Groundwater Modeling for Conjunctive Use Patterns Investigation in the Upper Central Plain of Thailand

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Abstract

In the upper part of the Central Plain of Thailand which covers about 38,000 km^2, due to the government price-subsidized policy, farmers tend to grow rice more often now resulting in a high demand for irrigation water, with the latter being drafted increasingly from groundwater resources. This has not only put pressurre on the regional aquifers but, owing to river-groundwater interactions, also on the surface waters in the region. As part of a major national effort, conjunctive water use patterns are to be explored to optimize the water resources in the upper Central Plain for the various stakeholders involved. In the present study conjunctive use pattern of surface- as well as groundwater are investigated by field surveys and groundwater flow modeling using the MODFLOW model. The groundwater basin of the upper Central Plain is 180 km x 300 km large and 40 – 200 meters thick and discharges to the lower basin in the south. A two-layer conceptual aquifer model, with an upper semi- confined and lower confined layer, is developed to simulate the groundwater movement over the last 10 years. Beforehand an investigation of the groundwater use was conducted. The latter can be categorized into 3 main types, namely, industrial, domestic and agricultural. Groundwater use patterns were considered for different seasons (wet and dry), different water availability situations (wet, normal, dry, drought, as well as within different administrative irrigation projects and precipitation zones. A pilot area in the study area was selected to investigate the actual water use patterns, farmers' irrigation behavior and constraints; i.e. harvest terms, groundwater pumping hours, pumping ability, maximum water drawdown etc. Furthermore, the surface water supply, calculated from the water balance, was compared with estimated groundwater extraction to recheck and redefine the conjunctively usable zone. As a major result our study shows that the farmers are the major groundwater users in the area consuming 91% of the total, versus 5% by the domestic and 4% by the industrial users The conjunctive patterns vary significantly as a function of the water availability conditions, such that the portion of groundwater covering the total water-demand in years of wet, normal, dry and drought conditions is 13%,17%,13%, and 19% respectively. The groundwater ratio in the dry and wet season is 6% and 38%, respectively, of the demand. The dominant area of groundwater use is in the irrigation project area. Finally, future groundwater demand in the groundwater basin has been predicted and it is found that the conjunctive use pattern is a key factor to estimate groundwater consumption and to assist in the proper conjunctive planning in order to mitigate future water shortages and to sustain the groundwater resources in the area.

Keywords: Groundwater; modeling; MODFLOW; conjunctive use; groundwater demand; Thailand

1. Introduction

In spite of the tremendous steps made in recent years towards becoming an industrialized country, Thailand still defines itself economically as an agricultural country, as the export of agricultural products, namely rice, is still bringing in a large portion of the national revenue. Boosting up rice production and, at the same time, the often precarious living conditions of the rice farmer has, thus, been an active policy of the Thai government in recent years and which has supported many irrigation projects and agricultural price-subsidized schemes to support farmers. At the same time both groundwater and surface water resources have been developed to respond to increased water consumption in the private, domestic and agricultural sector. The upper part of Central Plain of Thailand is located in a large plain that is very suitable for agriculture, as water resources are normally plentiful. However, with the active price policies mentioned, farmers nowadays tend to grow rice more often which can only be achieved through increased irrigation using both surface- and, lately, also more and more groundwater, putting more pressure on the totally available water resources in the region. This precarious situation asks for the use of techniques of so-called conjunctive management which is a management approach similar to IWRM (Integrated Water Resources Management), with the emphasis on the combined use of both surface- and subsurface waters to meet the total water demand.

In the upper Central Plain many large irrigation-serviced fields are scattered, making a central delivery of irrigation water through canals difficult. This has led farmers to mostly set up their own groundwater wells on their paddies and pump individually groundwater to compensate surface water shortages. This individual and uncontrolled pumping has induced a decline of the groundwater table in parts of the irrigated areas, causing future problems of groundwater accessibility for the farmers. Since the groundwater level is going down mainly in the dry season when pumping for rice paddy irrigation is at its highest, artificial aquifer recharge during the wet season has been suggested to alleviate the water storage problem in this region (Chulalongkorn, 1998). However, given its huge costs, such a recharge project has not been implemented yet up-to-date.

As it is not possible to provide sufficient surface water for irrigation, a conjunctive use scheme should be developed (RID, 2005). Although there are many long-term hydro-meteorology data and surface-water development projects available, no groundwater-use behavior study in this region has been conducted up to now, and most of the pumping wells are not well recorded. Moreover, groundwater levels have been monitored judiciously for just a few years. There is a lack of a comprehensive groundwater study which is necessary to understand the subsurface- and, because of the intertwined interaction, also the surface water resources, and which is prerequisite for a conjunctive use analysis.

Beforehand it is necessary to understand the present conjunctive use-pattern, i.e. the proportion of local agricultural, industrial and domestic water demand as a function of the prevailing conditions of surface-water supply and the geographical characteristics. These use-pattern have been established, sometimes sketchily, from field surveys and questionnaires handed out to farmers and are to be used in a groundwater model (MODFLOW) to simulate the long-term behavior of the exploited groundwater system and to come up, eventually, with sustainable conjunctive water use pattern for the future

2. Study area

The upper Central Plain, Thailand, covers about 38,000 km^2 (180 km x 300 km) of 8 provinces with a population of 4 million people. The main land use is 63% agricultural, out of which 21% is irrigated, and 24% forest. More than 90,000 groundwater wells exist in the region. The main groundwater basin is dissected by 5 main rivers that flow from north to south and which make the basis geologically a depositional flood plain. The basin is surrounded in the east and west by mountains of volcanic rocks. The average elevation of the basin is 40-60 m above MSL elevation. The basin drains into the lower basin in the south, though the free discharge is partially obstructed by crystalline rocks there. The annual rainfall on the basin ranges between 900 and 1,450 mm.

3. Groundwater modeling for conjunctive use pattern analysis

3.1 Methodology and data collection

Groundwater levels and movement in the study area are simulated with the GMS/MODFLOW groundwater flow model. The modeling approach follows the usual steps of building the conceptual model, the model design, followed by calibration, verification/prediction (cf. Anderson and Woessner, 1992). Groundwater use is a key input parameter in this study. There are three main types of groundwater use: agricultural, domestic and industrial. Questionnaires were distributed to farmers to inquire data on the estimated groundwater use. A further verification of the latter was gained from an analysis of the surface water shortage. The reported pumping rates were grouped and classified with respect to the surface-water availability in the year considered (wet, normal, dry, and drought), the season of the year (wet and dry) and the location (inside or outside an irrigation project, surface basins, aquifer characteristics). Groundwater levels were collected in the field and/or taken from historical records. The geohydraulic properties were estimated from pumping tests and groundwater

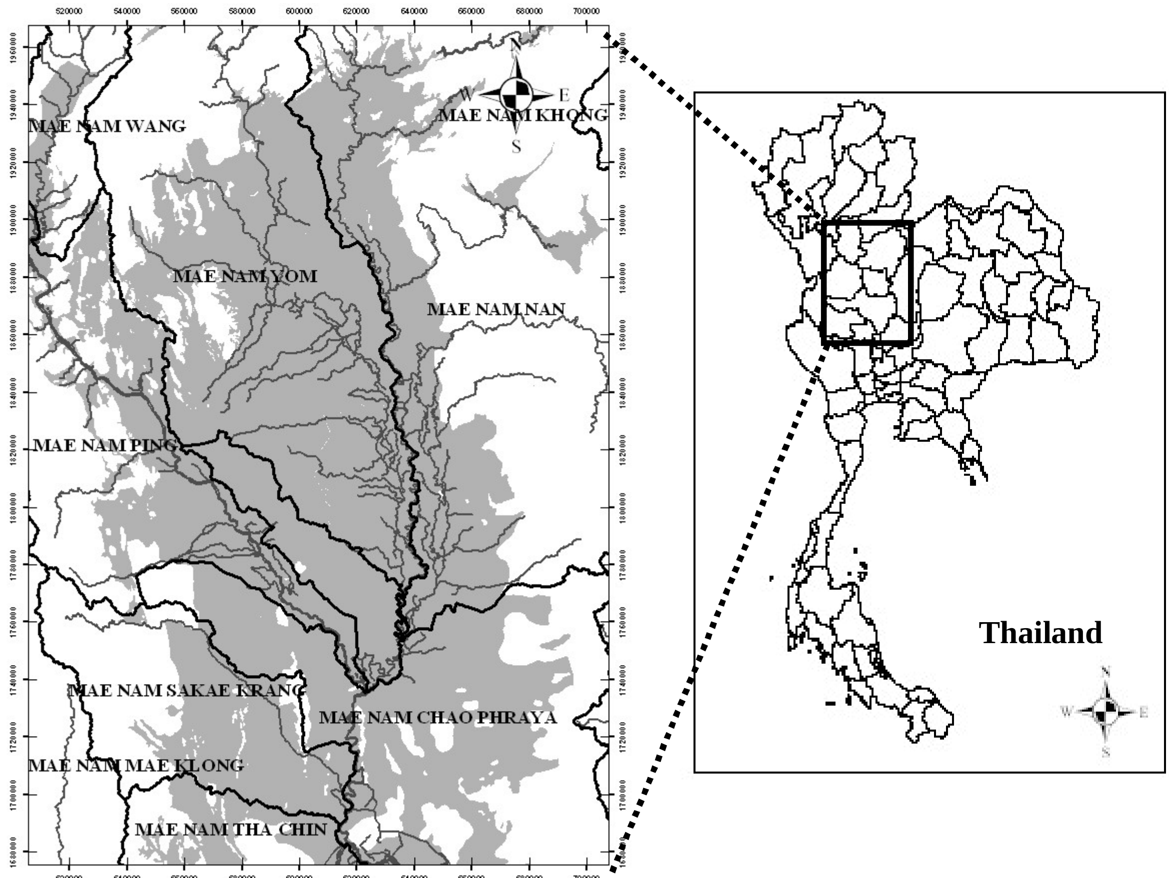

Figure 1: *Map of the study area with the alluvial aquifers*

recharge was computed from rainfall and an assumed infiltration rate (Koontanakulvong, 2002).

During the calibration of the model the groundwater pumping rates were further adjusted on the grid-cells, in order to wipe out as much as possible inconsistencies in the reported data. A surface water balance analysis (using Mike Basin and WUSMO) is eventually carried out to estimate the ratio between surface and subsurface water use and compare it with the actual water demand. A scheme of the methodology used is depicted in Fig. 2

3.2 Model Development

The groundwater conceptual model, namely the aquifers and their confining boundaries were defined using the concept of the hydrostratigraphic unit which is a geologic units of similar hydrogeologic properties. The aquifer system in this study was defined as a two-layer aquifer, whereby the thickness of the upper, semi-confined layer varies between 40-100m and lower, confined layer between 100-300m (cf. Fig. 3) . The 3D- block-centered grid model represent the groundwater basin has a grid-size 10 km x 10 km, resulting in 320 elements in the upper and 346 grids in lower layer (Fig. 4).

The western, eastern and northern borders of the model where assumed as impermeable body, consolidate rock, were defined as specific flow in boundaries (totally 587 million m^3/year) derived from the available head along these boundaries. The southern boundary which is partially blocked by impermeable rock and forms a narrow trough between the mountains in the east and west is set as a flow-out boundary. A previous study on the lower Central Plain groundwater basin (Siriputtichaikul, 2003) provided an outgoing flow rate between upper and lower plain of 56 million m^3/year and this number is also used here. An average areal recharge of 555 million m^3/year, derived from rainfall and from a map of the soil-type, and its infiltration rate (Koontanakulvong, 2002), was applied on to the top layer and on the outcropping sections of the lower layer. The stream recharges from the 5 main basin rivers average 337 million m^3/year comprise both flow in and out of the stream

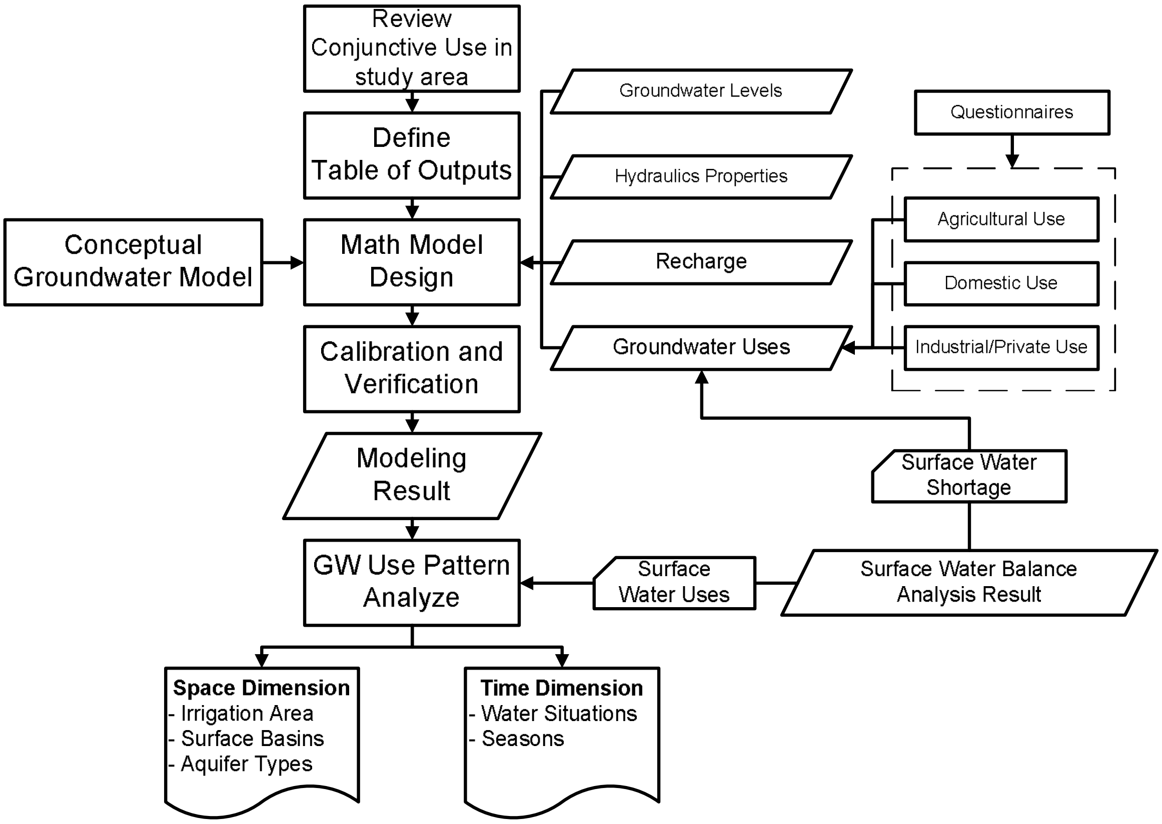

Figure 2: *Overview of study scheme*

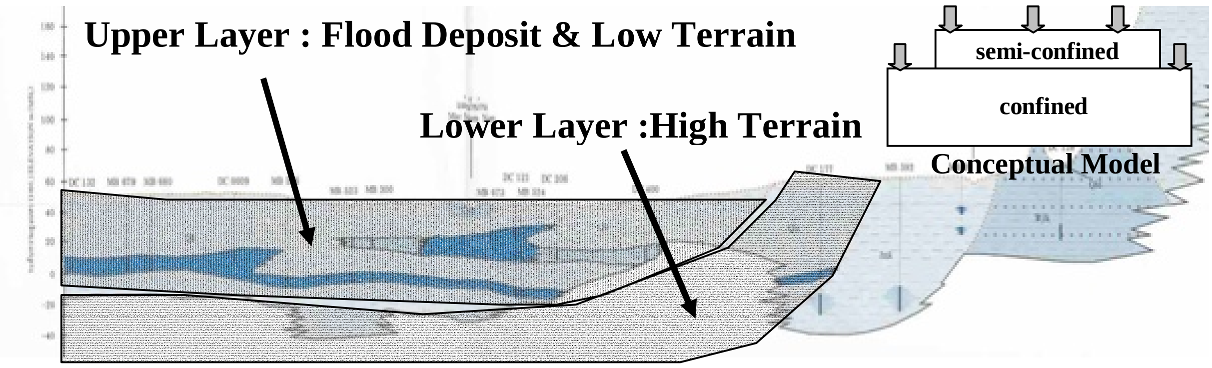

Figure 3: *2- layer aquifer conceptual model*

from and into the aquifer and were derived from the hydraulic properties of the river bed materials, the river cross-sections and the river stages.

The hydraulic properties of the aquifer, namely hydraulic conductivity, transmissivity and specific storage, were estimated from pumping tests. In addition, the aquifer properties as well as vertical leakage were obtained from three previous sub-region groundwater models of the area (Jindasagnon,1997; Chulalongkorn, 1998).

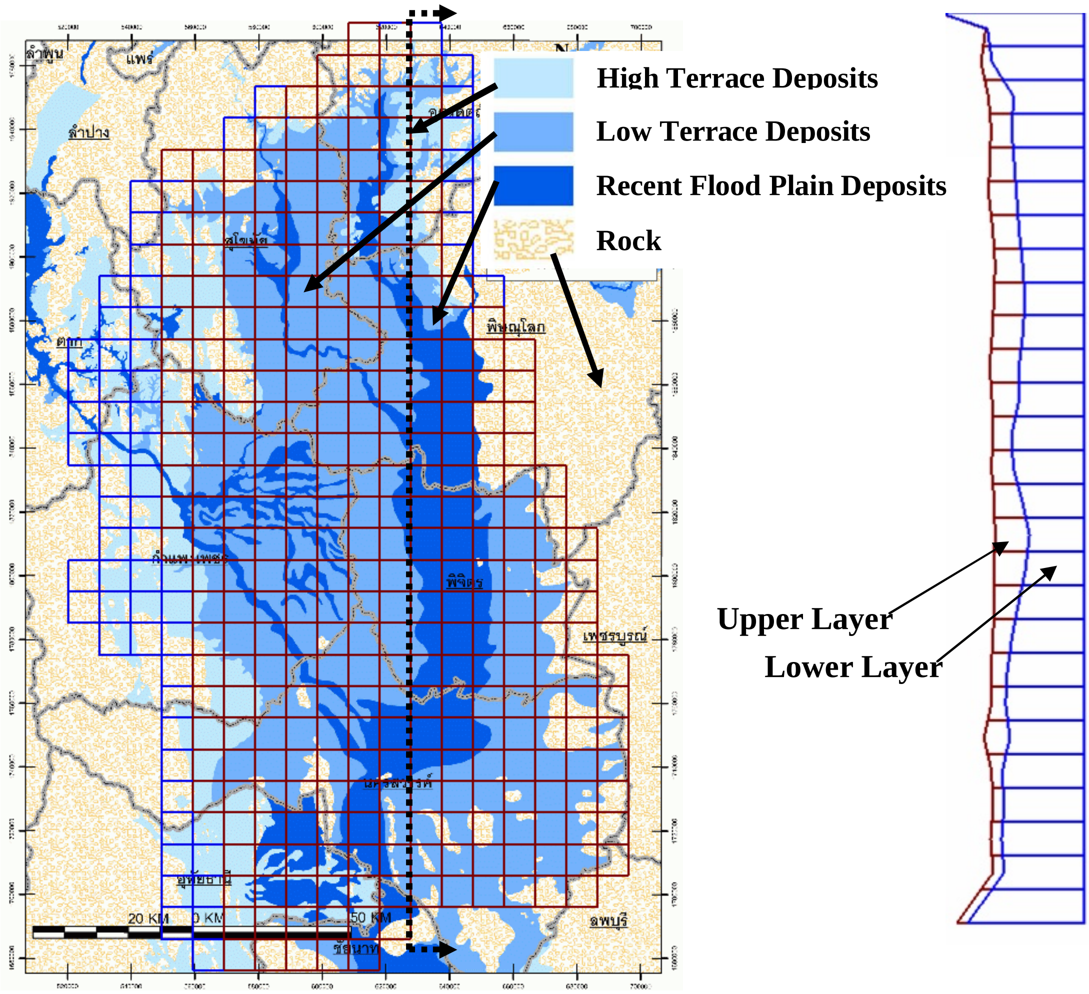

Figure 4: *Model grid design with vertical NS cross-section*

3.3 Groundwater use

As mentioned groundwater use estimation has been categorized into 3 main types: industrial, domestic and agricultural. Industrial groundwater use has been determined from government records that list the location of the well, its depth and the pump rate, with 992 registers that summarized pumping rate is 380 million m^3/year but only 26 million m^3/year extracted in the upper aquifer. Domestic groundwater use has been divided into 2 types: village tap-water and water from private wells. The groundwater use of the village tap-water depends on the number of families there and amounts to a total of 30 million m^3/year. The total number of shallow wells in the study area in 2003 has been 78,114 with a ratio of agricultural to personal consumption-well of 1:3 (Chulalongkorn, 2002) and an average personal consumption of 709 liters/well/day, amounting to a total personal consumption-well pump rate of 11 million m^3/year.

The major groundwater use in this area is for agriculture, namely rice and some sugar cane in the western section of study area. Since the crop pattern is seasonally planed, the agricultural stress period used in the model is also based on the seasonal, i.e. wet and dry cycle. Agriculture wells are usually installed by the farmer to supplement a shortage of surface irrigation water, therefore, records often do not exist and the pumping behavior is unknown. Because of this the C-38 service unit inside the Plychumpol irrigation project area in Phitsanulok Province has been selected as a pilot study area to investigate the actual water use pattern, farmers' behavior and constraints; i.e. harvest terms, groundwater pumping hours, pumping rates, maximum water drawdown, etc. Moreover, 500 questionnaires were distributed to 30 sample sub-districts located in 5 surface-basins throughout the entire study area.

The major pumping statistics retrieved from the survey is summarized in Table 1. From the data listed there one can deduced that the average pumping capacity is 41 m^3/hour/well, whereas the average pumping rate is 79 m^3/day/well inside the irrigation project and 76 m^3/day/well outside.

As for the groundwater-well database it is based on records of the year 2003. The historical yearly record of the wells in each province in 1993-2003 has been converted to growth rate of the well concentration for the future. As mentioned, besides the seasonally triggered agricultural water use, the latter is also dependent on the surface water supply available during the time under question which, in turn, is linked to the actual storage of two main upstream reservoirs (Koontanakulvong, 2002), namely, the Bhumibol and Sirikit reservoirs which provide surface-water and irrigation water to this area. The totally usable storage of the Bhumibol and Sirikit reservoirs on January, 1 was used to define the situation of surface water availability, namely, wet, normal, dry and drought, as shown in Fig. 5. The yearly pumping rates were weighted relative to this surface water situation using 1999 as the base year which has been a drought year, i.e. when the pumping rate has been at a maximum. In addition, agricultural groundwater use was rechecked by considering the amount of compensable water to the agricultural surface-water shortage which was calculated from water demand using the model WUSMO the and water balance using the model Mike Basin.

Table 1: *Average pumping frequency from 5 surface-basins with 500 questionnaires*

area	crops/year	season	pumping/crop	day/pumping	hours/day
irrigation	2.5	dry	6.0	2.6	19.3
		wet	3.8	2.3	19.3
rainfed	2	dry	6.5	3.1	22.0
		wet	3.1	2.1	16.0
pilot area (irrigation)	2.28	dry	5.4	4,9	20.4
		wet	3.5	4.5	23.8

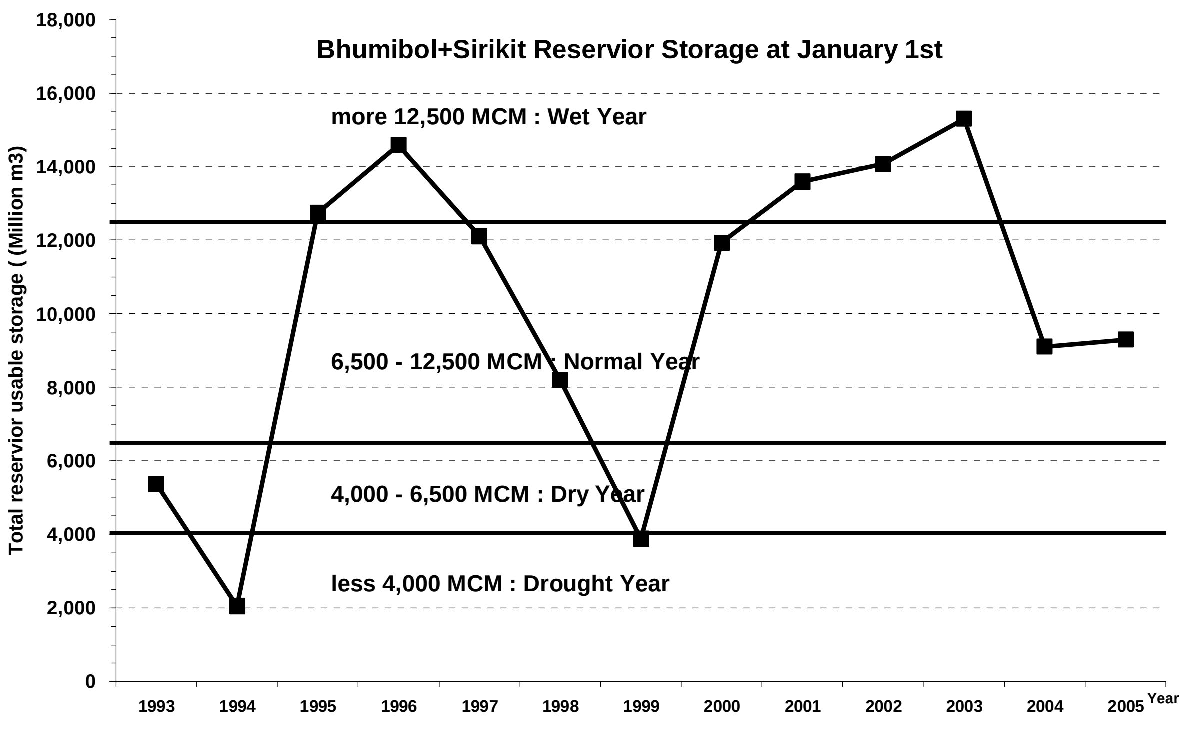

Figure 5: *Historical storages of the Bhumiphol and Sirikit Reservoir*

3.4 Calibration and verification

Model calibration and verification/prediction was performed in steady-state as well as transient state. Following the seasonal crop pattern, the seasonal stress period was used in the calibration of two years of recorded historical groundwater levels. The early water level data were obtained from registered wells that recorded water levels during well construction. The last updated well records are from 2003. Since during 2001-2003 the groundwater use was almost stable due to a constant situation for the surface water (see Fig.5), the average water level during the dry season of 2003 was selected to be the representative steady state water level used in the calibration. 13 groups of the hydraulic conductivity were adjusted during the steady state calibration process. Fig. 6. illustrates the observed and simulated steady-state groundwater levels for the semi-confined layer 1 and one

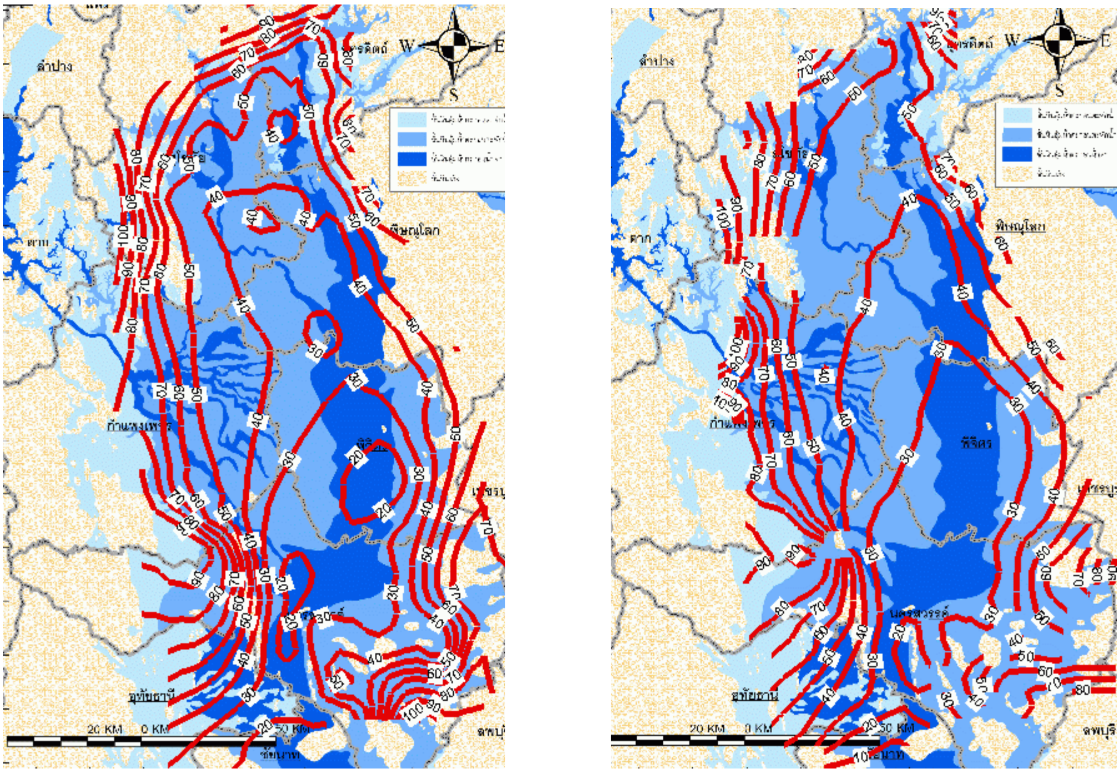

Figure 6*: Observed (left panel) and simulated (right panel) steady-state groundwater levels in 2003*

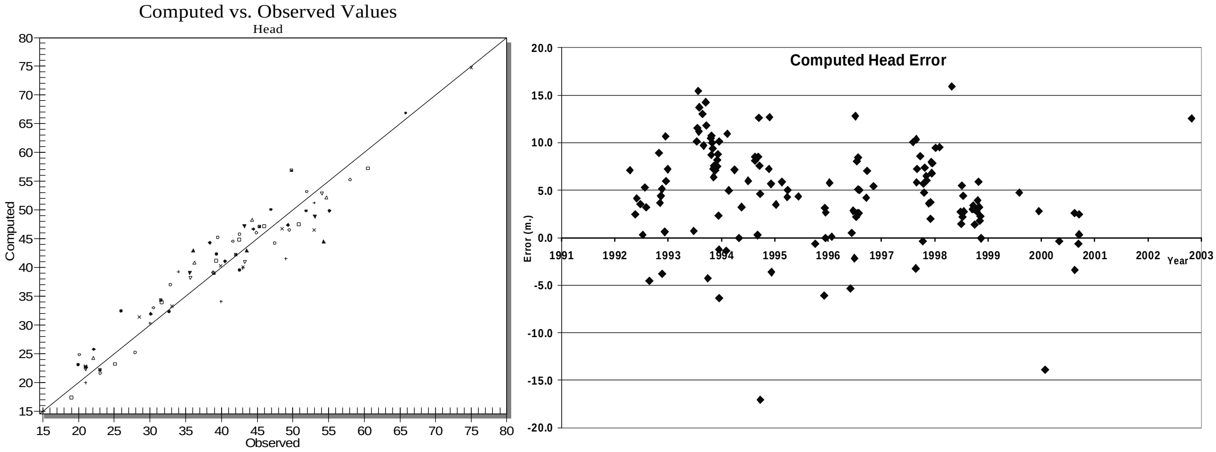

Figure 7*: Computed versus observed heads for layer 1 in steady state (left panel) and transient error as a function of time in layer 1 for the transient simulation (right panel)*

notes a rather good agreement between the two which is also manifested by the scatter-plot of the observed versus modeled heads shown in the left panel of Fig. 7 .

Calibration in transient state has been carried out using 1993-2003 historical water levels whereby groups of specific storage have been calibrated. The transient simulation is initialized from an average wet-season water level. During the transient state calibration the pumping rate weights were fine-tuned, as these are often prone to errors. In summary, the root mean square calibration error is 3.70m in steady state mode and 5.11m in transient mode (see Fig. 7, right panel). An a posteriori transient state verification/forecast, using two-year groundwater level monitoring data (2004-2005) and water level data from 50 extra observation wells collected during the study period (2005) has been performed, resulting in a root mean square error of 5.95 m.

3.5 Model results

The groundwater flow simulations in the study area show that the water levels are on the average about 4 m below ground surface in the wet season but drop to 6-9 m. below GS in the dry season depending on the surface water availability situation. Significant head drops of 2.5-7 m are observed between the wet and the dry season in one year, especially in the dry season of a drought year where the head changes amount to 3-8m. The water balance of year 2003 shows that the total groundwater use was 812 million m^3/year, with a total inflow of 1,142 million m^3/year and natural outflow out 489 million m^3/year. The total groundwater extraction in year 2005 has increased to 1,068 million m^3/year. The groundwater flow model has been used to compute historical seasonal groundwater uses, based on the assumption hat the ratio of groundwater use in the dry season is 2-4.3 times that in the wet season of the same year. Moreover, the results of the study show clearly that the farmers are the major groundwater users in this region with 715 million m^3/year, with a ratio of groundwater use of 91%:5%:4% for the agricultural, domestic and industrial sectors, respectively.

The groundwater use patterns vary significantly with the water availability situation, as farmers are attempting to compensate the lack of surface water by groundwater during drought years. For example, Fig.8 illustrates that groundwater use runs inversely with surface water use and that during the drought years 1994 and 1999 an increasing amount of had to make up for the scarcity of surface water. The conjunctive use ratios of groundwater and surface water as a function of water-demands in consequence of the surface water situation are listed in Table 2, and one notices that the groundwater use ratio increases when less surface water can be supplied. However, inside the irrigation area, the groundwater use ratio in a drought year is not too different from a normal dry year, as the irrigation policy is to restrict the irrigation water consumption in such precarious situations. The average ratio of groundwater use to water demand in a wet, normal, dry and drought year are 13%,17%,13%,19% and 6%,7%,9%,10% in the irrigation and rain-fed areas, respectively.

In Table 3 the conjunctive use ratios of groundwater to surface water use to water-demands are listed separately for the various surface basins. Obviously almost all of the groundwater use ratios are higher inside the irrigation project than for the rain-fed areas. The highest groundwater ratio is observed in the Nan basin where a potential high-yield groundwater aquifer is encountered. In fact, Table 4 indicates furthermore that the highest pump yields are obtained in those aquifers whose alluvial deposits are the most conducive to groundwater flow.

For the pilot study area located within the Plychumphon irrigation project, where there is concentration of rice farming (2.5 crops/year) the groundwater pumping behavior has been explored in more detail. Table 5 illustrates that whereas the groundwater use in the pilot study area in the wet season is much higher than the average use inside the irrigation area (see Table 2) , it is similar in the dry season. In the irrigation project water is allocated by a rotation rule, whereby farmers obtain irrigation water for one week but have to wait another 3 weeks for the next allocation. In the pilot study area, on the other hand, farmers tend to pump groundwater when irrigation water is rotated to other farms in order to keep their young rice alive. Even when irrigation water was allocated to farms, water was collected in ponds or ditches along the canal that caused the total water use to be much higher than required by the demand.

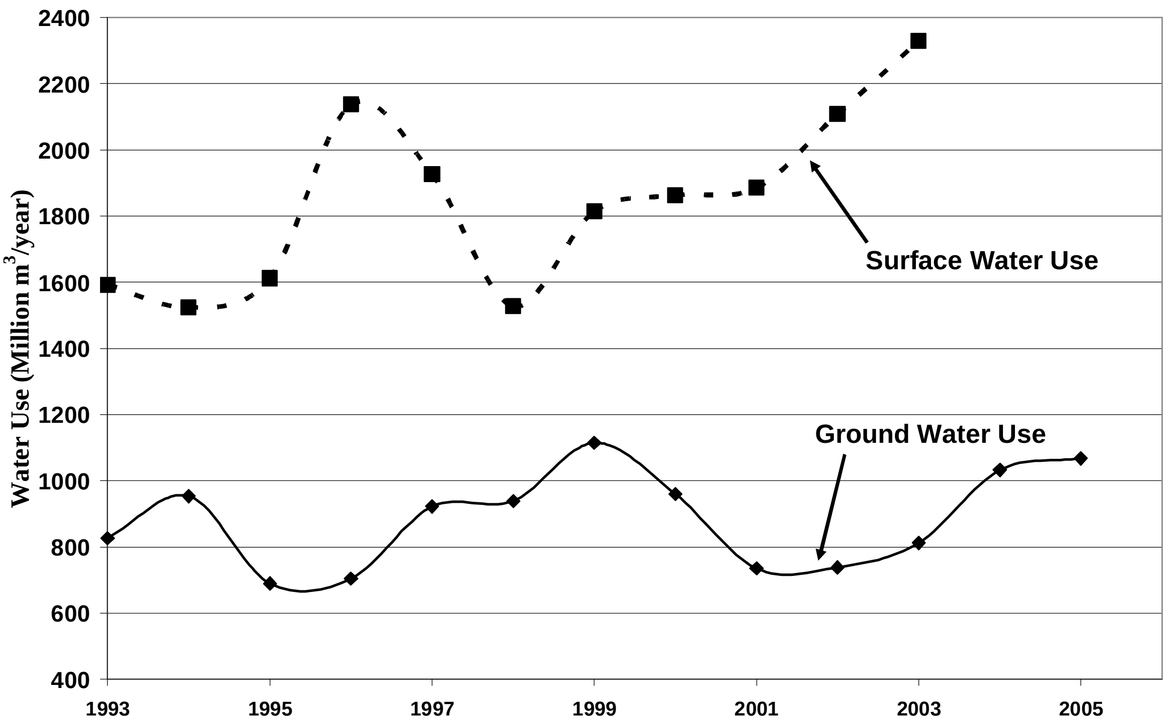

Figure 8: *Comparison of total groundwater and surface water use*

Table 2: *Average conjunctive use ratio as a function of the surface water situation*

irrigation condition	**water demand : SW : GW**		
water situation	**wet season**	**dry season**	**whole year**
irrigation area			
Wet	1 : 0.74 : 0.05	1 : 0.50 : 0.29	1 : 0.66 : 0.13
Normal	1 : 0.77 : 0.06	1 : 0.37 : 0.38	1 : 0.62 : 0.17
Dry	1 : 0.77 : 0.05	1 : 0.25 : 0.54	1 : 0.68 : 0.13
Drought	1 : 0.80 : 0.06	1 : 0.63 : 0.53	1 : 0.74 : 0.19
rain-fed (no irrigation)			
Wet	1 : 0.98 : 0.02	1 : 0.54 : 0.46	1 : 0.94 : 0.06
Normal	1 : 0.98 : 0.02	1 : 0.36 : 0.64	1 : 0.93 : 0.07
Dry	1 : 0.97 : 0.03	1 : 0.24 : 0.76	1 : 0.91 : 0.09
Drought	1 : 0.97 : 0.03	1 : 0.18 : 0.82	1 : 0.90 : 0.10

Table 3: *Conjunctive use ratio of 5 basins during times of normal surface water situation*

Basin	**water demand : SW : GW**	
	Irrigation area	**rain-fed area**
Mae Nam Ping	1 : 0.54 : 0.08	1 : 0.83 : 0.17
Mae Nam Yom	1 : 0.90 : 0.01	1 : 0.87 : 0.13
Mae Nam Nan	1 : 0.53 : 0.30	1 : 0.97 : 0.03
Mae Nam Chaophraya	1 : 1.00 : 0.02	1 : 0.99 : 0.01
Mae Nam Sakaekrang	1 : 0.83 : 0.01	1 : 0.99 : 0.01
all basins	1 : 0.62 : 0.17	1 : 0.93 : 0.07

Table 4: *Groundwater use for different aquifer types*

aquifer types	pump yield M^3/hr	average ratio of groundwater use to water demand
flood deposits	10-20	17%
Low terrace deposits	5-12	7%
high terrace deposits	1-10	2%

Table 5: *Conjunctive use ratio in pilot study area during dry season*

water situation	water demand : SW : GW
Wet	1 : 0.49 : 0.27
Normal	1 : 0.32 : 0.36
Dry	1 : 0.47 : 0.52
Drought	1 : 0.63 : 0.68

4. Conclusions and future development of groundwater resources

Our study shows that conjunctive use pattern significantly varies with surface water situation, season, aquifer characteristic and irrigation-rainfed area. The agricultural sector is the major user of groundwater resources in the study area (91% of the total groundwater use). Groundwater supplements 2-5% of the water-demand in the wet-season and 29-82% in the dry season when there is increased surface water shortage. The major area of groundwater use is that of the irrigation project (60% of the groundwater use).

Moreover groundwater demand in the groundwater basin was also examined by using the conjunctive use ratio to predict the groundwater use. Fig. 8 shows three lines obtained by using different calculation methods for the pumping rate, namely, (1) the average pumping rate, (2)an increasing pumping rate that reflects growth and, (3) pumping rates based on the conjunctive use ratio of this study, with a water situation as observed in the past. The groundwater use was set up as a constraint and, using the simulation model, the groundwater levels are predicted. The model results depicted in Fig. 9 show the different water levels encountered with these three approaches and one can clearly make out the one with the lowest water levels, i.e. the conjunctive use ratio approach. As the groundwater drawdown is an important factor in the consideration of the impact of groundwater extraction and, namely, sustainability, the groundwater levels in the pilot area are examined with the conjunctive use ratio approach using the same future cyclic water demand and water situations as in

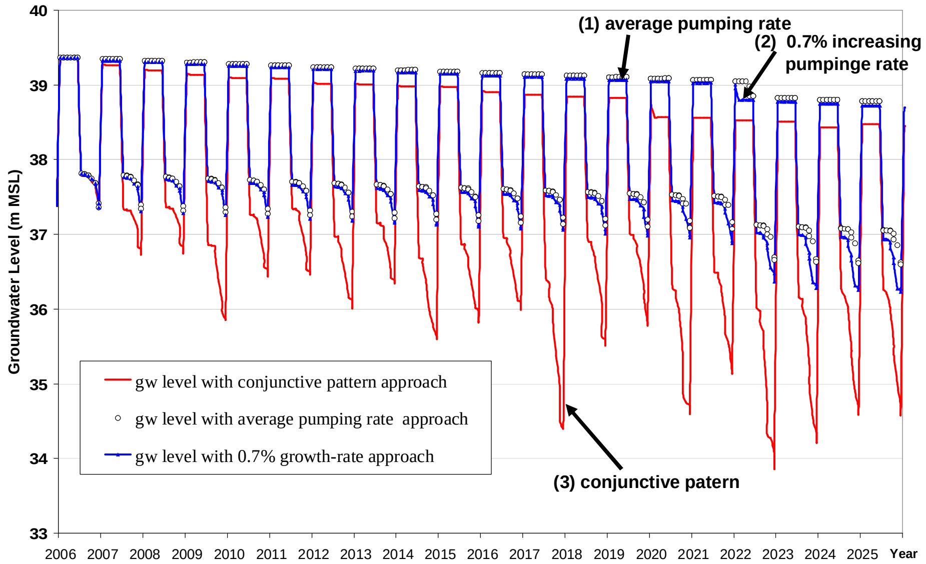

Figure 8*: Groundwater levels resulting from the use of different pumping calculations*

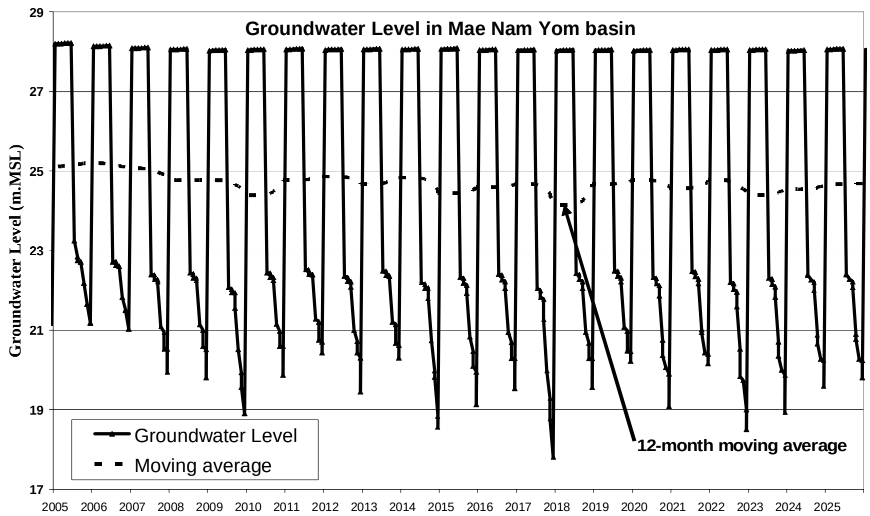

Figure 9: *Groundwater level at the pilot study area examined with the conjunctive use ratio approach*

the past. The simulation results for the groundwater level in the Mae Nam Yom basin, where groundwater is abundantly extracted, are depicted in Fig. 9 and one notes that the water levels would possibly decline by about 10 m from a wet season to a drought year, as the one mimicked for year 2018.

Finally, the future development of the groundwater table in the study ahead was predicted using the conjunctive use ratio. Fig.10 shows that in the year 2026 the water table will have inclined by an average of 2-3 m a in dry season under normal water situation as compared with a dry season in 2003. Therefore the conjunctive use pattern is the key factor for the estimation of future groundwater consumption and may assist in the proper conjunctive planning, especially in the future, in order to mitigate water shortages and sustain the groundwater resources for years to come.

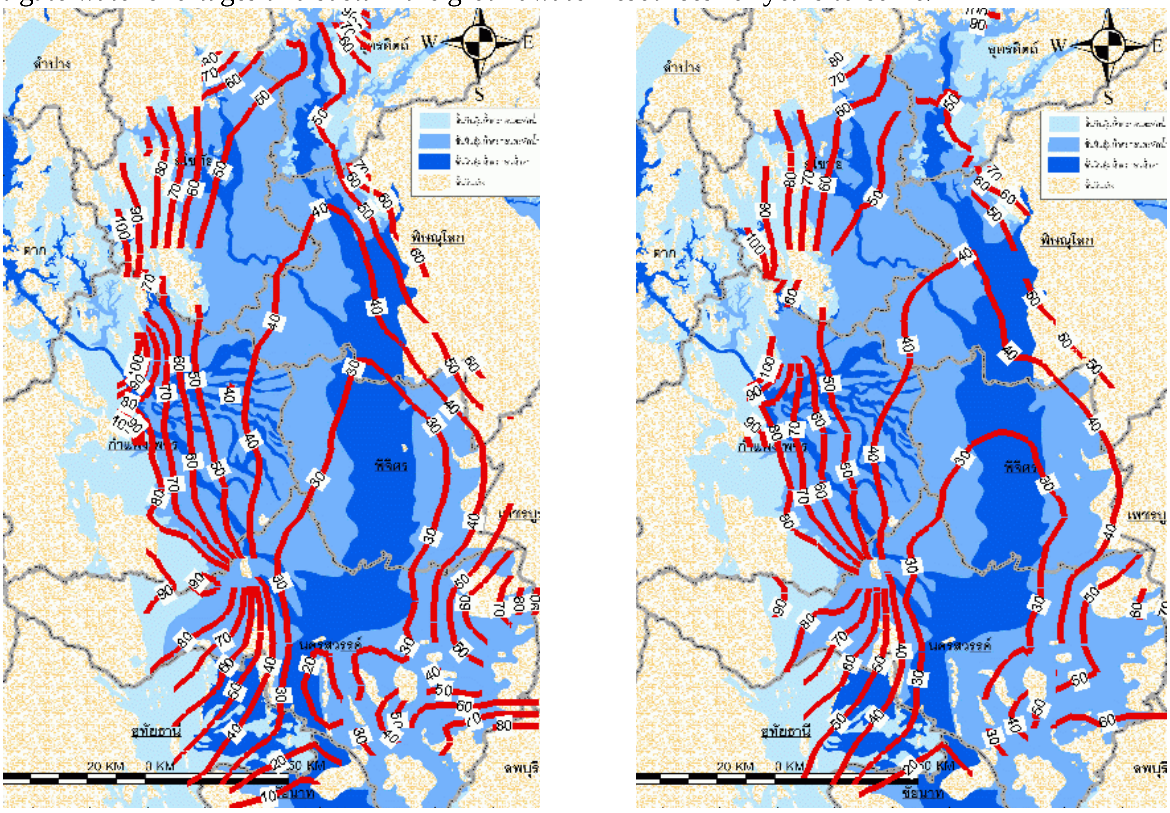

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Figure 10*:* *Simulated* development *of the groundwater table using the conjunctive use ratio*

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