GROUNDWATER FLOW MODELLING FOR THE DEVELOPMENT OF MANAGED AQUIFER RECHARGE SCHEME IN IRRIGATION PROJECTS, THAILAND

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ABSTRACT

Groundwater is one of the most important natural resource to supplement uses of limited surface water for irrigation and industrial sectors especially in the Phanomtuan–Song Phenong–Banglen Sub–irrigation Projects, Thailand. Surface water in this region has been extensively used for many purposes in both the basin and adjacent areas. Therefore, conjuctive use of surface water and groundwater has been proposed in this area so as to utilize available water resources and to satisfy agricultural water demand. However, the overuse of groundwater can lead to the depleted groundwater availability, soil collapses, land subsidence, and saltwater contamination of the water supply, etc. Accordingly, this study aims at developing groundwater flow model using the USGS's modular hydrologic model (MODFLOW) to determine the permissible yield of groundwater and to propose the Managed Aquifer Recharge (MAR) scheme for sustainable use of groundwater in future. The geohydrological data during 2000–2016 were used as input to simulate aquifer system. Nine different confined aquifers separated by aquitard layers were identified and 2 flow observation stations established along the Tha Chin River provided input in the model. Evapotranspiration and recharge rates were estimated and identified corresponding to different landuse types. Hundreds of pumping wells having atotal pumping rate of 212 m^3/day per well were input in groundwater flow model. Model calibration was accomplished under both steady state and transient state conditions to adjust model parameters comprising hydraulic conductivity, specific yield, and specific storage. The observed head data from 20 observation wells and calculated head were compared to find deviation of model calibration. It is found that the normalized root mean square and correlation coefficient were 9.36%, and 0.96, respectively. The simulation result of groundwater budget during 2000–2016 shows that recharge rate has remained higher than the amount of groundwater withdrawal. The total permissible yield is 185,760 m^3/day which is higher than the current status of groundwater pumping quantified as 62% of total permissible yield. Moreover, 10 designated injection wells proposed at the Phanomtuan site could help increase the hydraulic head of water over the entire area.

Keywords : Groundwater Flow Modelling, MODFLOW, Phanomtuan–Song Phenong–BanglenSub–irrigation Projects.

1. INTRODUCTION

Groundwater has been a major source of water for irrigation and industrial sectors where surface water is insufficient and difficult to access especially in the Mae Klong River Basin.Surface water in this region has been extensively used for many purposes in both the basin and adjacent areas. Therefore, the conjunctive water

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management combining uses of surface water and groundwater has been proposed to increasingly utilize available water resources in this area. Groundwater has been also used to satisfy agricultural water demand potentially in the Phanomtuan–Song Phenong–Banglen sub–irrigation area which is a part of the Greater Mae Klong Irrigation Project. The withdrawal of groundwater for agricultural and industrial sectorsis expected to increase due to the economic expansion and increasing number of people in this area.However, the excessive use of groundwater can lead to the depleted groundwater availability, soil collapse, land subsidence, and saltwater contamination of the water supply, etc. Therefore, the Manage Aquifer Recharge (MAR) has been proposed as an alternative to recover groundwater level and to develop the proper MAR scheme for sustainable groundwater management. MAR has been successfully implemented worldwide and numberousMAR schemes has been broadly existedto enhance recharge of groundwater sush as spreading method (infiltration ponds and basins, Soil Aquifer Treatment (SAT), controlled flooding), in–channel modification (sand storage dam, leaky dam and surcharge releases), well, shaft and borehole recharges, induced bank infiltration, and rainwater harvesting. Each scheme require different levels of technology and engineering knowledge (Gale, 2005). Accordingly, this study aims at developing groundwater flow model using the modular hydrologic model (MODFLOW) to determine the permissible yield of groundwater in the Phanomtuan–Song Phenong–Banglen sub–irrigation area and to propose the possible Managed Aquifer Recharge (MAR) scheme for sustainable use of groundwater in future.MODFLOW is a 3–dimensional finite–difference model that was developed by the United States Geological Survey (USGS). MODFLOW can be used for groundwater simulation in steady and non–steady flow conditions which aquifer system can be confined, unconfined, or a combination of confined and unconfined systems (Leake, 1997).

1.1 Study Area

ThePhanomtuan–Song Phenong–BanglenSub–irrigation Projects were selected as the study area. It is located in the upper part of the Greater Mae Klong Irrigation Project(GMKIP)in Mae Klong and Tha Chin Basins as shown in Figure 1. The total area is approximately 1,758 km^2 covering three provinces namely; Kanchanaburi, SuphanBuri, and Nakhon Pathom Provinces.Groundwater is used mainly for agricultural and industrial sectors in this region. In 2011 when severe flooding occurred in the central part of Thailand, this region was considered as flooded area to retain excess water from the Chao Phraya and Tha Chin Basins

Therefore, there is possibility of increasing groundwater recharge in these three sub–irrigation areas as a result of diverting excess water from adjacent basins. The main crops are paddy field and field crop which occupy 35.89% and 30.03% of the entire area, respectively. Irrigation water is supplied from the Mae Klong Dam through 1L and 2L canals with the total length of 57.8 km and 60.5 km, respectively.Most of the western part is upland area having the highestsurface elevation of +400 m above MSL and gradually become flat area in the east near mean sea level as illustrated in Figure 2.

1.2 Geological Regime

In this region, the groundwater basin comprises of 9 aquifer layers which are intervened by 8 aquitard layers. These include Bangkok Aquifer (BK), PhraPradeang Aquifer (PD), Nakhon LuangAquifer (NL), Nonthaburi Aquifer (NB), Sam KhokAquifer (SK), Phaya Thai Aquifer (PT), Thon BuriAquifer (TB), and Pak Nam Aquifer (PN) having the thickness of 10–70 meter.The bottom layer is bedrock comprising of sedimentary rock, metamorphic rock, granite, and volcanic rock.

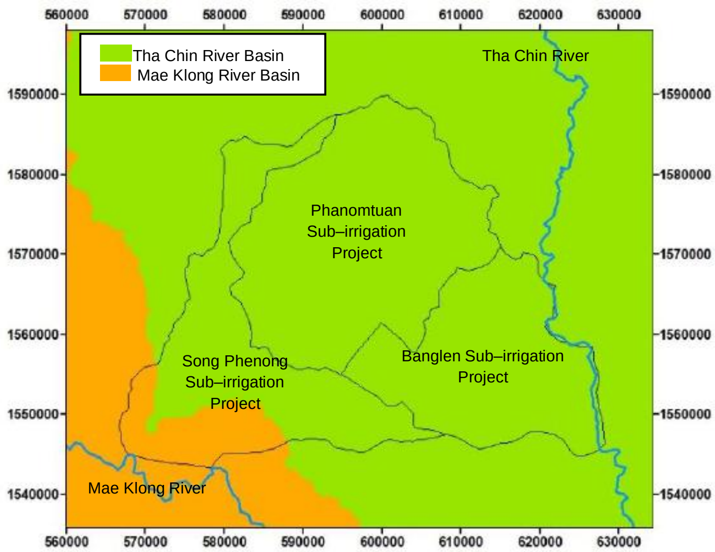

Figure 1. Phanomtuan–Song Phenong–BanglenSub–irrigation projects.

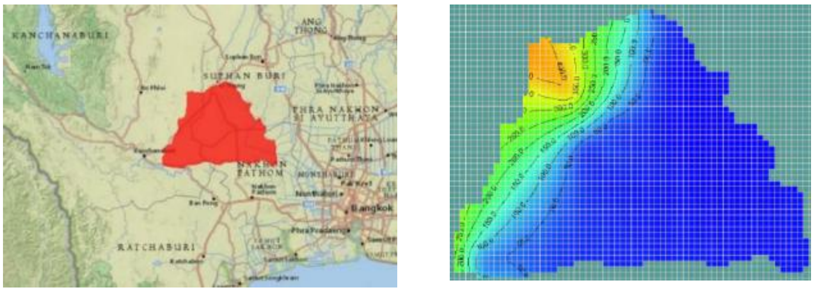

Figure 2. The boudary of study area and its surface elevation.

2. METHODS

2.1 Numerical Model and Boundary Conditions

MODFLOW was applied in this study to simulate groundwater dynamics in the study area.The model area was represented horizontally on a two–dimensional grid and vertically as one unconfined aquifer at the top layers and 8 confined aquifer layers below. All aquifer layers were intervened by aquitard and bedrock was indentified at the bottom layer. The vertical layers were assigned as heterogenous layers having the specific hydrological properties. The grid was divided by rectangular cells into 49 rows and 64 columns occupying the total area of 1,758 km^2. Each rectangular cell has size of 1000 x 1000 m^2 equally. The 3D model of aquifer system and layered structure are shown in Figure 3. and Table 1.

Hundreds of pumping wells belonging to the government and private sector were input in groundwater flow model with an average pumping rate of 212 m^3/day. The observed hydraulic head data from 20 observation wells obtained from the Department of Groundwater Resources was also input in the model. It was found that hydraulic heads were measured in some aquifer layers due to the depth of wells namely; Bangkok Aquifer, PhraPradeang Aquifer, Nakhon Luang Aquifer, Nonthaburi Aquifer, Sam Khok Aquifer, and rock layers. Grid cells outside the boundary were defined as inactive cells that were not used to calculate flow.

Table 1. The layered structure identified in groundwater flow model

Layer	Type	Layer no.
Bangkok clay (BKclay)	Unconfined aquifer	1
Bangkok aquifer (BK)	Confined aquifer	2
PhraPradeang aquifer (PD)	Confined aquifer	4
Nakhon Luang aquifer (NL)	Confined aquifer	6
Nonthaburi aquifer (NB)	Confined aquifer	8
Sam Khok aquifer (SK)	Confined aquifer	10
Phaya Thai aquifer (PT)	Confined aquifer	12
Thon Buri aquifer (TB)	Confined aquifer	14
Pak Nam aquifer (PN)	Confined aquifer	16
Rock	Confined aquifer	18
Aquitard	Aquitard	17 ,15 ,13 ,11 ,9 ,7 ,5 ,3

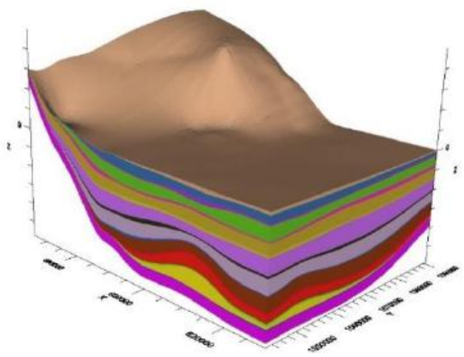

Figure 3. 3D model of aquifer system in the study area.

General heads werespecifiedat the northern, eastern, and southernborders using observed water levels of monitoring wells. Meanwhile, the observed hydraulic head of K.3 and K.11A streamflow stations were used to specify the general head at the southwest border as shown in Figure 4.

The top layer was defined as recharge area from precipitation. River boundary was applied along Tha Chin River using data from T.9 and T.13 flow stations. The lowest model boundary was –600 m MSL. Mountain ridge at thewestern border and bottom of the model were defined as impermeable boundary.

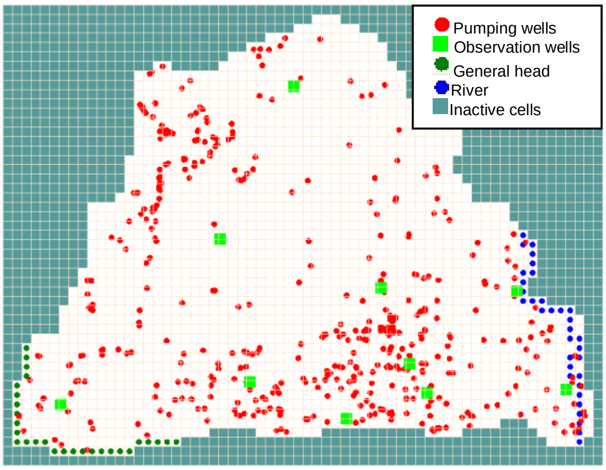

Figure 4. Numerical groundwater flow model and boundary conditions.

Evapotranspiration and recharge rates were estimated according to thedifferent landuse types using rainfall, runoff, and crop evapotranspiration values from the Department of Groundwater Resources as summarized in Table 2. Recharge ponding depth was specified equal to 0 m and extinction depth of evapotranspiration was equal to 2 m.

Table 2. Evapotranspiration and recharge rates used in the groundwater flow model

Landuse	Evapotranspiration (mm/yr)	Recharge rate (mm/yr)
Paddy field	833.3	29.0
Sugarcane	758.4	103.9
Forest	779.1	83.2
Other	799.8	62.5

2.2 Model Calibration

The model calibration of groundwater flow model is the process of integrating the hydrogeological data in the numerical model, and adjusting parameters until the output of the model could simulate the real situation. Model parameters are adjusted and refined to provide the best match between measured hydraulic head and calculated hydraulic head.

In this study, model calibration was accomplished under both steady state and transient state conditions using 20 observation wells monitored during 2000–2016. The aim of model calibration under steady–state groundwater flow was to determine the distribution of hydraulic conductivity required to match the observed water levels. The estimation of hydraulic conductivity distribution was achieved by a trial and error procedure using PEST module in Visual MODFLOW Flex. Model calibration under transient groundwater flow aimed to calibrate the storage coefficient and recharge parameter.The accuracy of calculated hydraulic head in the model was presented by residual mean, absolute residual mean, standard error of the estimate, normalized root mean square, and correlation coefficient. Model calibration processes were terminated when accuracy level of normalized RMS was less than 10% (Lukjan, 2012).

The results of model calibration show that the value of normalized RMS is 9.36 % which is within an acceptable range. The maximun residual, minimum residual, and correlation coefficient are7.084 m, –0.19 m,and 0.96, respectively which can be reasonably acceptable as shown in Figure 5 and Figure 6.

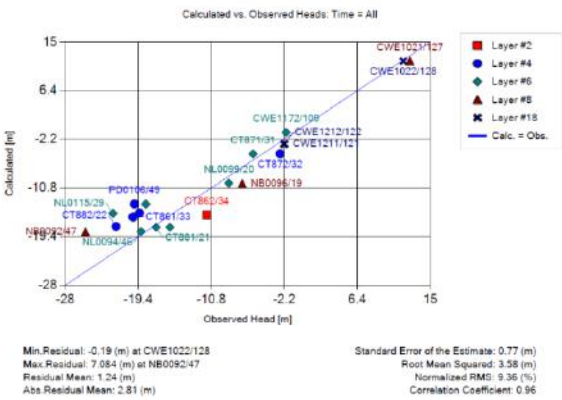

Figure 5. Calculated head versus observed headfrom model calibration under steady state flow condition.

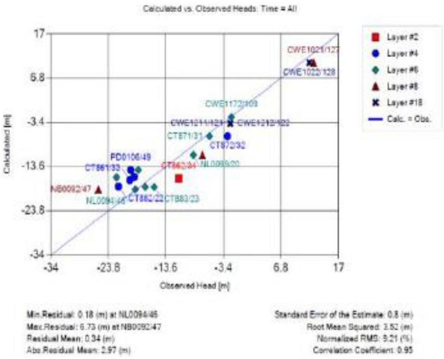

Figure 6. Calculated head versus observed head from model calibration under transient state flow condition.

3. RESULTS AND DISCUSSION

3.1 Water Budget

The water budget obtained from the transient groundwater flow simulation is summarized in Table 3 to describe the quantitative water in terms of total inflow and total outflow in a hydrogeological basin during 2000–2016. It could be seen that the major inflow of groundwater system in the study isfromhead flow boundary, precipitation recharge and river leakage of 42.25%, 37.87%, and 5.00% of the total inflow, respectively. The head flow boundary and evapotranspiration show high portion of major outflow of 64.63% and 14.90%, respectively.The amount of groundwater recharge is 2.03×10^9 m^3 which is higher than the amount of pumped discharge of 5.35×10^8 m^3.

Table3. Groundwater budgetunder transient groundwater flow simulationduring 2000–2016 in the study area

Water balance	Inflow		Outflow	
Unit	m^3	%	m^3	%
Storage	7.98×10^8	14.88	5.63×10^8	10.49
Constant head	0.00	0.00	0.00	0.00
Pumping wells	0.00	0.00	5.35×10^8	9.96
River leakage	2.68×10^8	5.00	9.09×10^5	0.02
Evapotranspiration	0.00	0.00	7.99×10^8	14.90
Head flow boundary	2.26×10^9	42.25	3.47×10^9	64.63
Recharge	2.03×10^9	37.87	0.00	0.00
Total	5.36×10^9	0.00	3.37×10^9	0.00
Percent discrepancy	–0.12			

3.2 Permisibleyield

The permisible yield is an important parameter determined from groundwater flowmodel. It can inform the policy makers towards the groundwater availability and the permissible amount of groundwater withdrawal from aquifer system. The concept of permissible yield was applied in this study for sustainable management of groundwater resources (Chung et al., 2014). The total permisible yieldwas defined as the total pumping rate which reduces the average hydraulic head in each aquifer equalling to

–1 m/year (DGR, 2008).To determine the permissible yield, the distribution of available pumping wells and discharge rates with 212 m^3/day were indentified every active cell of groundwater flow model until the hydraulic head was induced equal to –1 m/year.

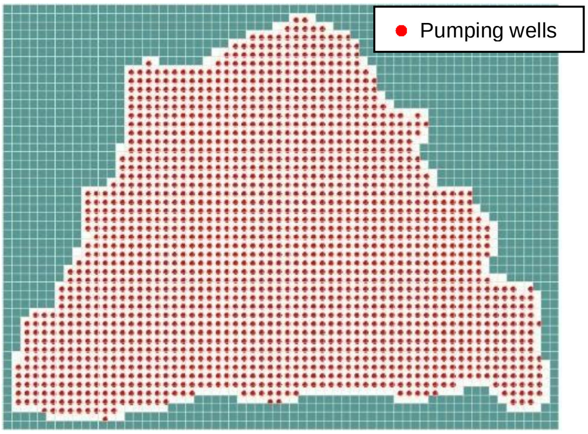

Figure 7. Distribution of pumping wells in every grid cells.

After the groundwater model simulation was done, itshow the total permissible yieldof 185,760 m^3/day in the study area. Meanwhile, the current status of groundwater pumping is 115,494 m^3/day which is quantified as 62% of total permissible yield. This information provides useful guidance for the policy makers to realize the pumping limit and to use a reasonable amount of groundwater from this basin.

3.3 Groundwater Drawdown Under Existing Pumping Conditions

The long term simulation in transient mode during 2000–2016 was made under the existing conditions of number of pumping wells and rates to estimate the groundwater drawdown in confined aquifers. The contourline of groundwater drawdown in Figure 8 illustrates that the simulated drawdown ranges between –0.50 m to nearly –2.00 m starting from the upper east to the lower west. The highest drawdown is noticed in the Phanomtuan Sub–irrigation Project where soil type is mostly sandy loam. In addition, the flow boundary conditions indentified in groundwater flow model is based on the hydrogeology and piezometry of aquifer system which groundwater moves eastward from the west to the lower east. This would result in increase to groundwater drawdown levels in this zone.

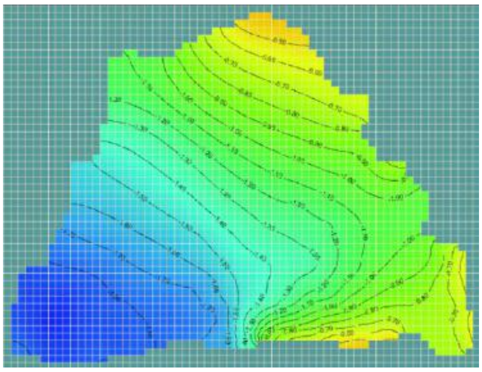

Figure 8. Contourline of groundwater drawdown in confined aquifers during 2000–2016.

3.4 Managed Aquifer Recharge Scheme

To replenish groundwater level and to develop the proper MAR scheme for sustainable groundwater management in the study area, 10designated injection wells with rate of 500 m^3/day each were proposed. The location of designated injection wells is considered based upon the groundwater drawdown limit, soil texture and available source of surface water to inject water underground. Consequently, injection wells are delineated in the Phanontuan Sub-irrigation area where soil texture is mostly sandy loam. In addition, this locatiion is also nearby Chorakhe Sam Phan and Tha San Bang Pla drainage canals as shown in Figure 9. The depth of designated injection wells is recommended as 20 m recharging water into Bangkok aquifer (BK).

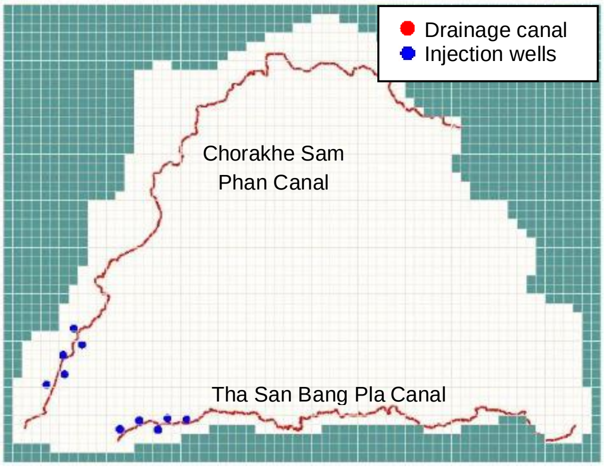

Figure 9. Location of designated injection wells.

The result of groundwater model simulation with MAR scheme shows the increase in hydraulic head in all confined aquifer layers over entire area. Moreover, the maximum hydraulic headsreach to +0.60 min the Phanontuan Sub-irrigation area as typically shown in Figure 10.

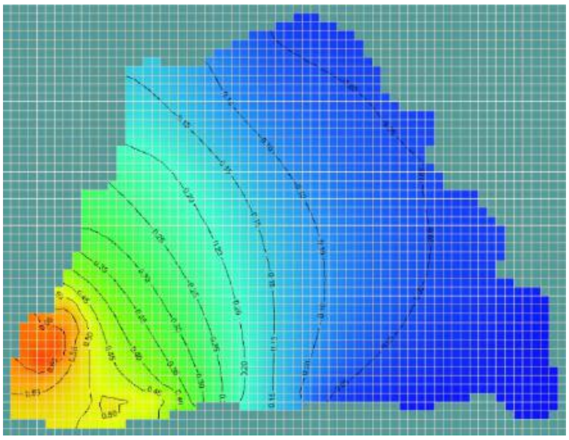

Figure 10. Increase in hydraulic head performed by designated injection wells.

4. CONCLUSIONS

The 3D groundwater flow model was established in the Phanomtuan–Song Phenong–Banglen Sub–irrigation Projects to estimate the permissible yield and to develop the possible MAR scheme. The simulation result of groundwater budget during 2000–2016 showed that recharge rate remained higher than the amount of groundwater withdrawal. The total permissible yield was 185,760 m^3/day which is higher than the current status of groundwater pumping quantified as 62% of total permissible yield. The highest groundwater drawdown was noticed in the Phanomtuan Sub–irrigation Project where soil type is mostly sandy loam. Moreover, the designated injection wells are proposed at the Phanomtuan site nearby drainage canals which could help increase the hydraulic head of water in the entire area.

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