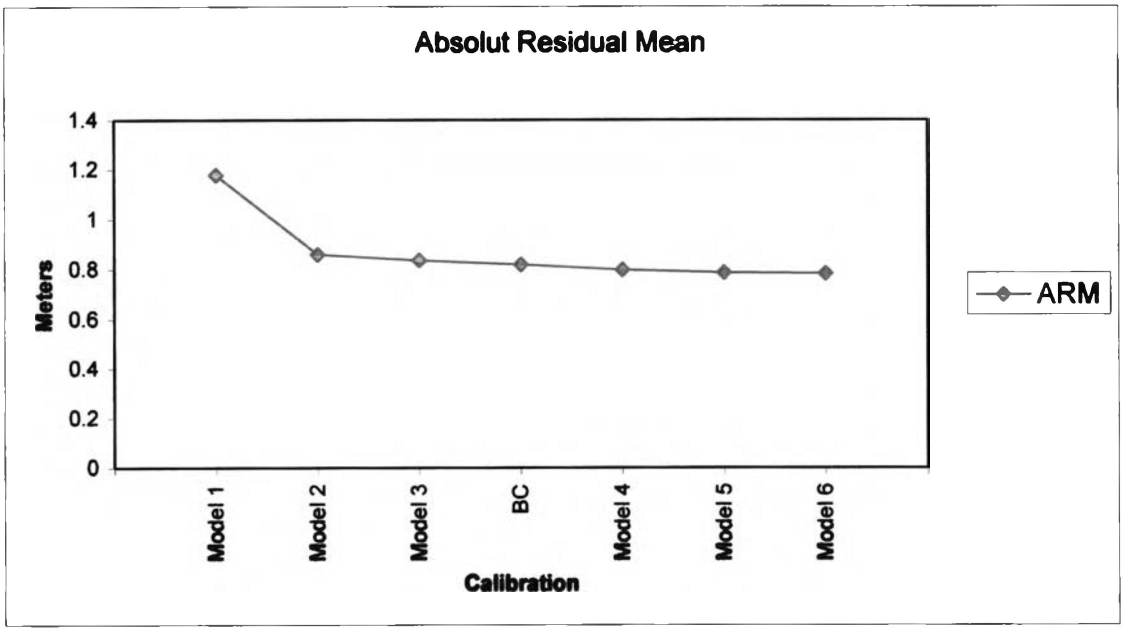


Figure 5.4. Absolute residual mean at Phra Padaeng aquifer

in the steady state condition.

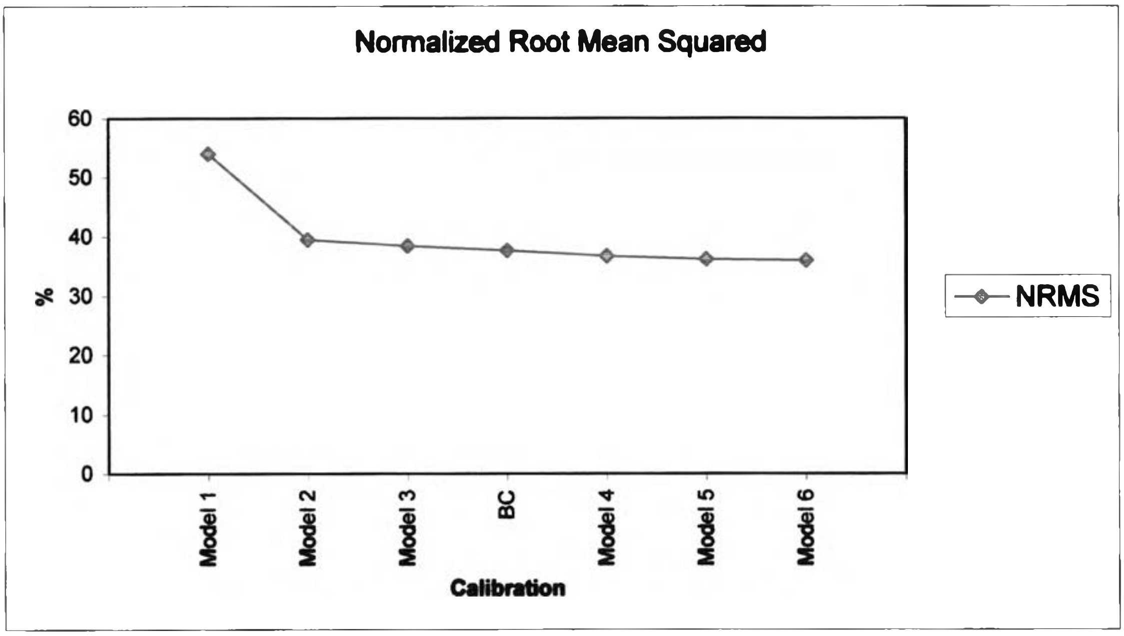


Figure 5.5. Normalized root mean squared at Phra Padaeng aquifer

in the steady state condition.

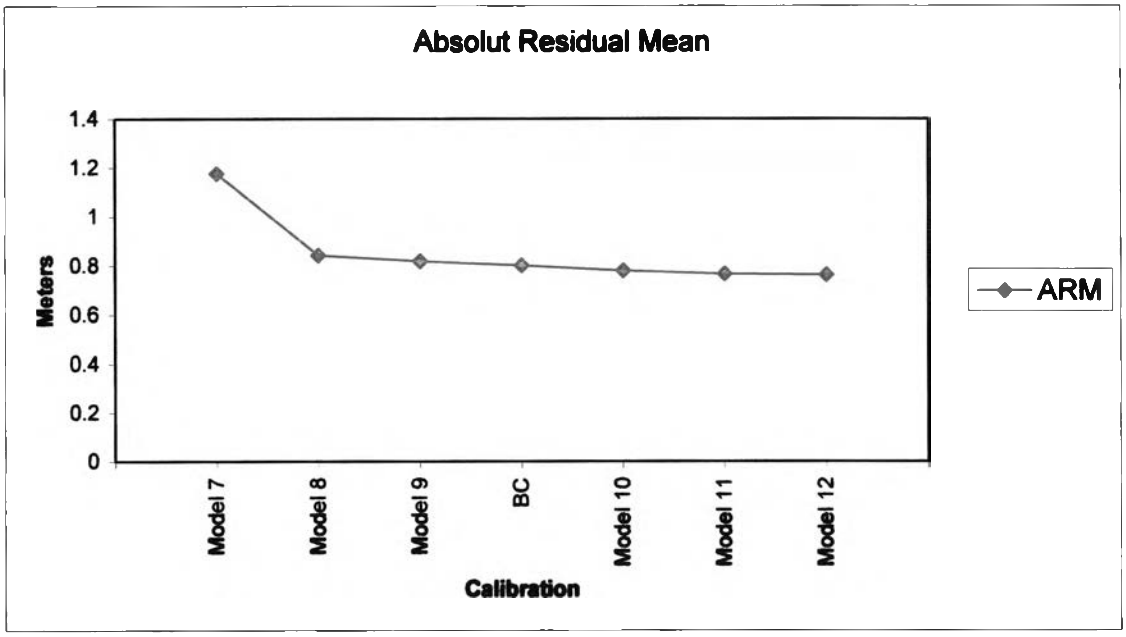


Figure 5.6. Absolute residual mean at Nakhon Luang aquifer in the steady state condition.

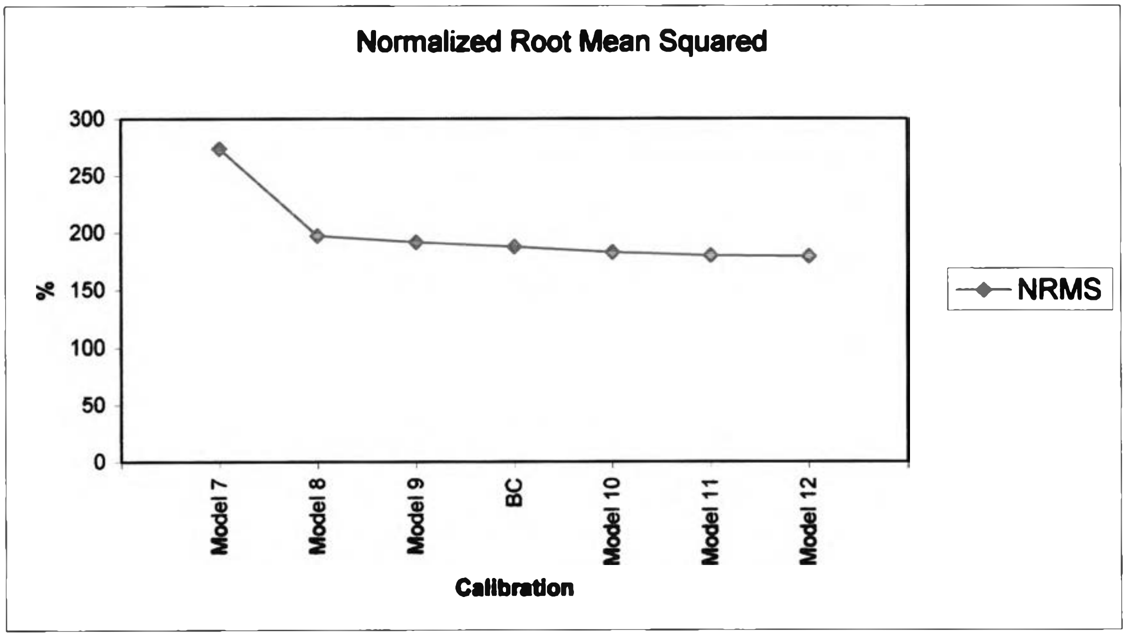


Figure 5.7. Normalized root mean squared at Nakhon Luang aquifer in the steady state condition.

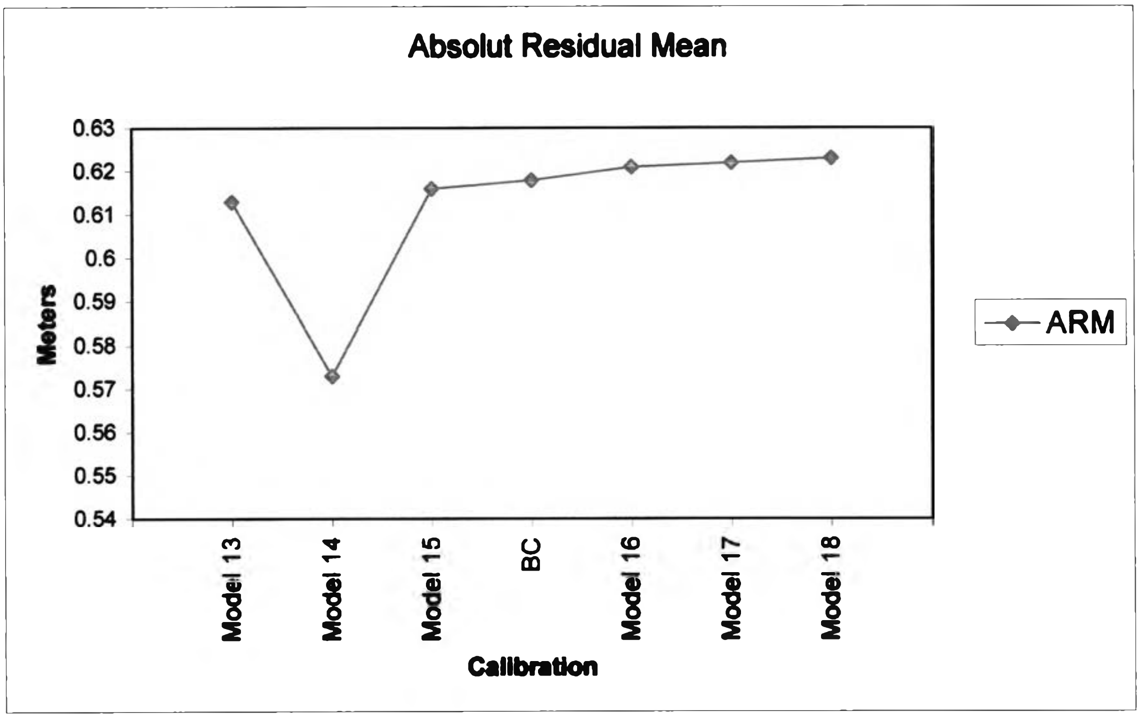


Figure 5.8. Absolute residual mean at Nonthaburi aquifer

in the steady state condition.

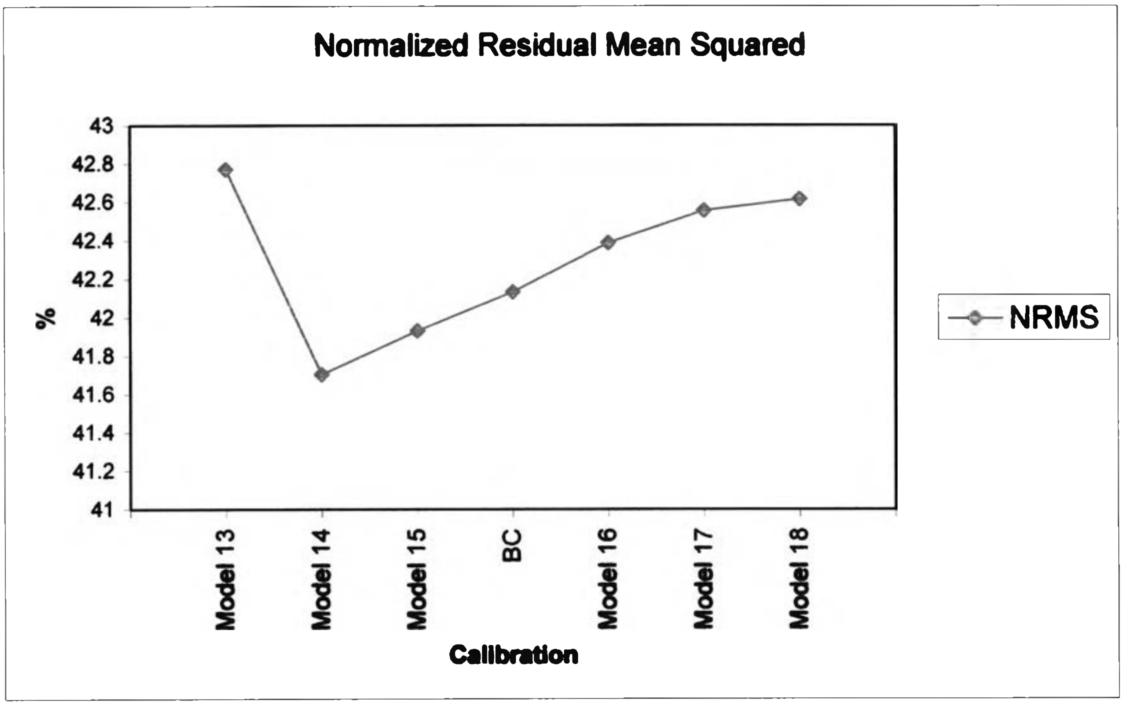


Figure 5.9. Normalized root mean squared at Nonthaburi aquifer

in the steady state condition.

5.1.11. Calibration of groundwater flow model in the transient condition

The transient simulation is performed based on the basecase model. The result of calibrated groundwater level from steady state simulation is used as an initial condition for transient model. In this simulation, two parameters hydraulic conductivity and storage coefficient of target aquifers are varied. The hydraulic conductivity and storage coefficient are varied within the range of minimum and maximum values defined from the field test and referred from previous studies.

To find the best model, the hydraulic conductivity values are varied from 0.178 m/day to 89 m/day , 0.16 m/day to 80.5 m/day, from 0.2722 to 136.1 m/day for Phra Padeang, Nakhon Luang and Nonthaburi aquifers, respectively. The specific storage values are varied from 10^{-5} to 10^{-3} 1/m for all aquifers. The details input parameters for all aquifers are summarized in Tables 5.7, 5.8 and 5.9.

Table 5.7. Calibration model and its parameters at Phra Padaeng aquifer.

Simulation	Parameters	Phra Padaeng	Nakhon Luang	Nonthaburi
Base Case	K (m/day)	17.8	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 1	K (m/day)	0.178	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 2	K (m/day)	1.78	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 3	K (m/day)	8.9	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 4	K (m/day)	12.46	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 5	K (m/day)	35.6	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 6	K (m/day)	89	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 7	K (m/day)	0.178	16.1	27.22
	Ss (1/m)	$1E^{-3}$	$1E^{-4}$	$1.29E^{-4}$
Model 8	K (m/day)	1.78	16.1	27.22
	Ss (1/m)	$1E^{-3}$	$1E^{-4}$	$1.29E^{-4}$
Model 9	K (m/day)	8.9	16.1	27.22
	Ss (1/m)	$1E^{-3}$	$1E^{-4}$	$1.29E^{-4}$
Model 10	K (m/day)	12.46	16.1	27.22

	Ss (1/m)	$1E^{-3}$	$1E^{-4}$	$1.29E^{-4}$
Model 11	K (m/day)	35.6	16.1	27.22
	Ss (1/m)	$1E^{-3}$	$1E^{-4}$	$1.29E^{-4}$
Model 12	K (m/day)	89	16.1	27.22
	Ss (1/m)	$1E^{-3}$	$1E^{-4}$	$1.29E^{-4}$
Model 13	K (m/day)	0.178	16.1	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 14	K (m/day)	1.78	16.1	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 15	K (m/day)	8.9	16.1	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 16	K (m/day)	12.46	16.1	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 17	K (m/day)	35.6	16.1	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 18	K (m/day)	89	16.1	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$

Table 5.8. Calibration model and its parameters at Nakhon Luang aquifer.

Simulation	Parameters	Phra Padaeng	Nakhon Luang	Nonthaburi
Base Case	K (m/day)	17.8	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 1	K (m/day)	89	0.322	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 2	K (m/day)	89	1.61	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 3	K (m/day)	89	8.05	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 4	K (m/day)	89	11.27	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 5	K (m/day)	89	32.2	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 6	K (m/day)	89	80.5	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-4}$	$1.29E^{-4}$
Model 7	K (m/day)	89	0.322	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-3}$	$1.29E^{-4}$
Model 8	K (m/day)	89	1.61	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-3}$	$1.29E^{-4}$
Model 9	K (m/day)	89	8.05	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-3}$	$1.29E^{-4}$

Model 10	K (m/day)	89	11.27	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-3}$	$1.29E^{-4}$
Model 11	K (m/day)	89	32.2	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-3}$	$1.29E^{-4}$
Model 12	K (m/day)	89	80.5	27.22
	Ss (1/m)	$1E^{-5}$	$1E^{-3}$	$1.29E^{-4}$
Model 13	K (m/day)	89	0.322	27.22
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 14	K (m/day)	89	1.61	27.22
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 15	K (m/day)	89	8.05	27.22
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 16	K (m/day)	89	11.27	27.22
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 17	K (m/day)	89	32.2	27.22
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 18	K (m/day)	89	80.5	27.22
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$

Table 5.9. Calibration model and its parameters at Nonthaburi aquifer.

Simulation	Parameters	Phra Padaeng	Nakhon Luang	Nonthaburi
Base Case	K (m/day)	17.8	16.1	27.22
	Ss (1/m)	$1E^{-4}$	$1E^{-4}$	$1.29E^{-4}$
Model 1	K (m/day)	89	0.322	0.2722
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$5.16E^{-4}$
Model 2	K (m/day)	89	0.322	2.722
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 3	K (m/day)	89	0.322	13.61
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 4	K (m/day)	89	0.322	19.054
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 5	K (m/day)	89	0.322	54.44
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 6	K (m/day)	89	0.322	136.1
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-4}$
Model 7	K (m/day)	89	0.322	0.2722
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$5.16E^{-3}$
Model 8	K (m/day)	89	0.322	2.722
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-3}$
Model 9	K (m/day)	89	0.322	13.61

	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-3}$
Model 10	K (m/day)	89	0.322	19.054
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-3}$
Model 11	K (m/day)	89	0.322	54.44
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-3}$
Model 12	K (m/day)	89	0.322	136.1
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-3}$
Model 13	K (m/day)	89	0.322	0.2722
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$5.16E^{-5}$
Model 14	K (m/day)	89	0.322	2.722
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-5}$
Model 15	K (m/day)	89	0.322	13.61
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-5}$
Model 16	K (m/day)	89	0.322	19.054
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-5}$
Model 17	K (m/day)	89	0.322	54.44
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-5}$
Model 18	K (m/day)	89	0.322	136.1
	Ss (1/m)	$1E^{-5}$	$5E^{-5}$	$1.29E^{-5}$

Note: Other parameters are the same as the basecase model.

The results from simulation of Phra Padaeng aquifer show that model 18 is the best model. In this model, the value of hydraulic conductivity is 89 m/day, and the storage coefficient is 1 x 10^{-5} 1/m. It provides the lowest value of ARM (1.5 meters) and NRMS (21.97%) (see Figures 5.10 and 5.11).

For the Nakhon Luang aquifer simulation, the best model is model 13, with the hydraulic conductivity of 0.323 m/day and the storage coefficient of 5 x 10^{-5} 1/m. It provides the lowest value of ARM (1.18 meters) and NRMS (22.46%) (see Figures 5.12 and 5.13).

For the Nonthaburi aquifer simulation, the best model is model 13, with hydraulic conductivity of 0.2722 m/day and storage coefficient of 1.29 x 10^{-5} 1/m. It provides the lowest value of ARM (1.32 meters) and NRMS (17.22%) (see Figures 5. 14 and 5.15).

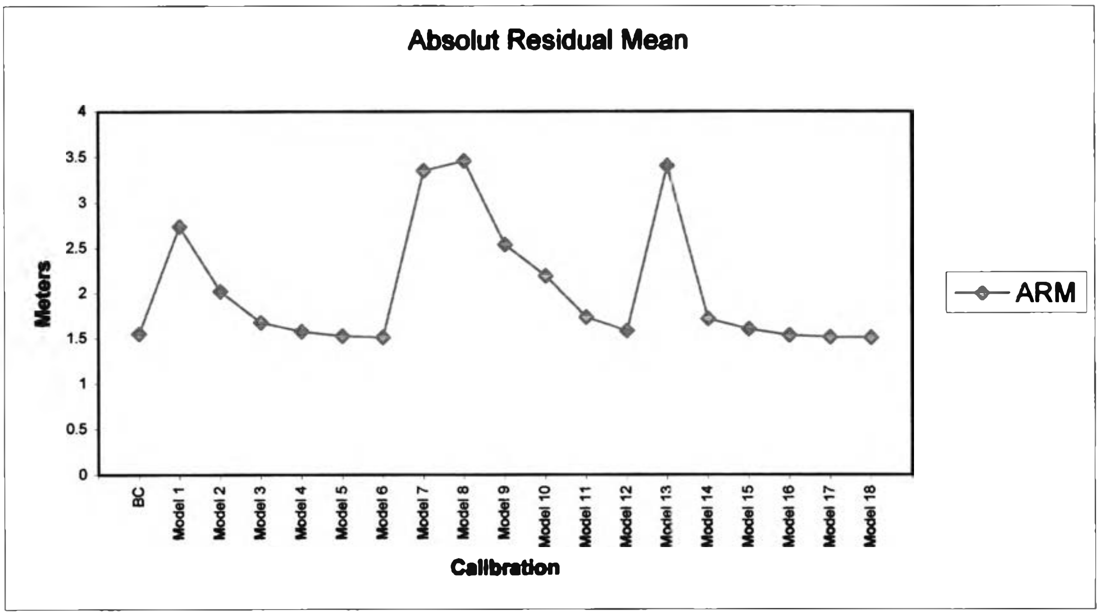


Figure 5.10. Absolute residual mean at Phra Padaeng aquifer

in the transient condition.

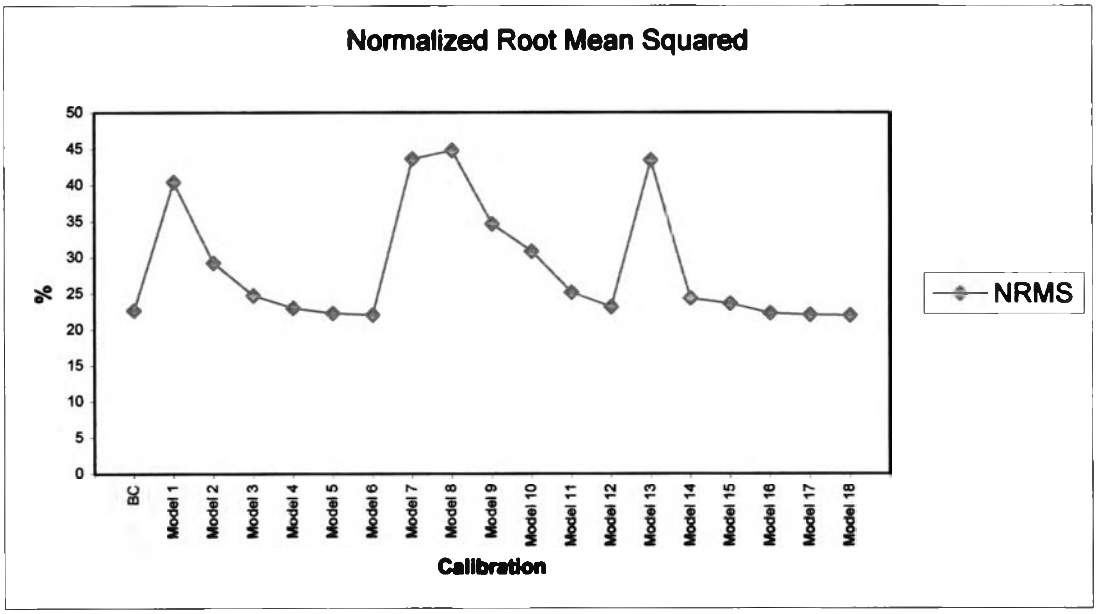


Figure 5.11. Normalized root mean squared at Phra Padaeng aquifer

in the transient simulation.

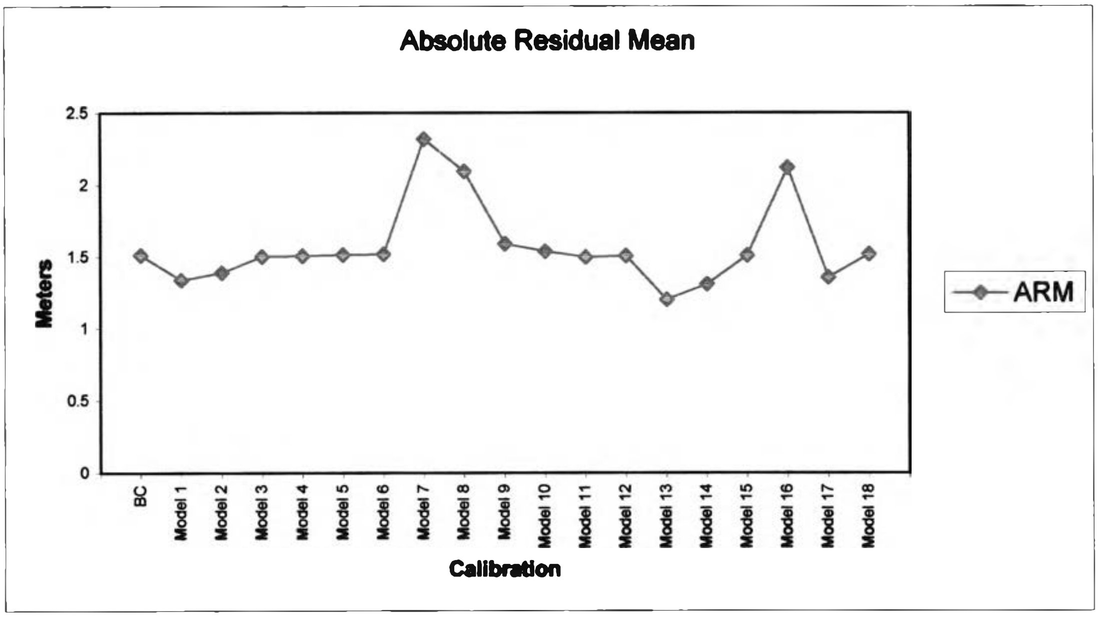


Figure 5.12. Absolute residual mean at Nakhon Luang aquifer in the transient condition.

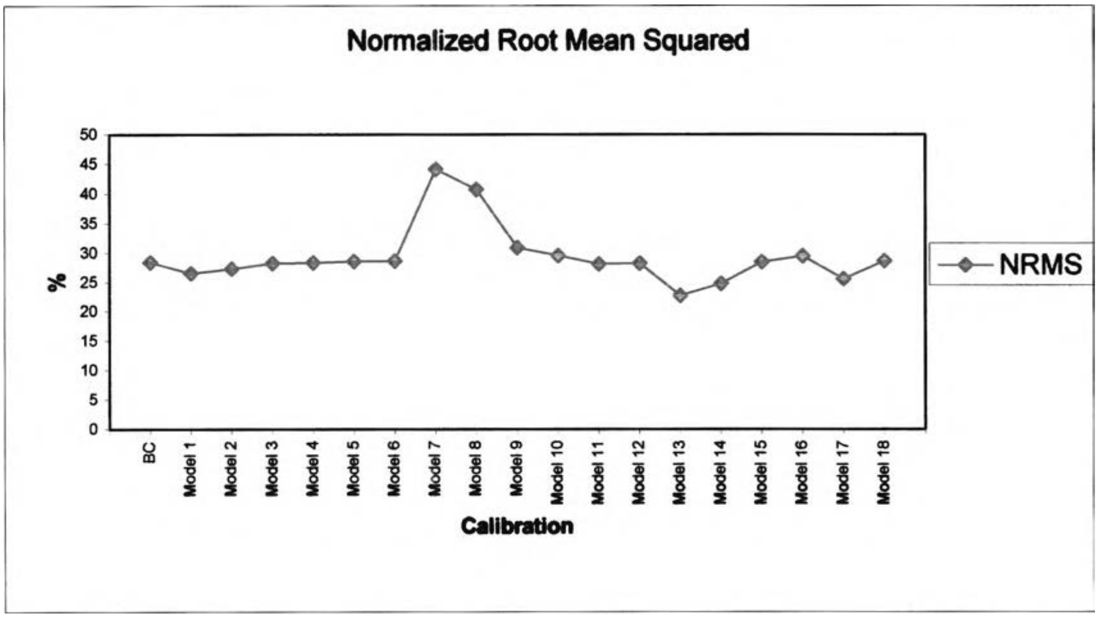


Figure 5.13. Normalized root mean squared at Nakhon Luang aquifer in the transient simulation.

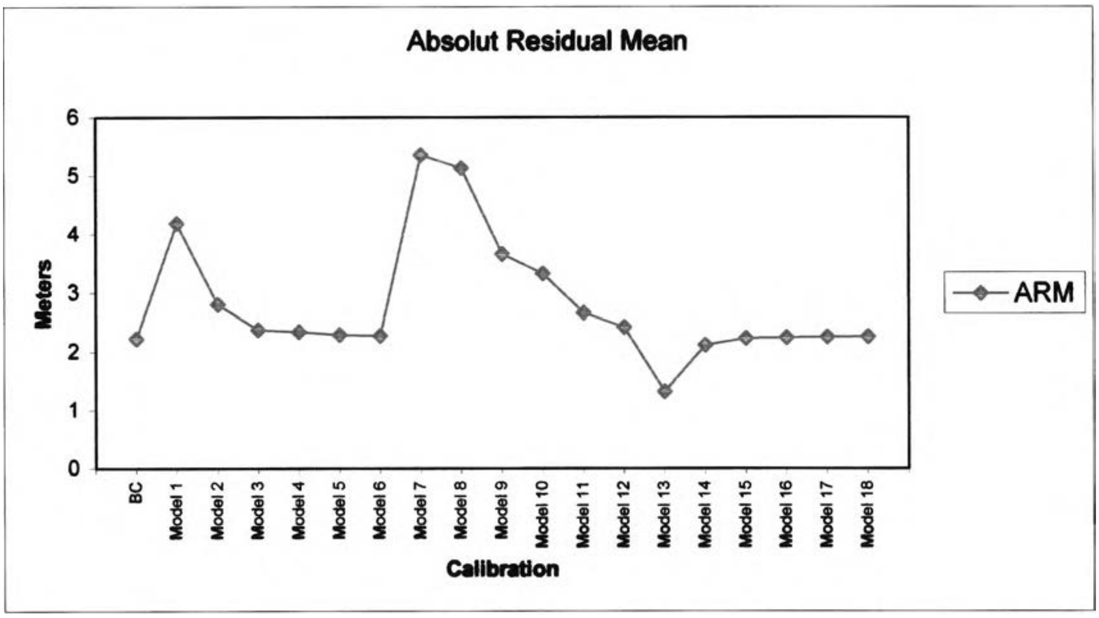


Figure 5.14. Absolute residual mean at Nonthaburi aquifer

in the transient condition.

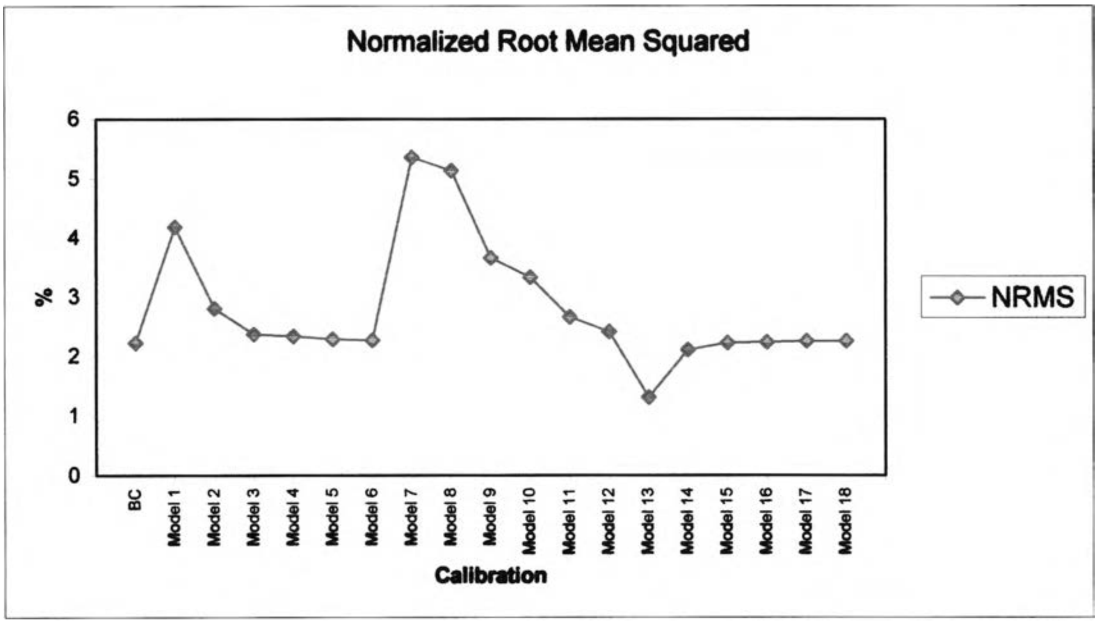


Figure 5.15. Normalized root mean squared at Nonthaburi aquifer

in the transient simulation.

5.1.12. Final model for transient simulation

After finishing all simulations and calibrations for target aquifers, the calibrated value with the lowest error are used as an input into the final model. While all parameters are remains the same as the basecase model (initial model).

Meanwhile, the final model is calibrated by taking into account of the clay layers. In general, it can be said that the results from calibration reveal that the final model has less error that that of the initial model. The calibration statistics are justified because the calibration of the initial model has already reduced the error involved in the model. Therefore, the input parameters are the best represent of the system. In the process, the hydraulic conductivity of clay layers are scaled up and down ten times (multiply and divide by 10) forPha Phradaeng clay, Nakhon Luang clay and Nonthaburi clay.

The simulations result show that changing the hydraulic conductivities of Phra Padaeng, Nakhon Luand and Nontaburi clays do not effect the aquifer system.

The results of ARM and NRMS in the final model for Phra Padaeng aquifer are 1.50 meters and 21.97%, Nakhon Luang aquifer with ARM of 1.18 meters and NRMS of 22.46%, and Nonthaburi aquifer with ARM of 1.32 meters and NRMS of 17.22 %. The ARM and NRMS of all aquifers are 1.33 meters and 13.31 % respetively.

Note that the dispersions between the measured heads and simulated heads are observed in monitoring wells PD74 and NL 78 of Phra Padaeng and Nakhon Luang aquifers respectively. These errors may arise from the incomplete information of groundwater well within the research area. It is recorded that only 17 wells from 53 wells are stored with complete well information (well depth, screen position and pumping rate). The extrapolation of well information from the closest well may cause some error in the process. However, the comparison between the measured heads and simulation heads of monitoring wells PD 68, NL 12 , NB 13 and NB 69 of Phra Padeang, Nakhon Luang and Nonthaburi aquifers provides a satisfactory results (Figures 5.16, 5.17 and 5.18).

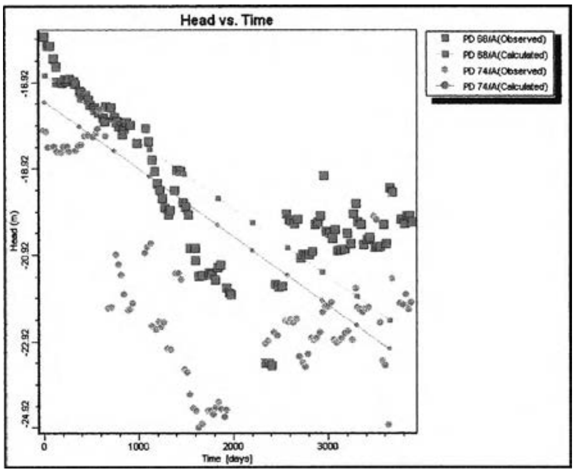


Figure 5.16. Comparison between measured and observed values at Phra Padaeng aquifer.

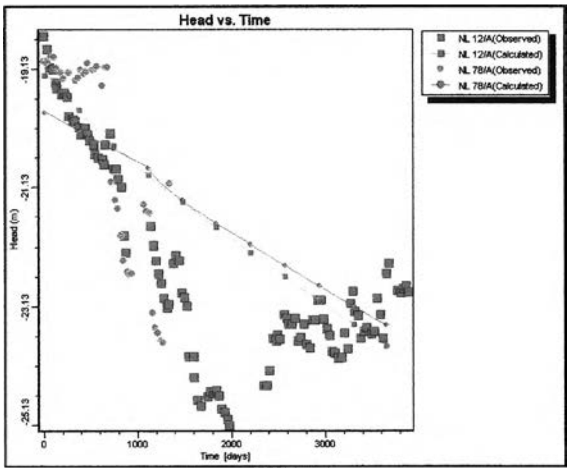


Figure 5.17. Comparison between measured and observed values at Nakhon Luang aquifer.

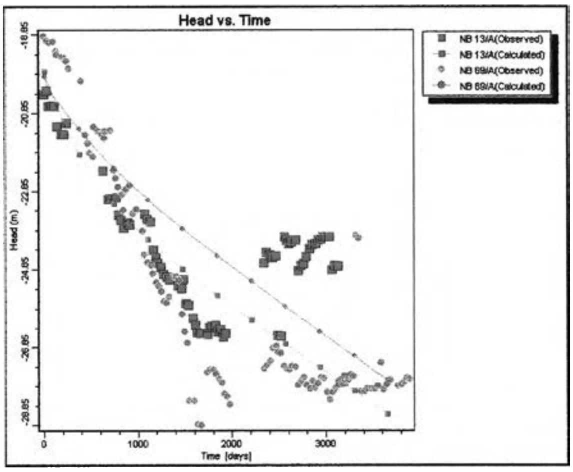


Figure 5.18. Comparison between measured and observed values at Nonthaburi aquifer.

5.13. Scenario for the future pumping

The prediction of groundwater level and groundwater balance in the research area are carried out by a final model of groundwater flow modeling. In this simulation, it has three scenarios.

Scenario 1 assumes that the new wells with partial penetration (DR 132, DR 133 and DR 134) are pumped with pumping rate 15 m/day for each well. The result from simulation in the next 5 years shows the drawdown reaches 2 meters and spreads out 0.5 km from the wells. In overall, the groundwater balance still maintained.

Scenario 2 assumes that the pumping rate is increased to 20 m/day for each well (DR 132, DR 133 and DR 134). The result from simulation in the next 5 years shows the drawdown of groundwater reaches 2 meters and spreads out 1 km from the wells. In overall, the groundwater balance also still maintained.

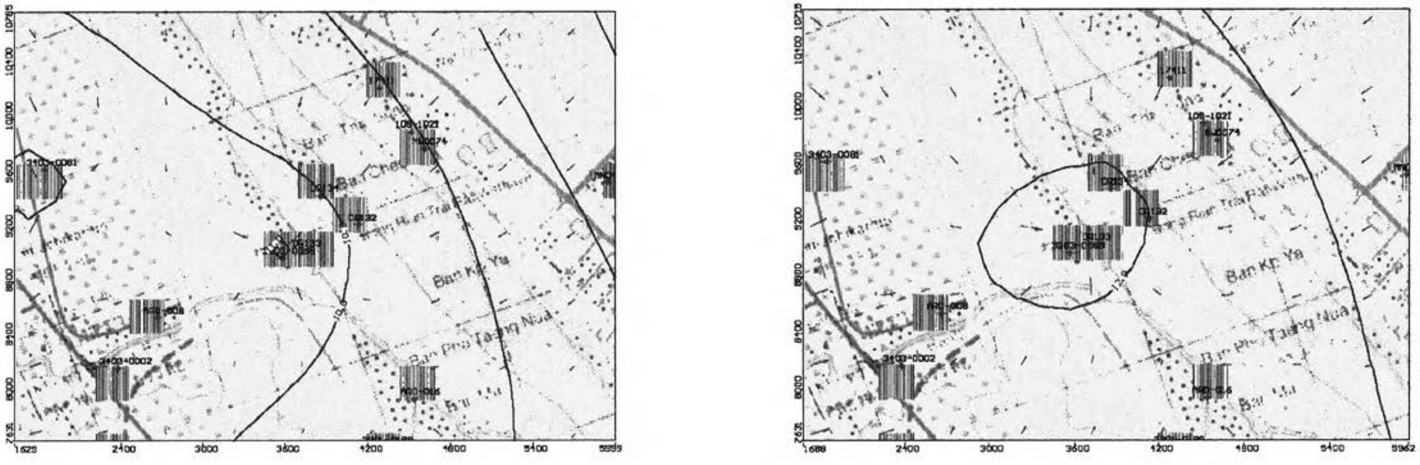
In the scenario 3 assumes that the pumping rate is increased to 25 m/day for each well (DR 132, DR 133 and DR 134). The result from simulation in the next 5 years shows the drawdown of groundwater reaches 2 meters and spreads out more than 1 km from the wells. In this case, the groundwater balance also still maintained. The result for simulations is showed in Figure 19.

5.2. Groundwater Potential

Potential of groundwater depends on the geologic and hydrology conditions. The research area is located in middle part of Chao Phraya river. The lithology consists of sediment layers that are formed from alluvial and marine deposit. The layers that contain sand and gravel sediments are water-bearing formation as aquifer.

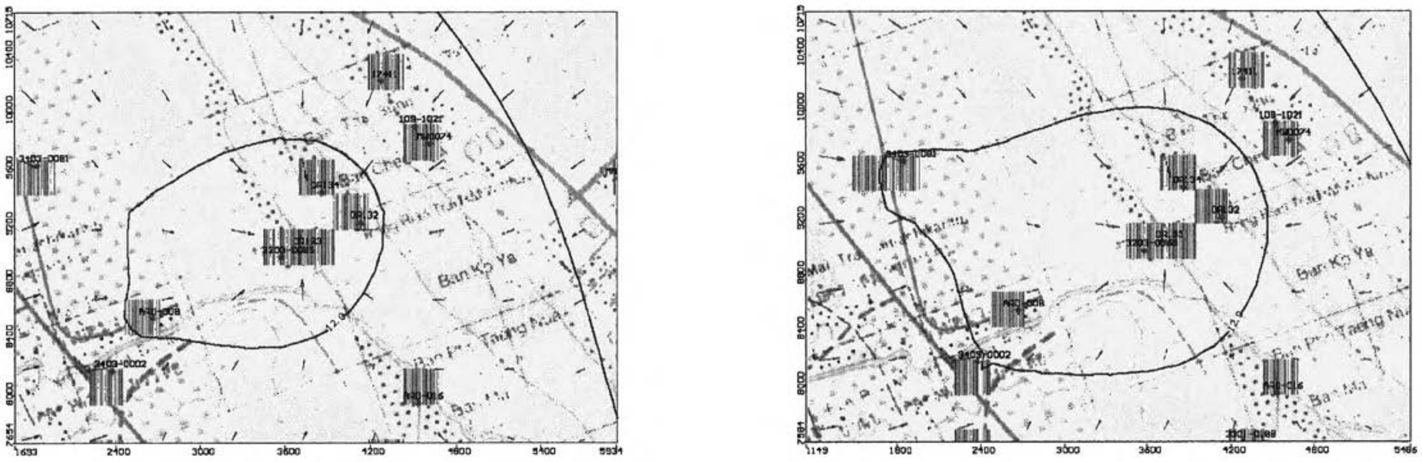
Based on the lithologic log, the depositional sediment shows thinning upward and repeating again. In a series from the bottom to top are very fine gravel, very coarse sand, coarse sand, sand and clay. This situation supports the forming of confined aquifer, with many of aquifer layers.

Generally, considering to the properties and characteristics of lithology, the groundwater system can be divided into 4 aquifers. The first aquifer located at approximate depth of 50 meters below SWL with the average thickness of 40.73 meters. The second aquifer is Phra Padaeng Aquifer, located at approximate depth of 100



a. Initial condition (2003)

b. Scenario 1



c. Scenario 2

d. Scenario 3

Figure 5.19. The drawdown map of pumping scenario simulations.

meters bellows SWL, with average thickness of 39.31 meters. The third aquifer is Nakhon Luang, located at approximate depth of 175 meters, with average thickness of 48.23 meters. The last aquifer is Nonthaburi aquifer, located at approximate depth of 250 meters with average thickness of 54.94 meters. In this analysis, only the groundwater potential of Phra Padaeng, Nakhon Luang and Nonthaburi aquifers are evaluated.

5.2.1. Quantity of groundwater

Basically, the quantity of groundwater can be divided into two types, static and dynamic. Static quantity is a total volume of groundwater that storage in the aquifer. Dynamic quantity is a total volume of groundwater that flowing to the aquifer in the unit time, this amount of groundwater is changing with time. Both static and dynamic quantities are estimated.

5.2.1.1. Static reserves

The static reserves in the research area are divided into three layers of aquifer; Phra Padaeng aquifer, Nakhon Luang aquifer and Nonthaburi aquifer. The volumes of groundwater at Phra Padaeng, Nakhon Luang aquifer and Nonthaburi are 849,304.17 m^3, 1,041,874.13 m^3, 1,530,990.81 m^3 respectively. The details of calculation are summarized in Table 5.10.

Table 5.10. The static reserves of groundwater.

Aquifer Name	Volume (m^3)	Storage Coefficient	Volume (m^3)
Phra Padaeng	8,493,041,661.43	1×10^{-4}	849,304.17
Nakhon Luang	10,418,741,305.70	1×10^{-4}	1,041,874.13
Nonthaburi	11,868,145,835.70	1.29×10^{-4}	1,530,990.81
Total			3,422,169.11

Source : Primary Analysis, 2004

5.2.1.2. Dynamic reserves

Similar a static reserves, the dynamic reserves also divided into three layers of aquifers. The volumes of groundwater that flowing into the Phra Padaeng, Nakhon Luang and Nonthaburi aquifers are 7,531.72 m^3/day, 9,334.02 m^3/day, 13,723.96 m^3/day respectively. The details of calculations are summarized in Table 5.11. It is important to note that there is a big number of total inflow, but only certain amount of groundwater volume can be exploited.

Table 5.11. The Dynamic Reserves of Groundwater

Aquifer Name	Hydraulic Conductivity (m/day)	Average Aquifer Thickness (m)	Average Hydraulic Gradient	Area Cross Section (m)	Total Inflow (m^3/day)
Phra Padaeng	17.8	39.31964	0.000497	21660	7,531.72
Nakhon Luang	16.1	48.23491	0.000555	21660	9,334.02
Nonthaburi	27.22	54.94512	0.000424	21660	13,723.96
Total					30,589.7

Source : Primary Analysis, 2004

5.2.2. Quality of groundwater

Based on the results from chemical analysis of groundwater sample from the field and also secondary data, they show that the quality of groundwater still acceptable for drinking water purpose in general. But some element has higher than the standard of water drinking requirements (see Table 4.12.). Therefore, the pumped water from this area must be treatment before used for water supply.

The quality of groundwater in the Phra Padaeng aquifer shows that the content of iron, chloride, total dissolved solid and total hardness are higher content than that of the standard of water drinking requirements (see Table 4.12.). Only in a small area (Northeast) where the water qualities record under the standard requirements (see Figure 5.20)

The Nakhon Luang aquifer displays groundwater qualities problem similar to Phra Padaeng aquifer. The elements have higher content than that of the standard for water drinking requirements are iron, chloride, total dissolved solid, total hardness and pH (see Table 4.12). However, the high concentration is located in the middle of the research area (see Figure 5.21).

The Nonthaburi aquifer has a good quality of groundwater. Based on the elements that being chosen for water chemical analysis of this aquifer, it shows that the quality of water is still meet with the requirements for drinking water (see Table 4.12 and Figure 5.22).

5.3. Groundwater Balance

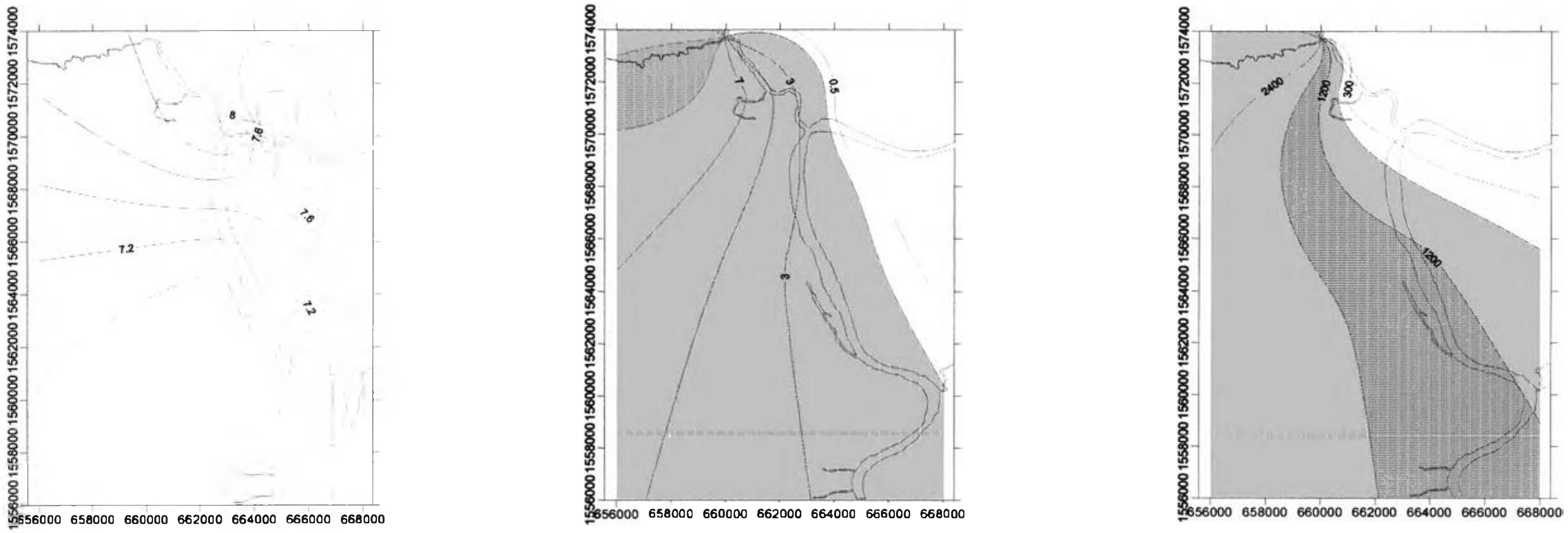
Groundwater balance in the study area is examined based on the result of the historical heads calibration. The modflow computes storage change, recharge from constant head, evapotranspiration, river leakage, horizontal and vertical exchange, and well discharge in the specified area for each aquifer unit.

The calculations for groundwater balance are performed for Phra Padaeng aquifer, Nakhon Luang aquifer and Nonthaburi aquifer. These values are calculated based on the final model simulation of groundwater flow.

Groundwater balance in the Phra Padaeng aquifer shows that it has output storage of 0 m^3/day and input storage of 87.68 m^3/day, and input of constant head of 31,720 m^3/day and output of 32,286 m^3/day. Total discharge from all wells is 158 m^3/day. The output vertical exchange is 0 m^3/day, and the input vertical exchange of 637.14 m^3/day. The total output and input in the aquifer is still balance. The details groundwater balance in the Phra Padaeng aquifer is summarized in Table 5.12.

Nakhon Luang aquifer has output storage of 0 m^3/day and input storage of 360.12 m^3/day. The constant head input is 36.23 m^3/day and output of 133.83 m^3/day. The total discharge from the well is 325.52 m^3/day. The output of vertical exchanges (3.72 m^3/day), and the input vertical exchanges (66.71 m^3/day) surplus around 63 m^3/day. The total output and input in the aquifer is still balance. The details of groundwater balance are summarized in Table 5.13.

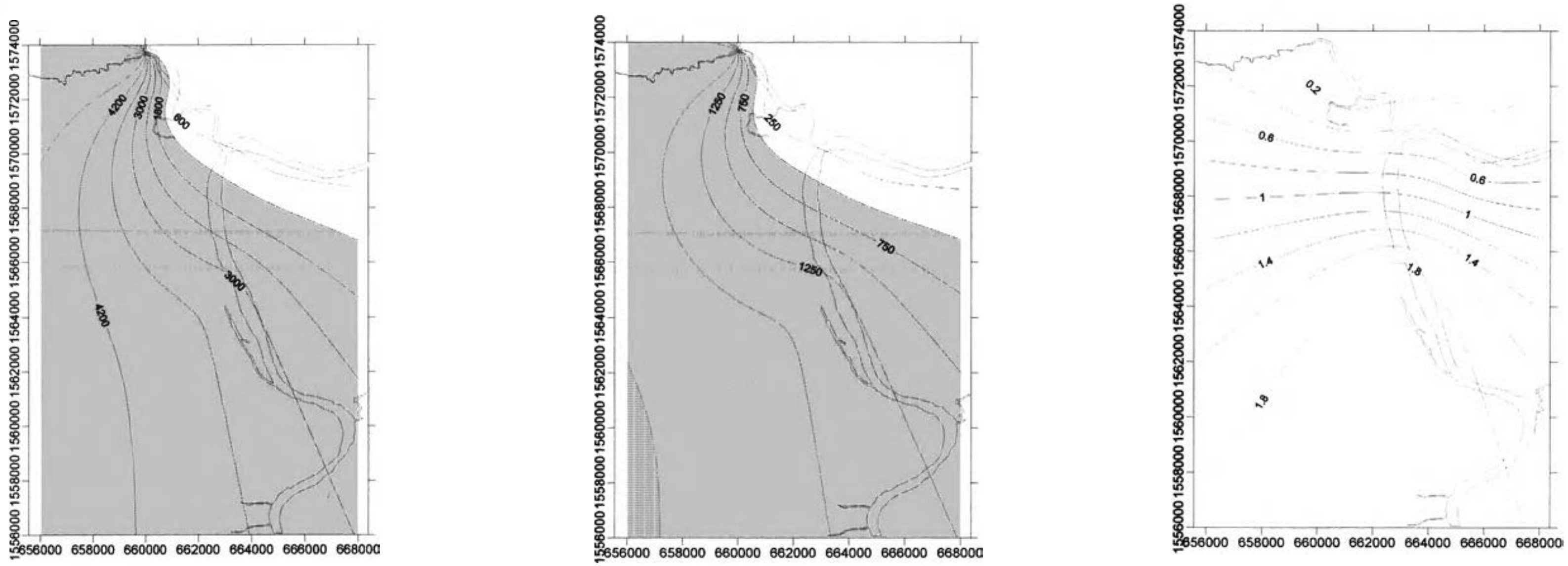
Nonthaburi aquifer has input storage of 168.22 m^3/day and output storage of 0 m^3/day. The total discharge from all well is 613 m^3/day. The constant head has input of 361.69 m^3/day and output of 3.29 m^3/day, with vertical exchange surplus around 86 ^{3}/day. The details of groundwater balance in the Nonthaburi aquifer are summarized in Table 5.14.



A. pH map

B. Iron Map

C. Chloride Map



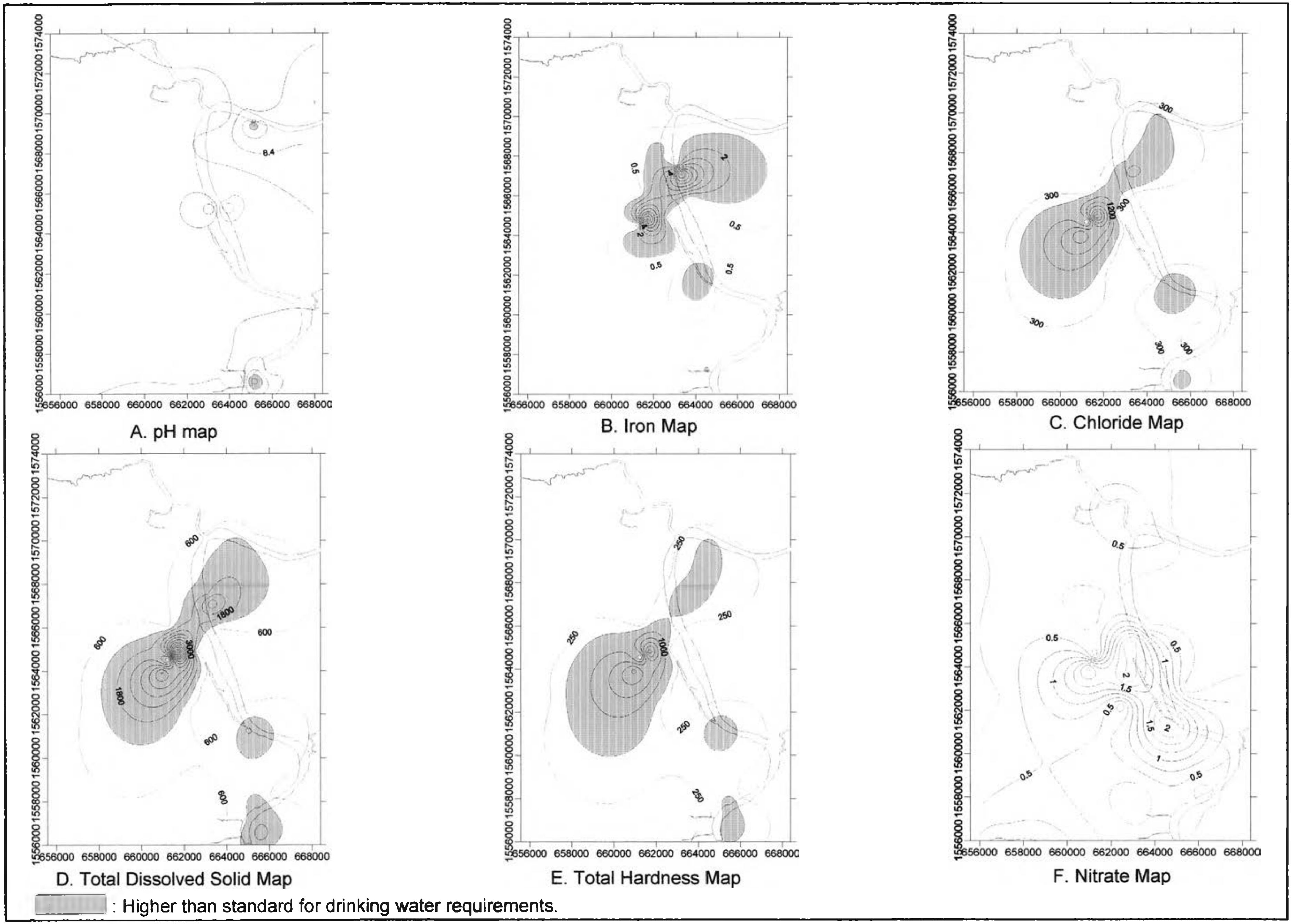
D. Total Dissolved Solid Map

E. Total Hardness Map

F. Nitrate Map

▨ : Higher than standard for drinking water requirements.

Figure 5.19. Groundwater quality maps at Phra Padaeng aquifer.


A. pH map

B. Iron Map

C. Chloride Map

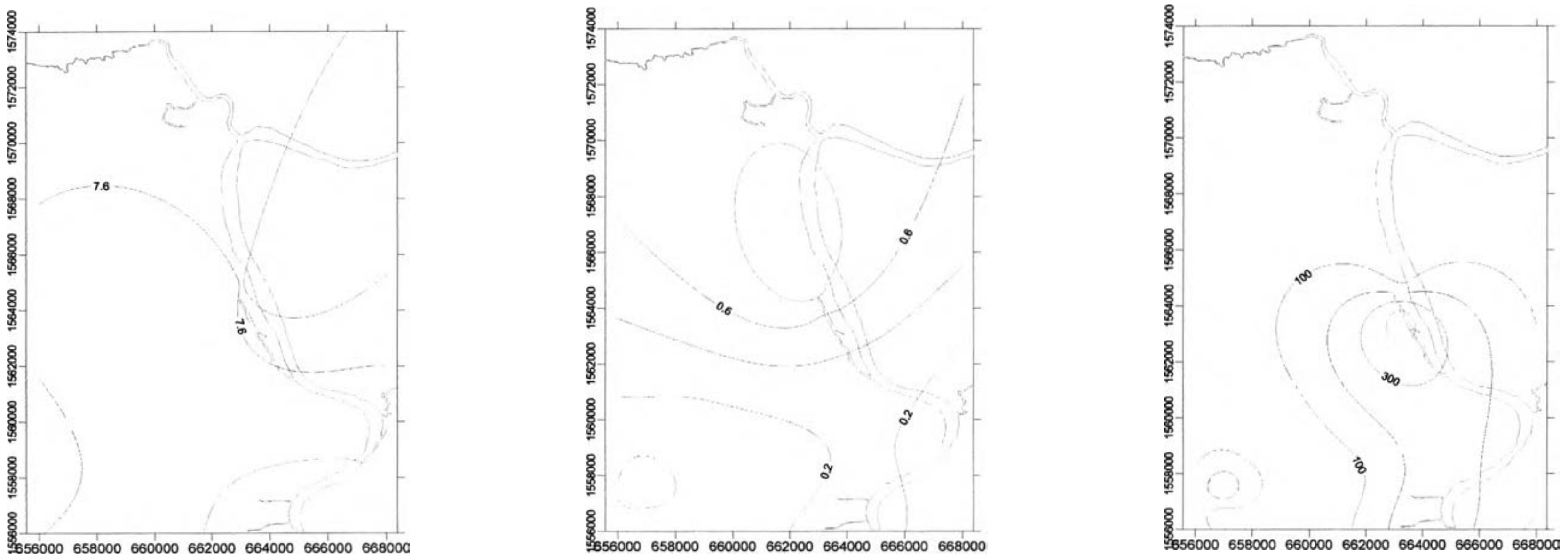
D. Total Dissolved Solid Map

E. Total Hardness Map

F. Nitrate Map

▨ : Higher than standard for drinking water requirements.

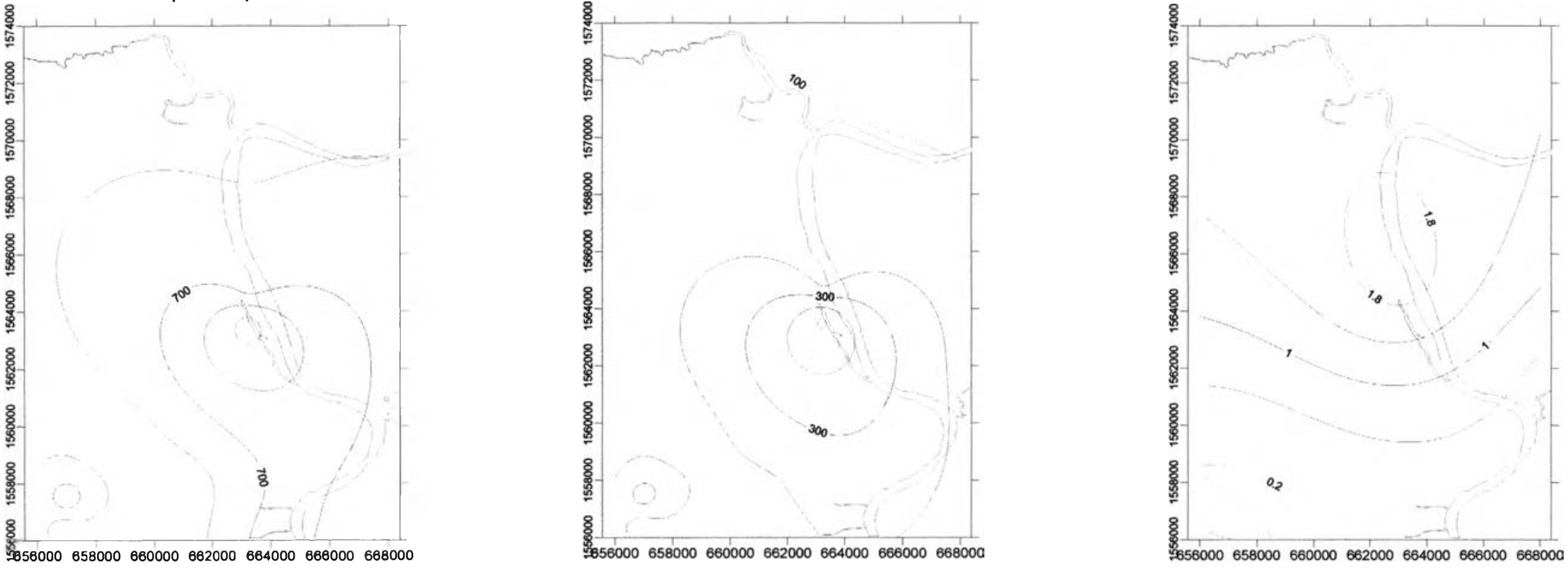
Figure 5.20. Groundwater quality maps at Nakhon Luang aquifer.



A. pH map

B. Iron Map

C. Chloride Map



D. Total Dissolved Solid Map

E. Total Hardness Map

F. Nitrate Map

Figure 5.21. Groundwater quality maps at Nothaburi aquifer.

Table 5.12. Groundwater balance in Phra Padaeng aquifer.

Parameters	Output (m^3/day)	Parameters	Input (m^3/day)
Storage	0	Storage	87.68
Constant head	32,286	Constant head	31,720
Wells	158	Wells	0
River leakage	0	River leakage	0
Et	0	Et	0
Recharge	0	Recharge	0
Vertical exchange	0	Vertical exchange	637.14
Total	32,444	Total	32,444

Source : Primary Analysis, 2004

Table 5.13. Groundwater balance in Nakhon Luang aquifer.

Parameters	Output (m^3/day)	Parameters	Input (m^3/day)
Storage	0	Storage	360.12
Constant head	133.83	Constant head	36.23
Wells	325.52	Wells	0
River leakage	0	River leakage	0
Et	0	Et	0
Recharge	0	Recharge	0
Vertical exchange	3.72	Vertical exchange	66.71
Total	463.08	Total	463.08

Source : Primary Analysis, 2004

Table 5.14. Groundwater balance in Nonthaburi aquifer.

Parameters	Output (m^3/day)	Parameters	Input (m^3/day)
Storage	0	Storage	168.22
Constant head	3.29	Constant head	261.69
Wells	613	Wells	0
River leakage	0	River leakage	0
Et	0	Et	0
Recharge	0	Recharge	0
Vertical exchange	0	Vertical exchange	86.34
Total	616.29	Total	616.25

Source : Primary Analysis, 2004

5.4. Groundwater Management

The management of groundwater in the research area, basically can be divided into two categories; quantity and quality managements. The quantity management depends on the aquifer potential. And, the aquifer potential depends largely on the hydrogeologic condition. Maintaining of the recharge area is necessary to guarantee supply of water to the aquifer.

Well management is the most important in the management of quantity. In general, the maximum pumping rate and screen position are defined for all pumping wells, although this condition is very difficult to apply in the field. In the research area, based on the hydraulic conductivity values and the average thickness of aquifer layers, the most productive aquifer is Nonthaburi aquifer. The data from monitoring well shows that the Nonthaburi aquifer has a biggest drawdown volume recorded from 1993 to 2003 (see Figure 5.23), and the lowest drawdown of groundwater level is recorded at Nakhon Luang aquifer. This condition expresses that almost all the wells in modeling area pump groundwater from Nonthaburi aquifer. The amount of groundwater volume released since 1993 to 2003 are 125,351.59 m^3, 120,425.75 m^3 and 225,741.24 m^3 for Phra Padeang, Nakhon Luang and Nonthaburi aquifers, rescpectively. The details of releasing groundwater volume are summarized in Table 5.15.

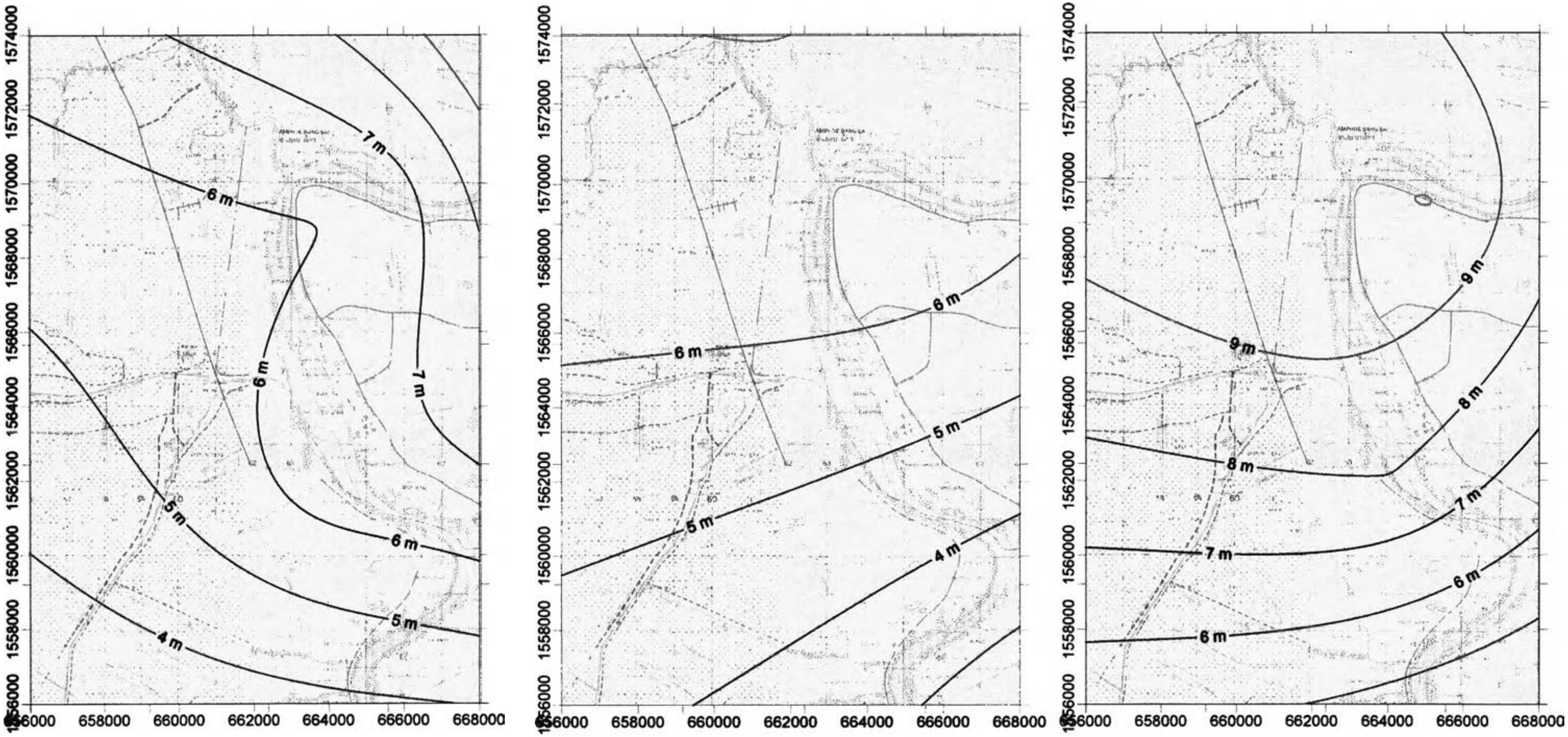
Table 5.15. The Groundwater volume released from each aquifer accumulated since 1993 to 2003.

No.	Aquifer	Volume Drawdown (m^3)	Storage Coefficient	Total volume groundwater (m^3)
1	Phra Padaeng	1,253,515,866.64	1×10^{-4}	125,351.59
2.	Nakhon Luang	1,204,257,495.77	1×10^{-4}	120,425.75
3.	Nonthaburi	1,749,932,072.71	1.29×10^{-4}	225,741.24
	Total	4,207,705,435.12		471,518.58

Source: Primary Analysis, 2004

Management of groundwater quality is also very important. Even though, the research area has a good groundwater potential but the groundwater quality has to take into consideration too. The quality of groundwater is relative to lithology in that area. In the research area, some of lithology is a marine sediment deposit that has a high chloride content. This condition contributes to the high content of chloride in some area (see Figures 5.19 and 5.21).

The groundwater drawdown and groundwater quality maps can be used as a tool to make recommendations for groundwater exploitation in the research area. Based on the overlay maps (drawdown and groundwater quality maps) on each aquifer, the areas of development and their characteristics are provided for the target aquifers. Figure 5.24. illustrates developing areas maps for target aquifers, and Table 5.16 provides the detail of aquifer characteristics and method of development.



A. Drawdown at the Phra Padaeng aquifer.

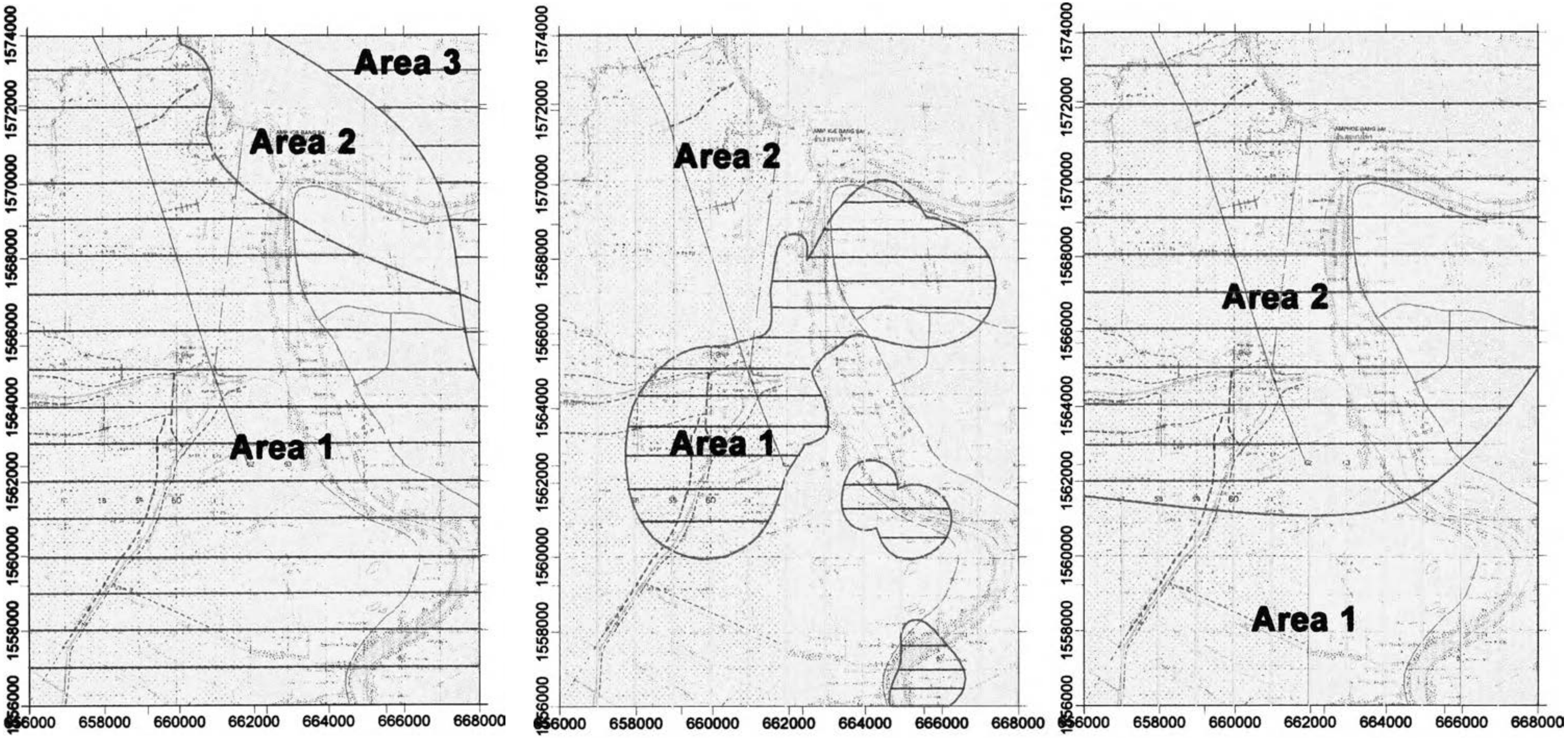
B. Drawdown at the Nakhon Luang aquifer.

C. Drawdown at the Nonthaburi aquifer.

Legend :

4 m ——— : Contour of drawdown groundwater level 4 meters.

Figure 5.22. The drawdown map of groundwater level from 1993 to 2003.



A. Developing area of Phra Padaeng aquifer.

B. Developing area of Nakhon Luang aquifer.

C. Developing area of Nonthaburi aquifer.

Figure 5.23. Developing areas map for each aquifer.

Table 5.16. Development of aquifer based on its characteristic.

Aquifer	Area 1	Area 2	Area 3
Phra Padaeng	**Characteristics** • Draw down of SWL is < 0.75 m/year. • Quality of groundwater is poor .	**Characteristics** • Draw down of SWL is < 0.75 m/year. • Quality of groundwater is good .	**Characteristics** • Draw down of SWL is ≥ 0.75 m/year. • Quality of groundwater is good.
	Method of Development • It can still be developed for new well. • Groundwater can be used for agricultural and industrial except for water supply system.	**Method of Development** • It can still be developed for new well. • The first priority using groundwater is a water supply system.	**Method of Development** • It has a limitation for new well. • The first priority using groundwater is a water supply system. • Development of artificial recharge.
Nakhon Luang	**Characteristics** • Draw down of SWL is < 0.75 m/year. • Quality of groundwater is good.	**Characteristics** • Draw down of SWL is < 0.75 m/year. • Quality of groundwater is poor.	
	Method of Development • It can still be developed for new well. • The first priority using groundwater is a water supply system.	**Method of Development** • It can still be developed for new well. • Groundwater can be used for agricultural and industrial except for water supply system.	
Nonthaburi	**Characteristics** • Draw down of SWL is < 0.75 m/year. • Quality of groundwater is good.	**Characteristics** • Draw down of SWL is ≥ 0.75 m/year. • Quality of groundwater is good.	
	Method of Development • It can still be developed for new well. • The first priority using groundwater is a water supply system.	**Method of Development** • It has a limitation for new well. • The first priority using groundwater is a water supply system. • Development of artificial recharge.	

Note : SWL = Static Water Level