Original Article

Numerical investigation of sustainable groundwater yields for the Wiang Pa Pao aquifer system in northern Thailand

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Abstract

Because of ongoing economic growth, the Kok River Basin in northern Thailand may suffer from near future water stress and its long-term sustainable groundwater yield has to be put into question. Based on a recent hydrogeological investigation of the Wiang Pa Pao aquifer system, which is one of the subsurface units within the Kok River Basin, a 3D groundwater model was set up to evaluate the sustainable groundwater yield for the near future. Steady-state and transient calibrations of the model were conducted for hydraulic conductivity, aquifer recharge, and storativity. The maximum allowable pumping rates to ensure that water levels in the aquifer do not fall below 20 m from the surface in the next 20 years were computed for various districts of the aquifer system. The results indicate that the present-day groundwater extraction rates may be exceeded by a factor of 100 during this time period before the sustainable yield constraint is violated.

Keywords: Wiang Pa Pao aquifer basin, groundwater model, sustainable yield, Thailand

1. Introduction

The Wiang Pa Pao aquifer system is one of the four subsurface systems of the larger Kok River Basin located near the Golden Triangle delta at the northern border of Thailand (Figure 1). This region forms the regional trade center among the southern parts of the Republic of China, Burma, Laos P.D.R, and Thailand, which all border the mighty Mae Khong River. Consequently, the economy in the Wiang Pa Pao Basin area has an enormous tendency to grow. As a matter of fact, as the infrastructure within the Wiang Pa Pao River Basin con-tinues to build up at an increasing pace to serve the economic growth in the future, the natural resources of the region, namely the water resources, will become more stressed which, in turn, could put a damper on further future economic development.

Although groundwater for the time being is still an abundantly available water resource in the Wiang Pa Pao River Basin, this may not be the case any more if future development continues as planned. Yet, no exhaustive groundwater investigation of the basin exists up-to-date with respect to quantity and future sustainability under increased withdrawal rates. For this reason the Department of Ground-water Resources (DGR) of Thailand, which is responsible for the groundwater resources management, has started to set up a comprehensive study of the hydrogeology and groundwater resources of the Wiang Pa Pao Basin aquifers.

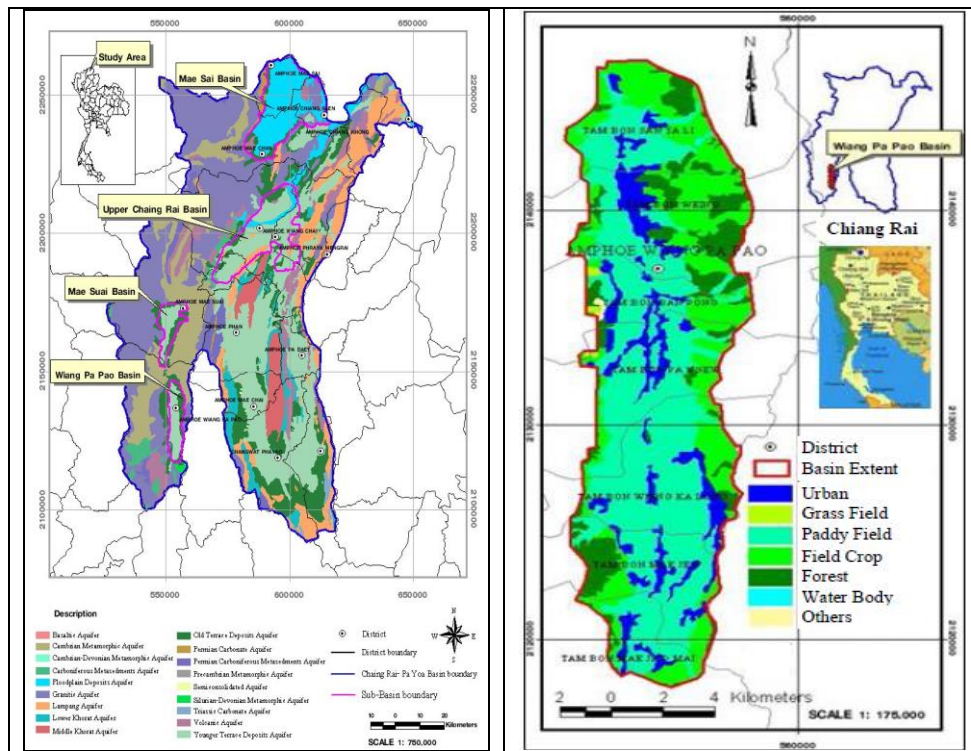*Corresponding author
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Figure 1.   Geological map (left panel) (modified from DMR, 2005) of the Kok River Basin and land-use map of the Wiang Pa Pao sub-basin (right panel).

In the present paper we report the first results of hydrogeological data gathered so far in the set-up of a 3D numerical groundwater flow model (MODFLOW) for the Wiang Pa Pao aquifer basin (Figure 1). The focus of this preliminary modeling study is an estimation of the future "sustainable groundwater yield" under external stresses on this aquifer, namely groundwater pumping, in order to plan well for future sustainable groundwater resources management in the basin.

There have been many, often different, definitions of the concept of sustainable yield (Alley & Leake, 2004; Alley *et al.*, 1998; Arlai *et al.*, 2006; Kalf & Woolley, 2005; Maimone, 2004) which depend on the local aquifer system as well as on the environmental and political constraints within a study region. In the present study we will define the sustainable yield in the study area as the maximum amount of groundwater that can be extracted in the long run, defined as 20 years into the future, such that the groundwater levels will not decrease below a minimum threshold level which in the present case is defined by the DGR as 20 m below the surface. In Section two the set-up of the conceptual model for the Wiang Pa Pao aquifer system and its numerical implementation in the MODFLOW model is described. In Section three the results of the model calibration and the sensitivity analysis are presented and Section four forms the heart of the study, i.e. the computation of the regional and sub-district long-term (20 years) sustainable groundwater yield in the study basin. The paper ends with some conclusions in Section five.

2. Mathematical Formulation, Conceptual Model and Numerical Implementation of the Groundwater Model

2.1 Mathematical formulation

The theoretical basis of any quantitative groundwater study is the so-called groundwater flow equation which allows the simulation of groundwater flow under various internal mechanisms, aquifer characteristics, and different external (hydrological and meteorological) driving scenarios.

The three-dimensional movement of groundwater through a porous earth media is described by the time-dependent groundwater flow equation, e.g., Bear (1978) and Anderson and Woessner (1992), as implemented also in the MODFLOW finite difference model (Harbaugh & McDonald, 1996):

$$\frac{\partial}{\partial x}\left(K_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz} \frac{\partial h}{\partial z}\right) - W = S_s \frac{\partial h}{\partial t} \qquad (1)$$

where K_{xx}, K_{yy}, and K_{zz} (LT^{-1}) are the values of the hydraulic conductivity along the x, y, and z coordinate axes which are assumed to be parallel to the major axes of the general hydraulic conductivity tensor K; h, the hydraulic head (L); W, the volumetric flux per unit volume which represents sources and sinks of water (T^{-1}), namely, groundwater recharge and groundwater pumping, respectively; S_s, the specific storativity

(specific yield for an unconfined aquifer and specific storage for a confined aquifer) of the porous media (L^{-1}); and *t,* time (T).

Since, this study aims in particular to determine the sustainable groundwater yield based on the volumetric groundwater budget, the latter has to be computed in a sub-zonal area of the groundwater environment using again the groundwater mass balance equation, defined as

$$-\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right] = \frac{1}{\rho_w}\frac{\partial}{\partial t}\left(\rho_w n\right) \qquad (2)$$

where ∂q is the net water flux (Darcy flow) in each Cartesian axis direction, ρ_w is the water density and *n* is the porosity (Bear, 1978).

2.2 Conceptual model of the Wiang Pa Pao aquifer system

The Wiang Pa Pao aquifer system is elongated approximately in the north-south direction and encompasses a total area of about 152 km². Due to the topography of the region (Figure 2, left panel), the basin is enclosed from all directions by mountain ridges and the Mae Nam Lao River cuts through the aquifer area and flows north. The ground-

water flow in the aquifer system converges mainly from the west, the east and the south towards the plain area in the middle of the basin where most of the groundwater pumping occurs. In the horizontal directions, the Wiang Pa Pao aquifer system is conceptualized in a model (Figure 2).

Based on the results of the geological investigations of the DGR (DGR, 2009), the geological map (Figure 1, left panel) and the hydrogeological cross-section of the aquifer system (Figure 3, top panel) were constructed. Using this hydrogeological information, the corresponding vertical conceptual model was set up (Figure 3, bottom panel).

One may notice that the Wiang Pa Pao aquifer system shows the classical features of a basin aquifer whose confined layers are mainly recharged at their surficial outcrops at the basin flanks. The aquifer system, as implemented into the groundwater flow model, is conceptualized by a top thin aquitard which overlies 3 confined aquifers each separated by another aquitard layer that results in a total series of 6 aquitards/aquifers. Thus the 1st, 3rd, and 5th layers are low-hydraulic conductivity layers (aquitards) and their thicknesses are 2, 4, and 4 meters, respectively. The 2nd, 4th, and 6th (confined) aquifer layers consist mainly of gravel, sand, and sandy clay, with average thicknesses of 53, 36, and 40 meters, respectively (Table 1). In addition to attributing different values for the hydraulic conductivity to each aquitard/aquifer, the former were further fine-tuned zone-wise in each layer during the calibration process.
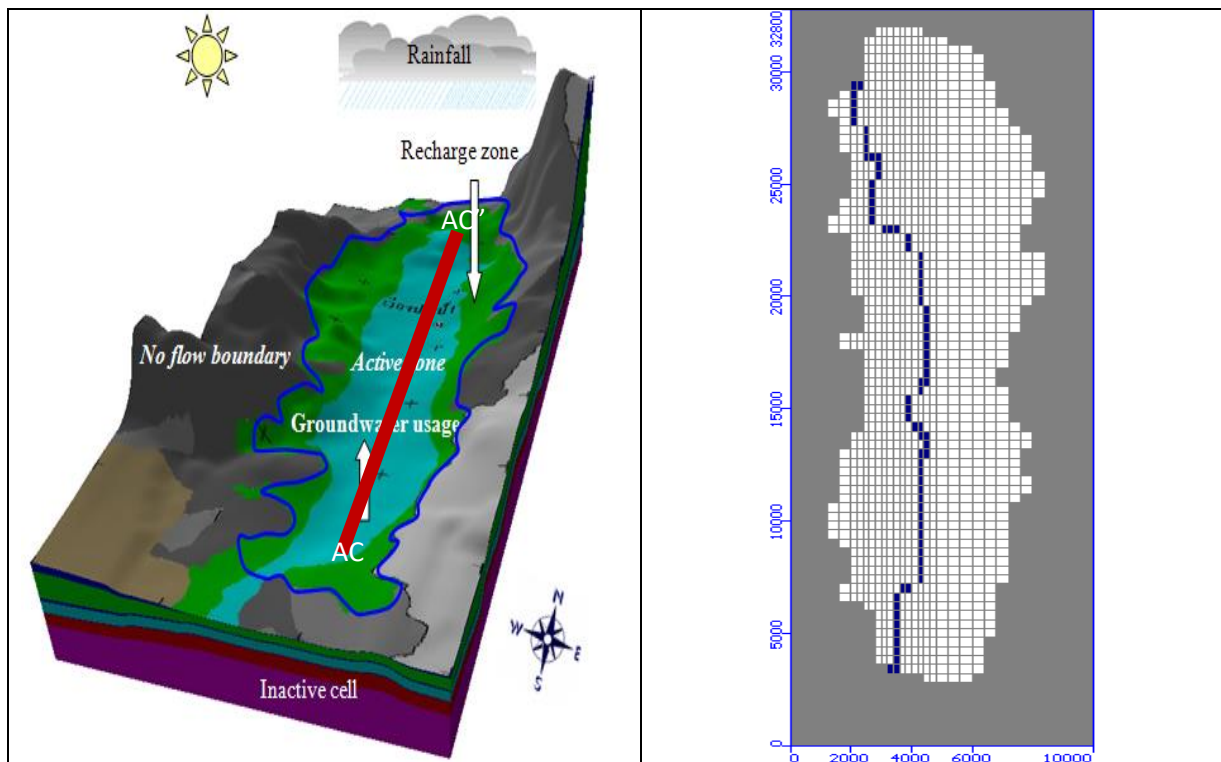

Figure 2. Left panel: conceptual model of the Wiang Pa Pao aquifer basin indicating the boundary of the model and the recharge zones. Right panel: corresponding horizontal optimal finite difference grid with the Wiang Pa Pao River delineated by a blue line. Horizontal scales are in meters.
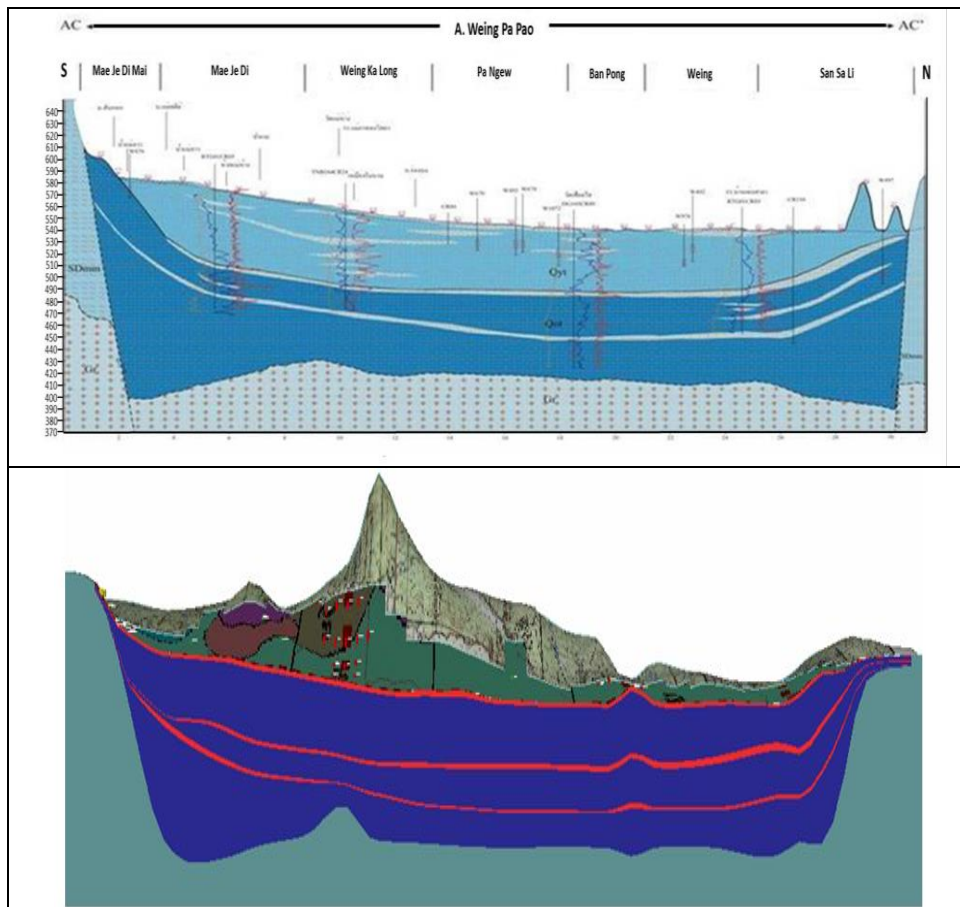
Figure 3. Top panel: geological cross-section of the aquifer system (with heights in m above MSL given on the left vertical axis). Light blue, darker blue, and white denote the first upper confined aquifer, lower two confined aquifers and the three aquitards/clay lenses, respectively.
Bottom panel: corresponding hydrogeological implementation into the conceptual model. The red lines mark the confining aquitards between the separate aquifer layers. Green and blue denote the unconfined and confined aquifer layers, respectively.

Table 1. Hydrostratigraphic units with hydrogeological conditions of the Wiang Pa Pao aquifer system.

Hydro-stratigraphic Unit	Layer Type	Porous Media Material	Layer Thickness (m)
1	Aquitard layer	Clay	2
2	Confined aquifer	Gravel, sand and sandy clay	53
3	Aquitard layer	Clay	4
4	Confined aquifer	Gravel, sand and sandy clay	36
5	Aquitard layer	Clay	4
6	Confined aquifer	Gravel, sand and sandy clay	40

2.3 Groundwater model set up

Following the build-up of the conceptual model of the Wiang Pa Pao aquifer system, the 3D finite difference MODFLOW groundwater flow model (Harbaugh & McDo-nald, 1996) was set up correspondingly, i.e. with one top unconfined model layer and 5 confined model layers with the vertical grid sizes adjusted to follow the various hydrographic units as delineated by the geological profile of Figure 3.

The top unconfined model layer represents the top low-hydraulic conductivity layer, while the aquitards and aquifers are consequently represented by confined layer models. The boundary condition at the top of the model was defined as a groundwater recharge boundary from which the amount of groundwater recharge was calculated by applying land use and the amounts of rainfall and evapotranspiration through a geographic information system over the study domain. The bottom layer and lateral basin flanks were specified as Neumann boundary condition. The course of the Mae Nam Lao River along the basin was specified as a river boundary.

Before the detailed calibration of the model was undertaken, the size of the optimal horizontal grid, i.e. the optimal number of horizontal grid points, was determined. This was achieved by repeated steady-state calibrations using coarse estimations of the important hydrological parameters entering the model and checking the root mean square error (RMSE) between the observed and modeled hydraulic heads.

Figure 4 shows the RMSE obtained in this way as a function of the assumed horizontal grid size. The plot clearly indicates that the most appropriate (optimal) grid spacing is 400 x 400 m^2 as the use of a smaller grid size would not lead to a further reduction of the RMSE but would only unnecessarily increase the computational burden of the modeling process. Based on this result, the aquifer system was modeled on the finite difference grid (Figure 2, right panel).

3. Model Calibration and Sensitivity Analysis

3.1 Steady-state calibration and sensitivity analysis

The groundwater model calibration is carried out to make sure that the model can reasonably mimic the groundwater flow system, namely to fit the observed piezometric heads. The latter were measured at numerous monitoring wells installed by the DGR during the year 2008 (Figure 8, left panel). The measurement period available in the present study was from January to June, 2009.

For the steady-state calibration, the horizontal and vertical hydraulic conductivities ($K_{xx} = K_{yy}$, and K_{zz}, respectively) as well as the groundwater recharge (specified by the term W in Equation 1 for model blocks that are open to the surface) usually turn out to be the most sensitive parameters of a groundwater flow system (Anderson & Woessner, 1992). Thus, these are firstly adjusted to meet the calibration targets. This was done taking the lateral heterogeneities of the land use and the geological soil structure into account.

More specifically, the calibration of the average annual recharge of the four different zones defined by the DGR (2009) was based on the assumed different land-use areas and soil types (Figure 5). The finally calibrated annual recharge values are also listed in Figure 5 and one can recognize that the values range from 0 for an urban area to 136 mm/year in forest areas, i.e. the recharge is characterized by different fractions of triggering precipitation also indicated in Figure 5.
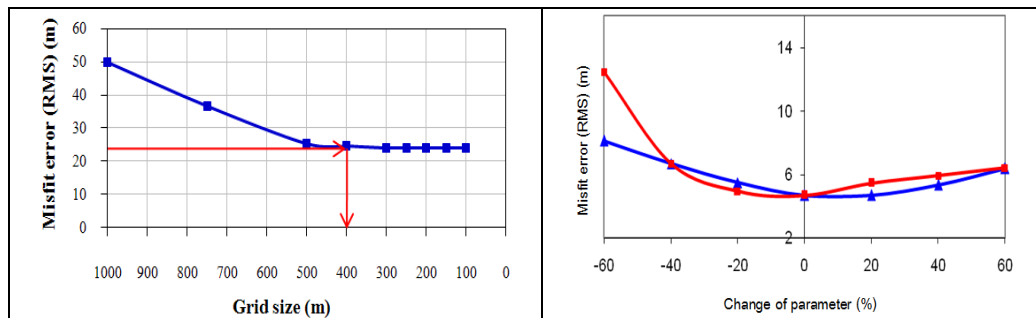

Figure 4.   Left panel: calibration error (RMS) as a function of the grid spacing. The vectors point to the optimal grid spacing. Right panel: sensitivity of objective (misfit) function to recharge W and horizontal hydraulic conductivity K_{xx}= K_{yy}, (denoted here as K_{xy}) as measured by the RMS when the calibration parameter is varied by a certain percentage from the optimal value (at zero). Note the high sensitivity of the RMS to K_{xy}.
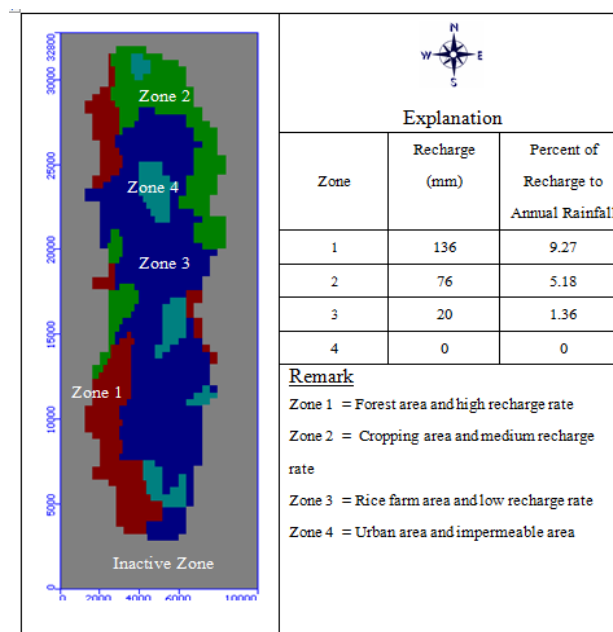

Figure 5. Zone-wise distribution of the calibrated annual recharge assuming four different land-use areas as indicated.

The horizontal hydraulic conductivities K_{xx} and K_{yy}, where isotropy was assumed, i.e. $K_{xx} = K_{yy}$, were calibrated on a smaller areal scale in each layer, were based on the geological soil structure as defined by the field surveys and investigations of the DGR (2009), i.e. the pump tests. Figure 6 shows the results of the zoned areal distribution of the calibrated $K_{xx} = K_{yy}$ for the six aquifer units and Table 2 lists the horizontal areal ranges across each unit of the aquifer. Finally, for the vertical hydraulic conductivity K_{zz}, which is important for the calculation of vertical leakage rates across the layer interfaces, it is commonly assumed to be 1/10 of the calibrated horizontal value $K_{xx} = K_{yy}$ resulting in a list of values (Table 2).
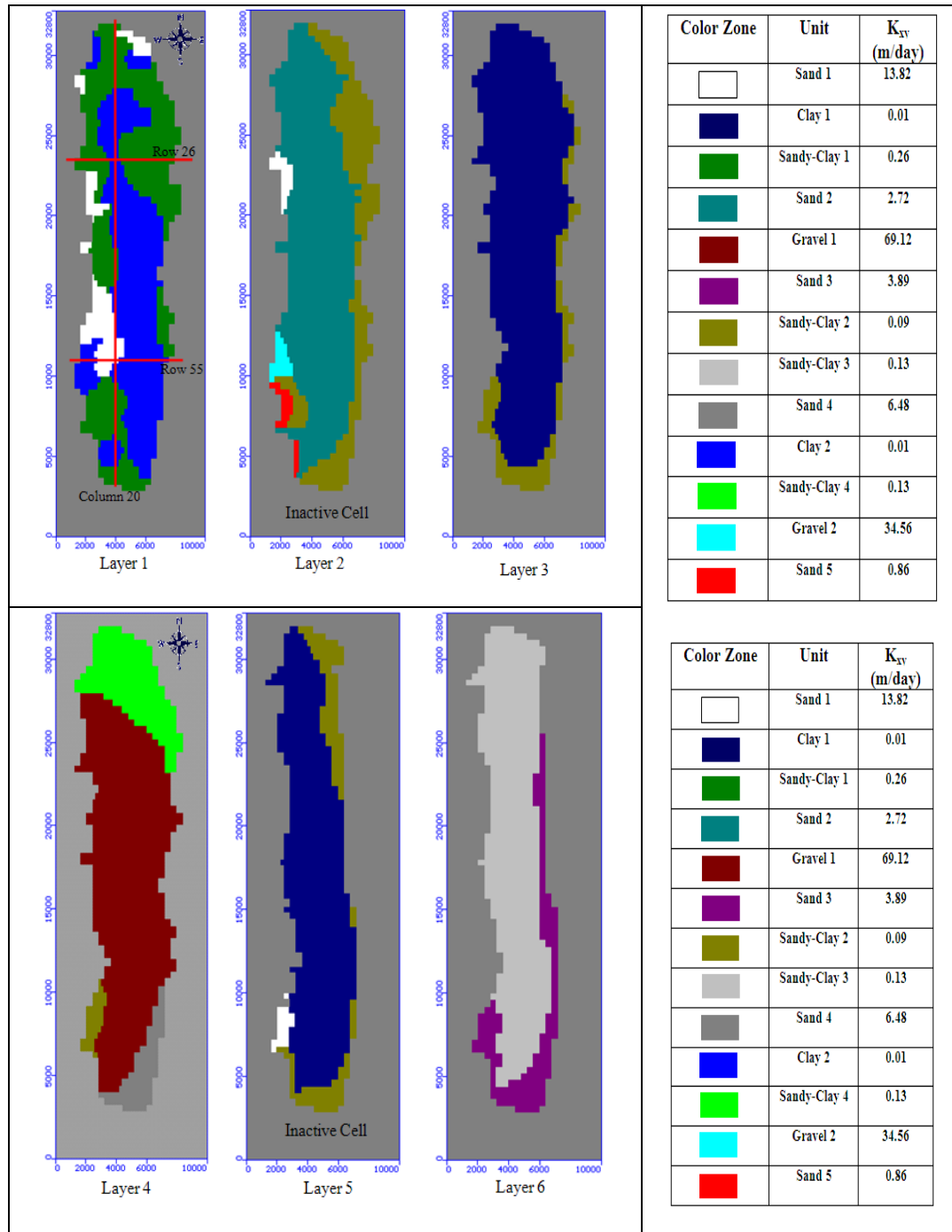

Color Zone	Unit	K_{xy} (m/day)
	Sand 1	13.82
	Clay 1	0.01
	Sandy-Clay 1	0.26
	Sand 2	2.72
	Gravel 1	69.12
	Sand 3	3.89
	Sandy-Clay 2	0.09
	Sandy-Clay 3	0.13
	Sand 4	6.48
	Clay 2	0.01
	Sandy-Clay 4	0.13
	Gravel 2	34.56
	Sand 5	0.86

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	Clay 2	0.01
	Sandy-Clay 4	0.13
	Gravel 2	34.56
	Sand 5	0.86

Figure 6.   Zone-wise distribution of the calibrated hydraulic conductivity K_{xy} in each layer of the aquifer system. The associations of the K_{xy} values with the zoning colors and soils are listed in the table. Horizontal scales are in meters.

Table 2. Wiang Pa Pao aquifer-units' calibrated parameter-range for steady-state and transient groundwater simulations. For the zone-wise distribution of the hydraulic conductivities across the aquifer units.

Hydro-stratigraphic Unit	Horizontal Hydraulic Conductivity, K_{xx} (m/day)	Vertical Hydraulic Conductivity, K_{zz}** (m/day)	Specific yield, Sy* or Specific Storage, Ss (m^{-1})
1	0.01	0.001	0.07*
2	0.26–13.82	0.026–1.382	6.30×10^{-4}–8.60×10^{-4}
3	0.01	0.001	2.00×10^{-3}–2.60×10^{-3}
4	0.26–69.12	0.026–6.912	8.5×10^{-4}–9.2×10^{-4}
5	0.01	0.001	2.00×10^{-3}–2.60×10^{-3}
6	0.13–34.56	0.013–3.456	6.00×10^{-4}–8.60×10^{-4}

**K_{zz} assumed as 1/10 of $K_{xx}=K_{yy}$

As discussed by Arlai *et al.* (2006), various approaches exist for optimal calibration, which basically consists of the minimization of the misfit function, as quantified by the RMSE, of the observed and modeled heads and the subsequent sensitivity analysis. Here we use the simplest one which varies the calibration parameter of interest by a certain percentage from its optimal (reference) value and measure the change of the RMSE of the calibrated model. Basically, this is equivalent to the exploration of the valley of the objective function. The more narrow and steep the valley, the more sensitive is the calibration parameter. This should be the property of a well-behaved groundwater flow model.

Figure 4 (right panel) shows the results of the steady-state sensitivity analysis for both the zoned horizontal hydraulic conductivities $K_{xx} = K_{yy}$ and the average recharge W. The trough-like variation of the RMSE, when perturbing one of the calibration parameters by a small percentage of their reference value, provides additional confidence in the quality of the model calibration of these two parameters and, in particular, of the horizontal hydraulic conductivity.

A quantitative assessment of the steady-state calibration is obtained from the scattered plot of the calculated and observed heads (Figure 7). From both the visual impresssion and the numbers describing the statistics of the calibration annotated in the plot, one may notice good agreement between the simulated and measured heads. In fact, all correlated points are lying well within the 95% confidence band of the slope = 1 from linear regression. Thus one can conclude that the steady-state aquifer parameters hydraulic conductivity K and average recharge W in question are well-calibrated.

The piezometric isolines for aquifer layer 2, as simulated with the optimally calibrated steady-state groundwater model, are shown in Figure 8 (right panel). The groundwater flow vectors are also indicated (not to scale). One may notice good agreement between the calculated and observed hydraulic heads which gives some confidence on the calibrations.
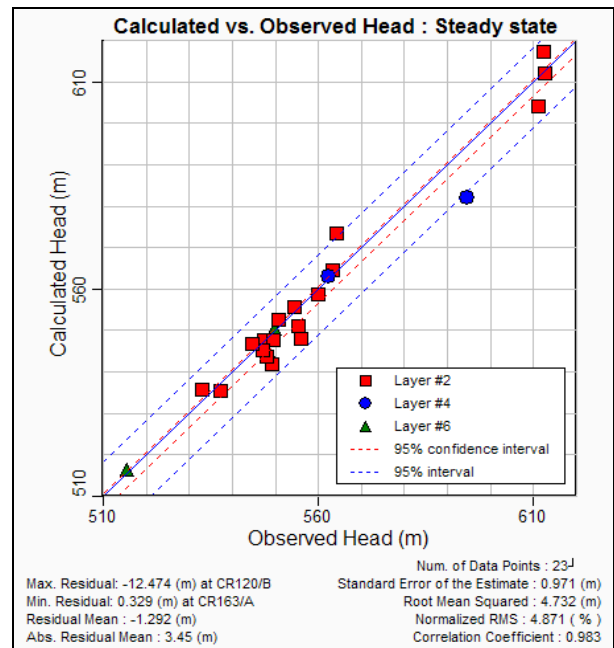

Figure 7. Scattered plot of observed versus calculated heads for aquifer layers 2, 4, and 6 in steady-state calibration. Also shown is the 95% confidence band of the slope = 1 from linear regression and various statistical results of the optimal calibration model.
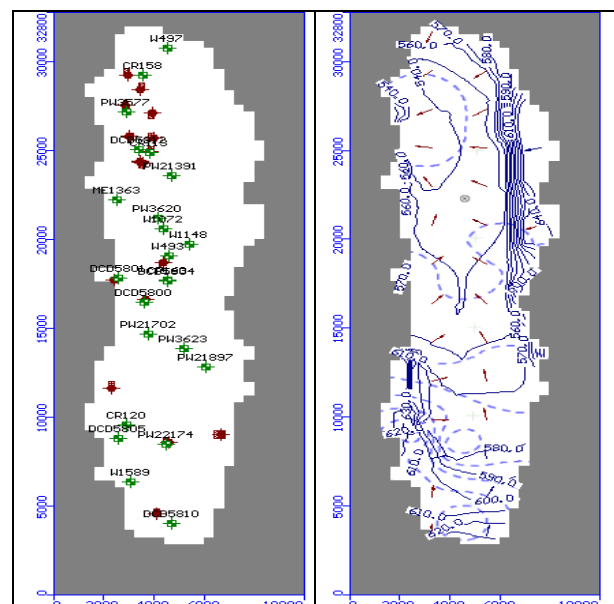

Figure 8. Left panel: monitoring wells in Wiang Pa Pao aquifers basin: the locations of monitoring wells and pumping wells.
Right panel: steady-state spatial distribution of observed (dashed lines) and calculated (solid lines) piezometric heads (m MSL) in layer 2, with arrows (not to scale) indicating the direction of the groundwater flow. Horizontal scales are in meters.

3.2 Transient calibration

The initial condition of transient calibration is used to compute the head distribution at steady state. In the subsequent transient calibration, using the measured hydraulic heads from January to June, 2009 as calibration targets, the storativity, i.e. the specific yield for the unconfined aquifer and the specific storage for the confined aquifers, were calibrated. In addition, a range of values for the different aquifer units was obtained (Table 2). Furthermore, the previously computed annual recharge was fine-tuned to monthly values to better represent the seasonal external driving meteorological conditions (rainfall) in the study region.

The calibration performance was assessed from both quantitative and qualitative points of view. By further adjustment of the specific yield and storage (Table 2) and the zone-wise recharge of Figure 5 on a monthly scale, which is dependent on the monthly rainfall, the success of the transient calibration can be assessed from Figure 9 which shows the piezometric heads of the optimally calibrated transient model. Also shown are the heads measured at the various piezometers over the 6-month calibration period. One may notice again reasonably good agreement of the two head groups. The optimal transient calibration results in a range of 0.07–0.28 for the specific yield in the unconfined aquifer layer and 2.8 x 10^{-5}–2.0 x 10^{-2} m^{-1} for the specific storage in the various confined aquifer layers.

4. Regional and sub-district sustainable groundwater yield

Each aquifer system has a unique definition of sustainable groundwater yield depending on many external environmental, ecological, and social factors (Alley *et al.,* 1999). Therefore, the first task of a sustainable groundwater yield evaluation must consist of an appropriate definition for the aquifer under question, which in this study is the Wiang Pa Pao aquifer system. For this aquifer system, the DGR defined the sustainable yield as "the maximum total pumping rate above the current pumping rate that ensures that the average piezometric head in each layer does not fall below a vertical distance of 20 meters from the land surface during the next 20 years". This concept of the sustainable yield was then introduced as a constraint into the groundwater flow model, whereby each active cell of the finite difference grid was associated with a pumping well.

With this somewhat peculiar and apparently unrealistic approach, the worst-case scenario of groundwater pumping across the entire basin can be simulated and the maximum sustainable yield for all active cells can be computed. Furthermore, the pumping rates across the active cells were divided into 2 zones (Figure 10). Zone 1 is along the western flank of the Wiang Pa Pao Basin where the aquifer thickness is less than 50 m. Zone 2 covers the remainder and the majority of the basin area with aquifer thicknesses greater
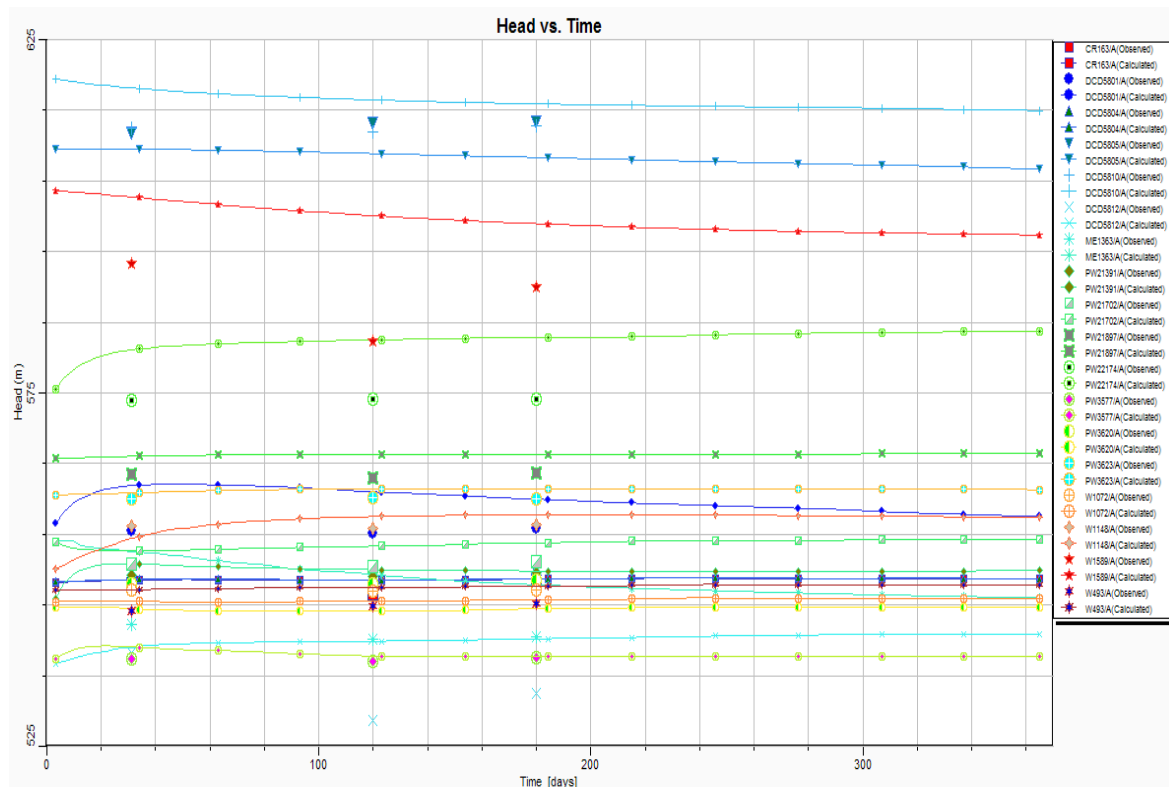

Figure 9.   Measured heads (large dots) (observed from January to June, 2009) and corresponding traces of the calculated piezometric heads (m MSL) in layer 2 at all measuring piezometers for the transient computation period from January, 2009 to January, 2010.
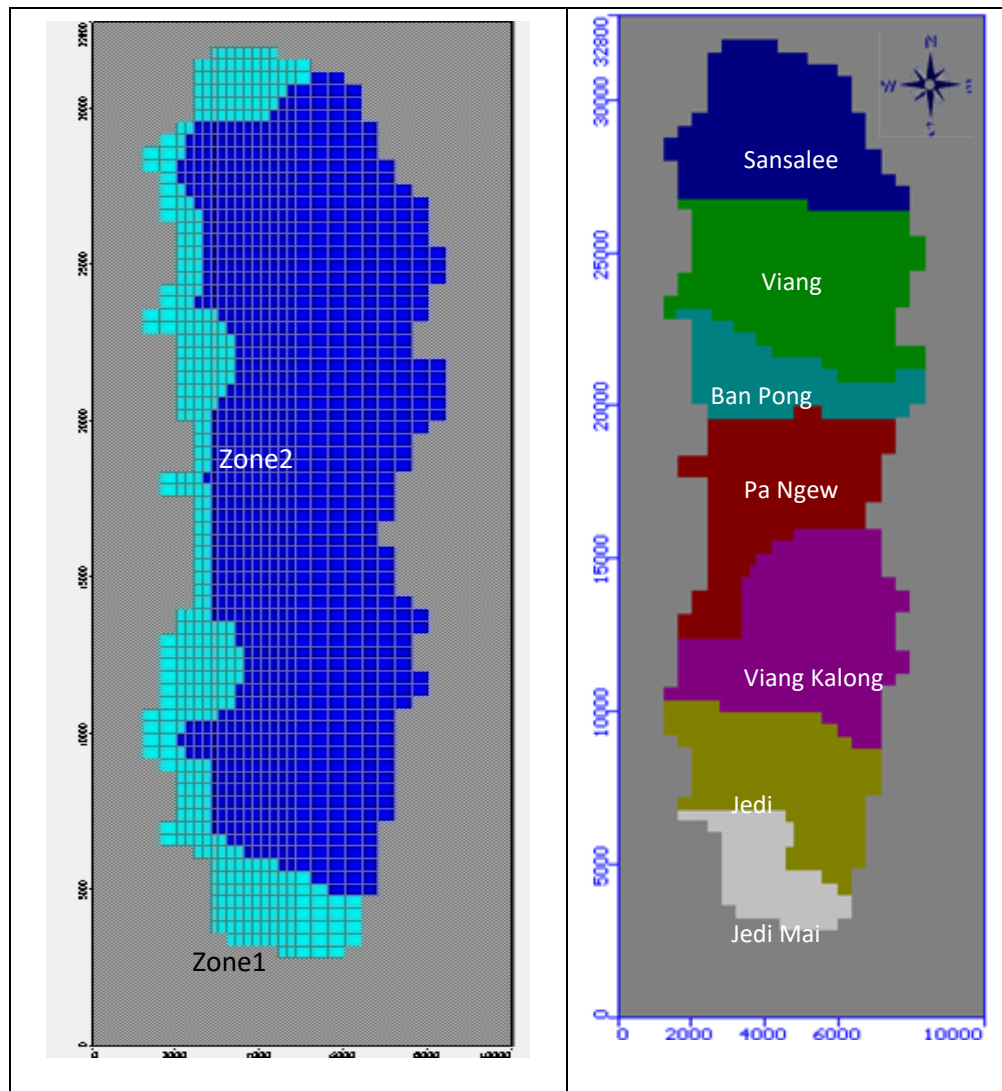
Figure 10.   Left panel: zoning of the pumping rates within the Wiang Pa Pao aquifer system. Zone 1 and zone 2 represent the areas where the aquifer thickness is less than or greater than 50 m, respectively.
Right panel: sub-districts in the Wiang Pa Pao Basin used for the calculation of zone-wise sustainable yields. Horizontal scales are in meters.

than 50 meters. This particular zoning is a consequence of the bowl-like cross-section of the Wiang Pa Pao aquifer system (Figure 3) and the thinning of the aquifer layer thicknesses at the outcropping sections in the western boundaries of the basin (leading to a lower transmissivity T= Kb). Using the same pumping rate across the entire basin would lead to completely different piezometric heads in these two zones owing to the different aquifer thicknesses. On the other hand, across each of these two zones, the pumping rates were assumed to be the same.

The initial pumping in each active cell for each zone was calculated from the averaged values of the current total pumping rate in the corresponding zone. Based on these estimates, the initial pumping rates were specified as 0.698 and 0.24 m^3/day in the active cells of pumping zones 1 and 2, respectively.

The sustainable total pumping rates for the Wiang Pa Pao Basin were found in an iterative trial-and-error manner. As discussed by Arlai *et al.* (2007), a more sophisticated and elegant approach would be to treat the problem as "constrained optimization" and solve it automatically. In that approach the groundwater flow model is run many times at various pumping rates until a sustainable groundwater yield under the water level constraint is met, i.e. the permitted water level drawdown of 20 meters from the surface. Using this iterative approach, a total sustainable groundwater yield for the next 20 years of 169,794 m^3/day was found for the Wiang Pa Pao Basin. With the present-day groundwater withdrawal of only 1,575 m^3/day, this results in a future sustainable yield of 168,220 m^3/day for this basin.

In the subsequent step, the zone-budget module implemented in MODFLOW, which computes the water

budget in a particular zone by considering lateral exchange of flow to adjacent zones, was used to calculate the sustainable yields sub-district-wise. The pumping rates in each of the 7 sub-districts were adjusted in an iterative manner starting from the initial average base pumping rate until the sustainable yields in each zone were attained (Table 3).

Finally, in Table 4 the zone-wise sustainable yields computed for each of the three aquifer layers of the Wiang Pa Pao Basin were cumulated in order to get the total sustainable yield for each aquifer. One may notice from the table that the upper shallow aquifer of the system is the most productive one and the lowest aquifer is the least productive one. This interesting result means that future groundwater extraction systems in the study region should be designed accordingly.

Table 3.   Sustainable yield and yield during the next 20 years for each sub-district of the Wiang Pa Pao aquifer basin.

Sub-district	District	Yield in next 20 Years (m^3/day)	Sustainable Yield (m^3/day)
Sansalee	Wiang Pa Pao	25,835	25,345
Viang	Wiang Pa Pao	33,573	33,153
Ban Pong	Wiang Pa Pao	15,993	15,993
Pa Ngew	Wiang Pa Pao	29,308	29,183
Viang Kalong	Wiang Pa Pao	29,785	29,285
Jedi	Wiang Pa Pao	24,502	24,477
Jedi Mai	Wiang Pa Pao	10,798	10,783
Total		169,794	168,219

Table 4.   Cumulative sustainable yield for each of the aquifer layers of the Wiang Pa Pao basin.

Aquifer	Modeled Layer	Sustainable Yield (m^3/day)
1	2	79,117
2	4	57,818
3	6	31,285
Total		168,220

5. Conclusions

Our comprehensive groundwater flow modeling analysis indicates that while groundwater is still abundant in the Kok River Basin at the present time, attention should be paid to the future groundwater consumption in order to avoid over-drafting with subsequent adverse environmental impacts. Applying the concept of sustainable groundwater yield under external stresses, i.e. groundwater pumping, to one of the aquifers in the basin of the Wiang Pa Pao aquifer system, maximum groundwater extraction rates for the next twenty years were computed to ensure that the average piezometric head in each layer of the aquifer will not fall below a vertical distance of 20 meters from the land surface. Based on this politically prescribed and somewhat arbitrary constraint, the calibrated groundwater flow model shows high sensitivity to the zoned hydraulic conductivities of the various layers. The results indicate a total sustainable yield of 168,219 m^3/day for the Wiang Pa Pao sub-basin as a whole.

Using a zone budget module within the groundwater model, the sustainable yields were then calculated sub-district wise, as well as for the different aquifer layers. The results show basically that the present-day groundwater extraction rates could be exceeded by a factor of ~100 during the next two decades before the sustainable yield constraint would be violated. While this appears to be a reassuring result in terms of the future economic development of the region, one should not forget that the transient groundwater flow predictions have been made under the assumption that no intermediate climatic changes will occur that may adversely impact the groundwater system. Since there is some evidence that climate changes are occurring now in the world and in Thailand (Koch, 2008), further groundwater studies to that regard are necessary in the region.

References

Alley, W. M., & Leake, S. A. (2004). The journey from safe yield to sustainability. *Groundwater, 42*, 12–16.

Alley, W. M., Reilly, T. E., & Franke, O. L. (1999). *Sustainability of ground-water resources. U.S. Geological survey circular 1186.* Denver, CO: U.S. Government Printing Office. Retrieved from https://pubs.usgs.gov/circ/circ1186/pdf/circ1186.pdf

Anderson, M. P, & Woessner, W. W. (1992). *Applied groundwater modeling: Simulation of flow and advective transport.* Amsterdam, The Netherlands: Elsevier.

Arlai, P. (2007). *Numerical Modeling of possible saltwater intrusion mechanisms in the multi-layer coastal aquifer system of the gulf of Thailand* (Doctoral thesis, University of Kassel, Hesse, Germany).

Arlai, P., Koch, M., & Koontanakulvong, S. (2006). Statistical and stochastical approaches to assess reasonable calibrated parameters in a complex multi-aquifer system. *Proceedings of CMWR XVI – Computation Method in Water Resources*, Copenhagen, Denmark. Retrieved from http://proceedings.dtu.dk/fedora/repository/dtu:1689/OBJ/article.pdf

Arlai, P., Koch, M., & Koontanakulvong, S. (2006). Modeling flow and transport for sustainable yield estimation of groundwater resources in the Bangkok aquifer system. *Proceeding of European Geosciences Union General Assembly 2006,* Vienna, Austria.

Arlai, P., Koch, M., & Koontanakulvong, S. (2007). Embedding an Optimization module within a 3d density dependent groundwater and solute transport model to determine an effective groundwater management scheme in the Bangkok aquifers system. *Proceedings of Asian Simulation and Modeling 2007*, Chiang Mai, Thailand.

Bear, J., (1979). *Hydraulics* of *groundwater.* New York, NY: McGraw Hill.

Department of Groundwater Resources. (2009). *Groundwater resources assessment in the Wiang Pa Pao river basin, Bang Wiang Pa Pao.* Bangkok, Thailand: Author.

Harbaugh, A. W., & McDonald, M. G. (1996). *User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey, Open-file report.* Reston, VA: Office of Ground Water, U.S. Geological Survey. Retrieved from https://water.usgs.gov/software/code/ground_water/modflow/doc/ofr96485.pdf

Kalf, F. R. P., & Woolley, D. R. (2005). Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeology Journal, 13*, 295-312.

Koch, M. (2008). Challenges for future sustainable water resources management in the face of climate change. *Proceedings of the 1st NPRU Academic Conference*, Nakhon Pathom University, Thailand.

Maimone, M. (2004). Defining and managing sustainable yield. *Groundwater, 42*, 809-814.