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Groundwater Modelling of Chiang Rai Basin, Northern Thailand

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ABSTRACT

Chiang Rai basin, situated in Chiang Rai and Phayao provinces covering an area of 11,000 km^2, is consisted of high mountains, hills and plains. The economic and population growth in the basin cause a rapid increase in groundwater use, partly due to the lack of surface water supply. This study aimed at developing a groundwater flow model that can be used to estimate extractable and sustainable groundwater quantity especially in the unconsolidated aquifers. Data required for modeling were obtained thorough hydrogeologic investigations, monitoring of hydraulic heads in groundwater wells, and analysis of surface water hydrology. MODFLOW and PEST programs were used to simulate and calibrate the flow model, respectively. Major input of groundwater in unconsolidated aquifers วห natural recharge and its sustainable yield was estimated, based on steady-state model, to be 0.67 Mm^3/yr in addition to the existing pumping rate of 3.98 Mm^3/yr.

Keywords: Chiang Rai Basin, Groundwater Model, Unconsolidated Aquifers

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Introduction

Chiang Rai and Phayao provinces are considered as a regional trade hub of the upper Mekhong countries (China, Myanmar, Laos PDR, and Thailand) according to the quadrangle economic cooperation policy. The Chiang Rai basin (Figure 1), covering both provinces, has an area of approximately 11,000 km^2 of alternating hills and plains. The basin can be divided into four sub-basins, namely Mae Sai, Chiang Rai-Mae Chan (Chiang Rai basin), Mae Suai-Wiang Pa Pao, and Phan-Phayao basins (Department of Groundwater Resources or DGR, 2009). Main rivers in the basin include Lao, Kok and Ing rivers. The aquifers in the area consist of both fractured rocks and unconsolidated sediments (DGR, 2009).

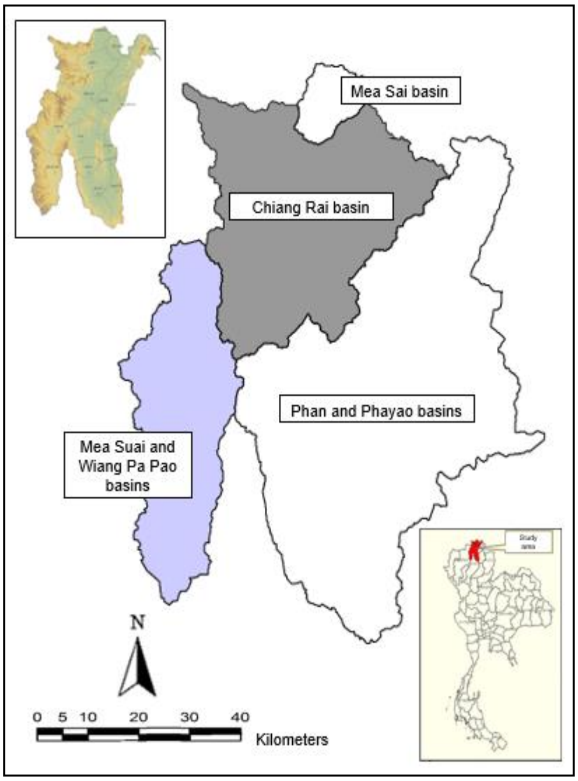

Figure 1 Chiang Rai basin (modified from DGR (2009)).

The economic growth of Chiang Rai province has exerted some environmental stress on the natural resource demand of the region especially the water resources (Koch et al., 2012). Groundwater usage in the basin has been increasing due to city expansion, and agriculture and industrial development. Rapid climate change across the region as a whole further acute these adverse effects such as drought especially in Chiang Rai province (DGR, 2009). Lack of surface water supply causes an increase in uncontrolled groundwater usage in the area. It is therefore necessary to better manage the use groundwater resource in the area. Such groundwater management is usually achieved by conducting a thorough hydrogeologic investigation and monitoring of hydraulic heads (e.g., DGR, 2009). These data can then be analyzed to obtain a better understanding of groundwater systems as well as to impose a reasonable maximum allowable groundwater extraction. A well calibrated groundwater flow model can also be constructed based on hydrogeological data and used as a tool to quantitatively assess sustainable yield of groundwater resources of the area. It is expected that this research project on modeling of groundwater flow system in Chiang Rai basin will provide valuable information on basin's groundwater resource for subsequent efficient groundwater management.

Objectives of the study

This research aims to develop a well-calibrated, steady-state, numerical groundwater flow model of the Chiang Rai Basin focusing on unconsolidated aquifers. The model will then be used to assess sustainable yield of groundwater resource in unconsolidated aquifers based on 2-m drawdown criteria.

Background Information

Geology of the Chiang Rai Basin

Chiang Rai basin is located in the Tertiary intermontane basin which is covered by unconsolidated sediments and have underlain by basement rock. Basement rocks consist of Silurian-Devonian metamorphic rocks, Carboniferous metasedimentary rocks, Permian clastic and volcanic rocks, Mesozoic sedimentary rocks and granite. Unconsolidated sediments are mostly Quaternary deposits (DGR, 2009). The tectonic model explaining the formation of these basins is described either as pull-apart basins associated with strike-slip faulting or extension and changing stress system related to the Tertiary-aged escape tectonics of southeast Asia (Morley, 2002).

Hydrogeology of the Chiang Rai Basin

DGR (2009) conducted comprehensive hydrogeological investigations and produced a map of groundwater aquifers in Chiang Rai basin (Figure 2). The aquifer materials are consisted of seven hydrogeologic units which can be categorized into three main aquifers: alluvial sediments, low terrace and high terrace. Alluvial sediments aquifer consists of gravel, sand, silt and clay and thickness is 20-40 meters. Low terrace aquifer is the thick clay layer with gravel or sand chamber, thickness is 30-100 meter with yield of up to 30 m^3/hr. High terrace aquifer is likely low terrace aquifer, deposit in higher elevation, depth 50-250 meters with yield of up to 50 m^3/hr.

DGR (2009) also conducted comprehensive resistivity surveys in the Chiang Rai basin (Figure 2). The resistivity surveys showed that the aquifers can be divided into 3 unconsolidated aquifers, (1) Floodplain aquifer (Qfd) is composed of fine to medium sands and thickness 20-30 meters, (2) Young terrace aquifer (Qyt) is composed of sands and gravels with interbedded clays and thickness 30-65 meters, (3) Old terrace aquifer (Qot) is composed of sands and gravels with interbedded clays and thickness is more than 150 m (DGR, 2009).

Methodology

Conceptual Model Development

The conceptual model of any groundwater system represents overall hydrogeological and physical characteristics of the aquifer system. The conceptual model of Chiang Rai basin which is conceptualized based on the geological data, hydrogeology, topography, groundwater extraction, soil conditions and land uses data collected by DGR (2009). The Conceptual model has been simplified for four aquifer model layers, namely, Quaternary Floodplain Deposits (Qfd) aquifer, Quaternary Young Terrace Deposits (Qyt) aquifer, Quaternary Old Terrace Deposits (Qot) aquifer, and fractured Basement Rock. Conceptual model of the aquifers system in Chiang Rai basin and its cross-section are illustrated in Figure 3. The conceptual model was subsequently converted to numerical groundwater flow model to quantitatively investigate groundwater resource potential.

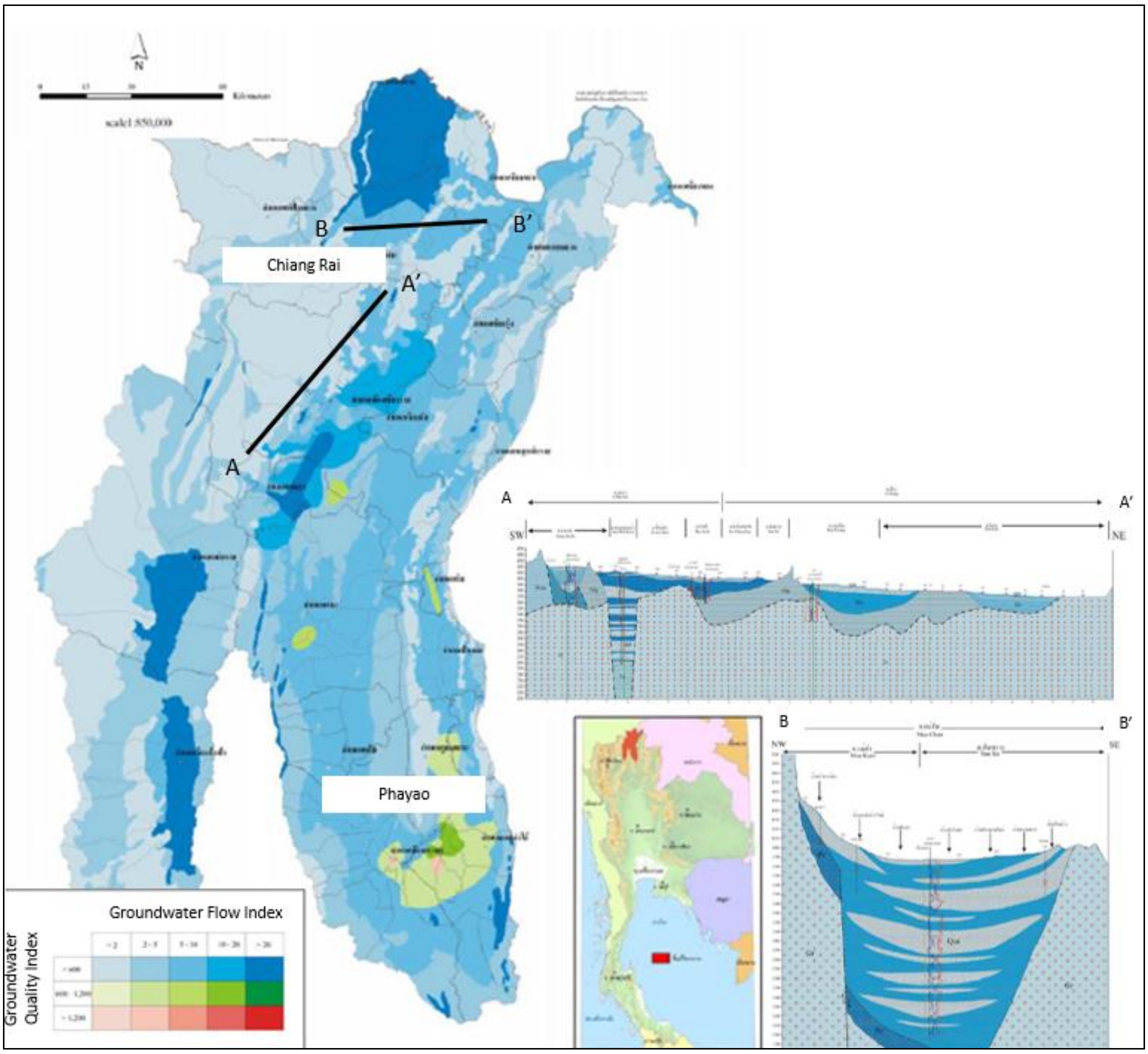

Figure 2 Hydrogeologic map and cross-sections of Chiang Rai basin (DGR, 2009)

Numerical Model Simulation and Calibration

A computer program MODFLOW (Harbaugh et al., 2000) was used to simulate *steady-state* groundwater flow of the Chiang Rai basin. Specifically, the program will approximate the solution, i.e., hydraulic heads, at numerilcal grids based on the governing equation shown in (1).

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} \pm W = 0, \qquad (1)$$

where K_x, K_y and K_z are hydraulic conductivities along the x, y, and z directions, respectively. The variable h refers to hydraulic head, and the term W refers to source(+)/sink(−) of groundwater (i.e., boundary conditions such as rivers, recharge, evapotranspiration, and pumping wells). The regional-flow model extent is approximately

85-km long, 45-km wide, and the depth extends to 560 m bgs. The 3-D Finite-difference grid consisted of 110 rows, 110 columns and 8 layers. The row and column width is uniform of 1×1 km^2. Groundwater usage (i.e., extraction from registered groundwater wells with DGR) was obtained by the courtesy of DGR whereas the extraction from private shallow wells were approximated based on the survey. Initial estimates of the hydraulic conductivities of the aquifer units were obtained from Chusanathas et al. (2010) based on the field survey by DGR (2009) as shown in Table 1.

Table 1 Hydraulic conductivities of the unconsolidated aquifers (DGR, 2009; Chusanathas et al., 2010).

Aquifer Units	Hydraulic Conductivity (m/d)
Flood Plains (Qfd)	0.19-493
Young Terrace (Qyt)	0.08-190
Old Terrace (Qot)	0.02-42.9

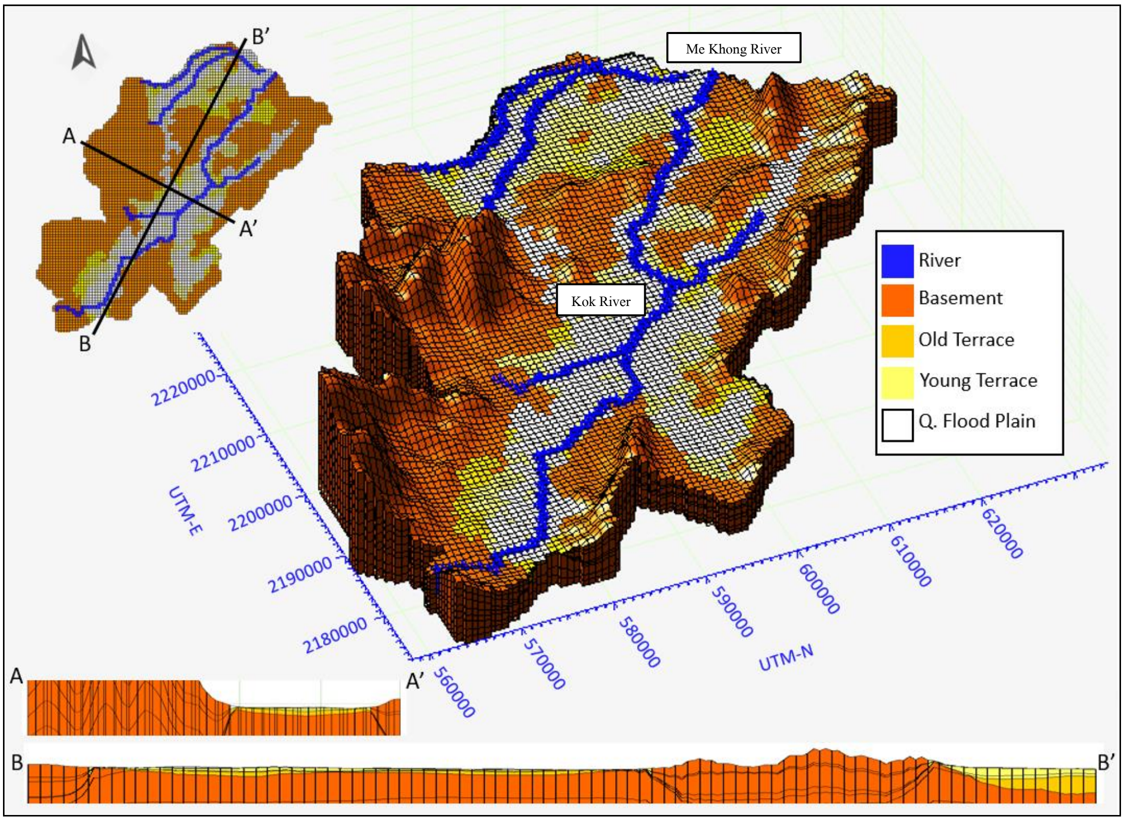

Figure 3 Conceptual model of the Chiang Rai basin showing hydrogeologic unit distribution and model cross-sections.

The model calibration is achieved by using automatic parameter estimation code, PEST (Doherty, 1994) using Pilot Points and Regularization capabilities. The automatic model calibration allows a systematic adjustment of parameter values as piezometric heads (from 55 groundwater monitoring wells; 6-month average heads were used as calibration target) to achieve a reliable model outcome. Calibrated parameters included recharge, hydraulic conductivities, river-bed conductance, and evapotranspiration rates. Figure 4 illustrates examples of model parameter zonation for hydraulic conductivity (layer 2) and recharge. It should be noted that, although parameter zonation was used to conceptualize the aquifer types and recharge zones, the pilot points and regularization capability of PEST (Doherty, 2003) allow the distribution of parameter within the zone to be non-constant or variable (or heterogeneous).

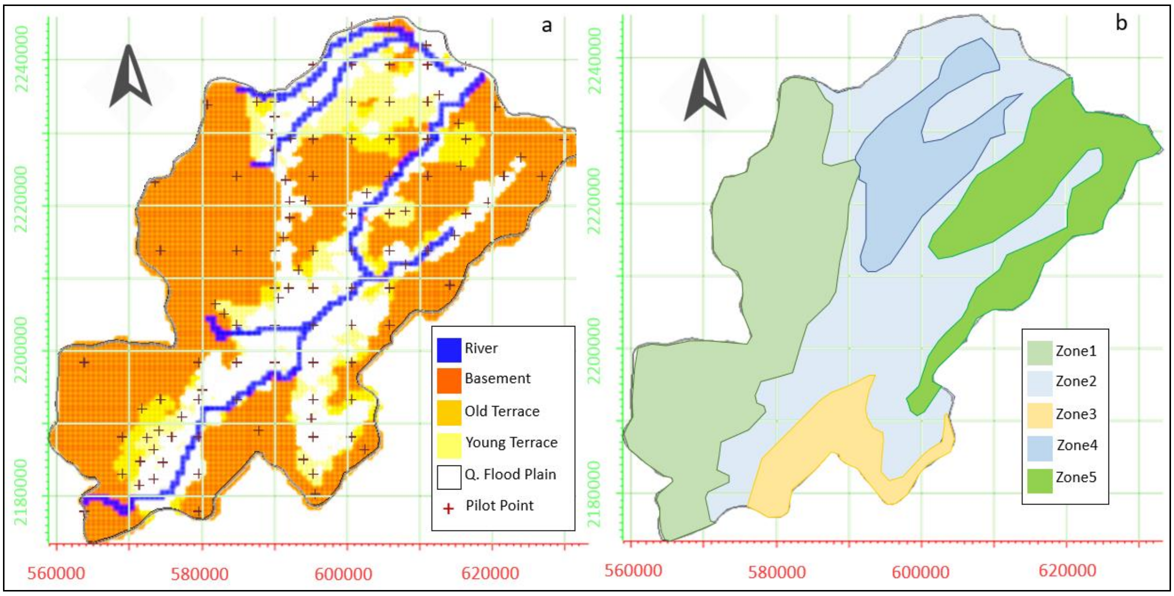

Figure 4 Examples of parameter zonation for (a) hydraulic conductivity (layer 2) and (b) recharge zones.

Results and Discussion

The hydraulic head distribution (i.e., contour lines) from steady-state simulation based on MODFLOW and PEST is illustrated in Figure 4. The regional flow model from MODFLOW simulation shows that groundwater in unconsolidated aquifers generally flows downhill from the highlands in northwest, southeast, and southwest toward the central plains of the basin and discharges along Kok river and eventually toward the Mekhong river in the northeast. The flow pattern corresponds to the findings based on field survey by DGR (2009) and Chusanathas et al. (2010), and based on groundwater flow modeling by Koch et al. (2012). Hydraulic heads (averaged over 6-month period) from 55 DGR-registered wells were used to calibrate the steady-state model by coupling MODFLOW program with PEST algorithm. The calibration result is shown in Figure 5 where most of the simulated hydraulic heads in observation wells agree reasonably well with the measured values with acceptable the normalized root-mean-square error of 2.29%. Sensitivity analysis showed that highly sensitive parameters in the model include, as expected, the hydraulic conductivities and recharges. Groundwater budget was also calculated and shown in Table 2.

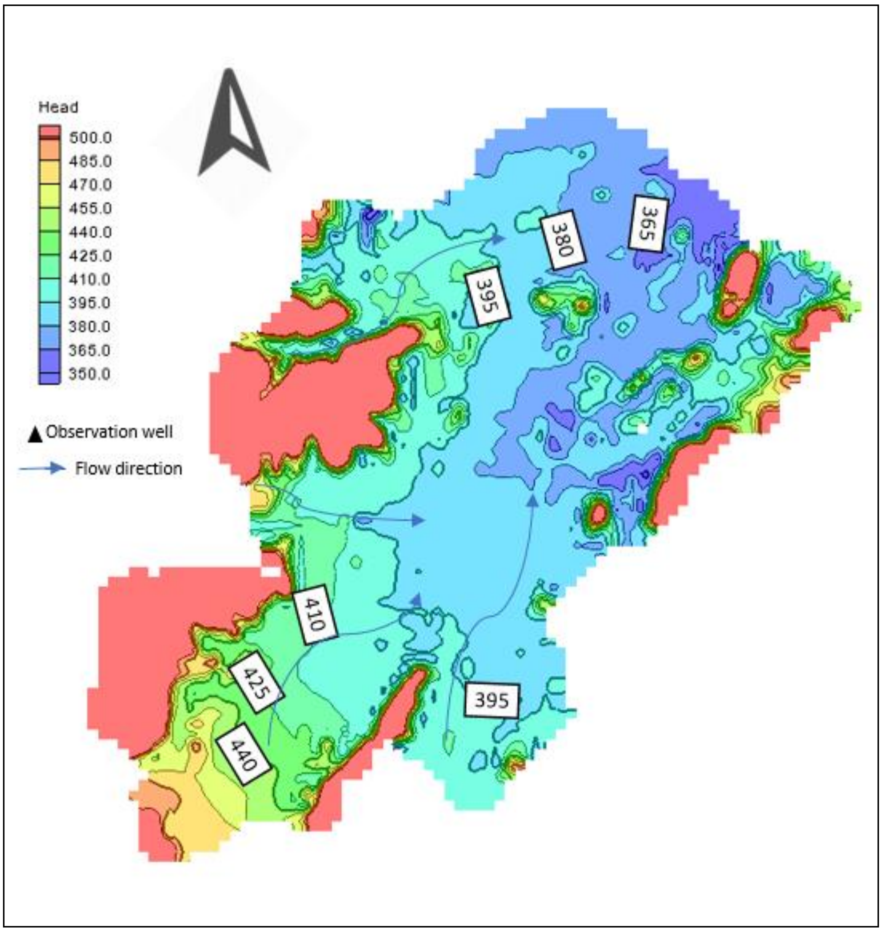

Figure 4 Steady-state head distribution of the Chiang Rai basin.

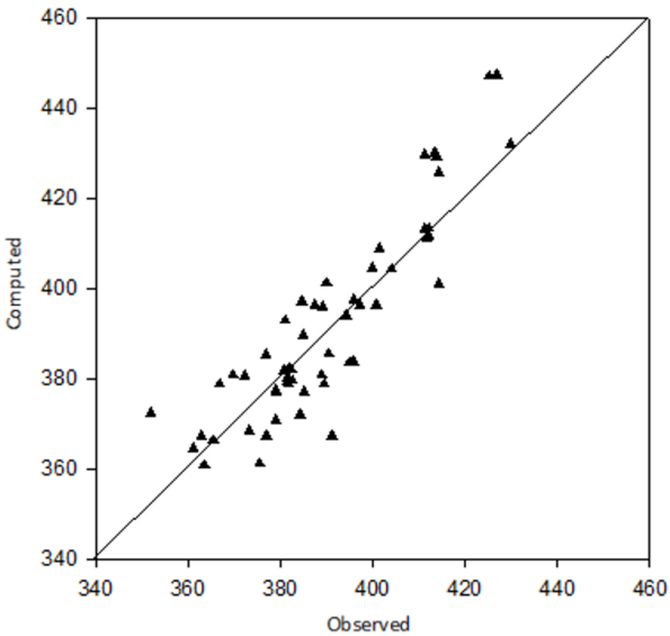

Figure 5 Computed vs. Observed head (m, amsl) in monitoring wells.

Table 2 Steady-state groundwater balance (averaged over the period of June 2016-Present).

Hydrogeologic Components	IN (Mm^3/yr)	OUT (Mm^3/yr)
River	520	527.3
Recharge	51.4	–
Evapotranspiration	–	40.1
Pumping Wells	–	3.98

Note: $Mm^3 = 10^6\ m^3$

MODFLOW simulation results also found that there exists some flooded grids (cells) in the basin which support the presence of ubiquitous flowing artesian wells (locally known as "cooled springs"). The calibrated model was further used to analyzed for safe-yield of the aquifers where groundwater extraction rates were increased (while keeping other parameters constant) until the piezometric heads drop, on average, not-more-than 2 m. The safe-yield of the basin was found to be 0.67 Mm^3/yr.

Conclusions

Numerical groundwater flow model of the Chiang Rai basin was conducted by using a finite-difference based MODFLOW program and the automatic calibration was achieved by using PEST algorithm. Regional flow pattern of high-yield unconsolidated groundwater aquifers (Qfd, Qyt, and Qot) in general flow from highlands toward the center of the basin and, eventually, discharge at the Mekhong river. There are ubiquitous presence flood grid blocks from simulation which supports the finding of flowing artesian wells in the Chiang Rai basin. The safe-yield of the area was determined to be 0.67 Mm^3/yr based on 2-m drawdown criteria.

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