CHAPTER 13

Groundwater modelling 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 km², 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 pressure 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 optimise 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 modelling, using the MODFLOW model. The groundwater model of the upper Central Plain is developed to simulate the groundwater movement over the last 10 years, before an investigation of the groundwater use was conducted. The latter can be categorized into three main types, namely, industrial, domestic and agricultural. Groundwater use patterns were considered for different seasons (wet and dry) and different water availability situations. A pilot area in the study area was selected to investigate the actual water use patterns, farmers’ irrigation behaviour and constraints; i.e. harvest terms, groundwater pumping hours, pumping ability, etc. The conjunctive patterns vary significantly in response to the water availability situation, 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. Finally, the future groundwater demand in the groundwater basin has been predicted and it is found that the conjunctive use pattern is a key factor for the estimation of groundwater consumption and for the assistance in the proper conjunctive planning in order to mitigate future water shortages and to sustain the groundwater resources in the area.

Keywords: Groundwater demand; river-aquifer interaction, modelling; MODFLOW; conjunctive use; Thailand.

1 INTRODUCTION

In spite of the tremendous steps made in recent years towards becoming an industrialised 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 has lead it to develop many irrigation projects and agricultural price-subsidized schemes to support local farmers. At the same time, both groundwater and surface water resources have been developed to respond to an increased water consumption in the private, domestic and agricultural sector.

The upper part of the 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 groundwater, putting more pressure on the available water resources in the region. This precarious situation asks for the use of techniques of so-called conjunctive management (Chun, 1964) 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 (cf. Bealaineh, 1999; Azaiez and Hariga, 2001). 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 groundwater individually to compensate surface water shortages. The subsequent and often uncontrolled heavy 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-behaviour 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 only just a few years. Hence, 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, both of which are prerequisites 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 the groundwater model, MODFLOW (Harbaugh et al., 2000), to simulate the long-term behaviour of the exploited groundwater system and to come up, eventually, with sustainable conjunctive water use patterns for the future.

2 STUDY AREA

The upper Central Plain, Thailand, covers about 38,000 km² (180 km × 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 five major rivers that flow from north...
to south and which have formed the basis geologically as 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.a.s.l. The basin drains into the lower basin in the south, though the free discharge is partially obstructed by crystalline rocks there. The 900–1450 mm annual rainfall within the study region is apportioned to 81% in the wet (Apr.–Sep.) and to 19% in the dry season (Oct.–Mar.).

3 GROUNDWATER MODELLING FOR CONJUNCTIVE USE PATTERN ANALYSIS

3.1 Methodology and data collection

Groundwater levels and movements in the study area are simulated with the GMS/MODFLOW groundwater flow model. The modelling approach follows the usual steps of building the conceptual model, the model design, calibration and verification/prediction (cf. Anderson and Woessner, 1992). Groundwater use is a key input parameter in this study. There are three main types of groundwater uses: agricultural, domestic and industrial. Questionnaires were distributed to farmers to acquire data on the estimated groundwater use. A further verification of the latter was gained from an analysis of several recent surface water shortages. 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 and 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 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) was eventually carried out to estimate the ratio between surface and subsurface water use and compare this 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 units which is defined as 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 and 100 m and that of the lower, confined layer between 100 and 300 m (cf. Fig. 3). The 3-D block-centred grid model representing the groundwater basin has a grid-size $10 \text{ km} \times 10 \text{ km}$, resulting in 320 elements in the upper and 346 elements in the lower layer (Fig. 4).

The western, eastern and northern borders of the model where assumed as an impermeable body of consolidated rock and were defined as specific inflow boundaries (total 587 million m$^3$/year) derived from the available head distribution along these boundaries. The
southern boundary, which is partially blocked by impermeable rocks and forms a narrow trough between the mountains in the east and west, was set as an outflow boundary. A previous study on the lower Central Plain groundwater basin (Siriputtichaikul, 2003) provided an outgoing flow rate between the upper and lower plain of 56 million m$^3$/year and this number was 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 the top layer and on the outcropping sections of the lower layer. The river-aquifer interaction of the five main rivers giving an average annual recharge of 337 million m$^3$ were derived from the hydraulic properties of the river bed materials, the river cross-sections, the river stages and the seasonally varying computed groundwater table. As for the possibility of return flow of irrigated water into the canals, we assumed it negligible since, (1) the drainage canals in the irrigation area are usually nearly dried out, except during the flood season and, (2) the irrigation area covers only 13% of the entire model where the overall recharge takes place.

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-regional groundwater models of the area (Jindasagnon, 1997; Chulalongkorn, 1998). The recharge, river stages, surface – and groundwater use were adapted in response to the climatic conditions, namely, in terms of the amount of rainfall and the reservoir storage.

3.3 Groundwater use

As mentioned, groundwater-use estimation has been categorized into three 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, all in all 992 registered items. The summary pumping rate is 380 million m$^3$/year, but with only 26 million m$^3$/year extracted in the upper aquifer. Domestic groundwater use has been divided into two 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 domestic consumption-well of 1:3 (Chulalongkorn, 2002) and an average daily domestic consumption of 0.71 m$^3$/well, amounting to a total domestic-consumption from wells of 15 million m$^3$/year in 2003.

The major groundwater use in this area is by agriculture, namely, for 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 climatic conditions, i.e. the wet and dry seasonal cycle. Agricultural wells are usually installed by the farmer to supplement a shortage of surface irrigation water, therefore, records often do not exist and the pumping behaviour 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’ behaviour 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 five surface-basins throughout the entire study area.

The major pumping statistics retrieved from the survey is summarised in Table 1. From the data listed there one can deduce that the average pumping capacity per well is 41 m$^3$/hour, whereas the average pumping rate per well is 79 m$^3$/day inside the irrigation project, and 76 m$^3$/day 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 during 1993–2003 has been converted to a growth rate of the well concentration for the future. As mentioned, besides the seasonally triggered agricultural water use, the latter depends also 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), the Bhumibol and Sirikit reservoirs which provide surface-water and irrigation water to this area. The usable storage of these two reservoirs on January 1st 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 as it 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 (1) the water demand using the model WUSMO and, (2) a water balance using the model MIKE BASIN.

### 3.4 Calibration and verification

Model calibration and verification/prediction was performed in steady state as well as in transient state. Following the seasonal crop pattern, the seasonal stress period was used in

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**Table 1.** Average pumping frequency from five surface-basins with 500 questionnaires.

<table>
<thead>
<tr>
<th>Area</th>
<th>Harvest frequency (crops/year)</th>
<th>Season</th>
<th>Number of pumpings for each crop (times)</th>
<th>Duration of each pumping (days)</th>
<th>Pumping period each day (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation</td>
<td>2.5</td>
<td>dry</td>
<td>6.0</td>
<td>2.6</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wet</td>
<td>3.8</td>
<td>2.3</td>
<td>19.3</td>
</tr>
<tr>
<td>Rainfed</td>
<td>2.0</td>
<td>dry</td>
<td>6.5</td>
<td>3.1</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wet</td>
<td>3.1</td>
<td>2.1</td>
<td>16.0</td>
</tr>
<tr>
<td>Pilot area (irrigation)</td>
<td>2.28</td>
<td>dry</td>
<td>5.4</td>
<td>4.9</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wet</td>
<td>3.5</td>
<td>4.5</td>
<td>23.8</td>
</tr>
</tbody>
</table>

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**Figure 5.** Historical storages of the Bhumiphol and Sirikit reservoirs.
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 construc-
tion. The last updated well records are from 2003. Since during 2001–2003, the groundwa-
ter 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 for the calibration. 13 groups of the hydraulic conductivity were
adjusted during the steady-state calibration process. Figure 6 illustrates the observed and
simulated steady-state groundwater levels for the semi-confined layer 1. One notices a
rather good agreement between the two which is also manifested by the scatter-plot of the
observed versus modelled heads shown in the left panel of Fig. 7.
Calibration in transient state has been carried out, using the 1993–2003 historical water levels, whereby groups of specific storage have been calibrated. The transient simulation is initialised 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 3.70 m in steady-state mode and 5.11 m in transient mode (see Fig. 7, right panel). An a posteriori transient-state verification/forecast, using two years of 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 show that, depending on the surface water availability, the water levels are, on average, about 4 m below ground surface in the wet season, but drop to 6–9 m below GS in the dry season. 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, when the head changes amount to 3–8 m. The water balance (shown in Fig. 8 for both the wet and dry season) illustrates that the total groundwater use was 812 million m$^3$/year in 2003, increasing to 1,068 million m$^3$/year in 2005. For the year 2003, the total inflow amounts to 1,142 million m$^3$/year and the natural outflow to 489 million m$^3$/year. Furthermore Fig. 9 indicates that the aquifer contributes only an average 12% of the annual aquifer-recharge into the rivers in the wet season, but is recharged from the rivers in the dry season with 42% of the total recharge in dry season. Moreover, Fig. 9 shows that over recent times, while the groundwater use has been increasing and the surface water supply decreasing, the river-aquifer interaction has been declining.

The groundwater flow model has been used to compute historical seasonal groundwater uses, based on the assumption that 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. 9 illustrates that the groundwater use runs inversely with the surface water use, and that during the drought years 1994 and 1999, an increasing amount of groundwater 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

![Figure 8. Average seasonal water balance in year 2003 (unit: million m$^3$/day).](image)
response to the surface water situation are listed in Table 2. 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 that of a normal dry year, as the irrigation policy is to restrict the irrigation water consumption in such precarious-time situations. The average ratios 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 a concentration of rice farming (2.5 crops/year), the groundwater pumping behaviour 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 area, water is allocated by a rotation rule, whereby farmers obtain irrigation water for one week, but have to wait another three 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.

### 4 CONCLUSIONS AND FUTURE DEVELOPMENT OF GROUNDWATER RESOURCES

Our study shows that conjunctive use pattern significantly varies with the surface water situation, season, aquifer characteristics and irrigation-rainfed area. The agricultural sector is

<table>
<thead>
<tr>
<th>Basin</th>
<th>Water demand: SW:GW</th>
<th>Irrigation area</th>
<th>Rain-fed area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mae Nam Ping</td>
<td>1:0.54:0.08</td>
<td>1:0.83:0.17</td>
<td></td>
</tr>
<tr>
<td>Mae Nam Yom</td>
<td>1:0.90:0.01</td>
<td>1:0.87:0.13</td>
<td></td>
</tr>
<tr>
<td>Mae Nam Nan</td>
<td>1:0.53:0.30</td>
<td>1:0.97:0.03</td>
<td></td>
</tr>
<tr>
<td>Mae Nam Chaophraya</td>
<td>1:1.00:0.02</td>
<td>1:0.99:0.01</td>
<td></td>
</tr>
<tr>
<td>Mae Nam Sakaekrang</td>
<td>1:0.83:0.01</td>
<td>1:0.99:0.01</td>
<td></td>
</tr>
<tr>
<td>All basins</td>
<td>1:0.62:0.17</td>
<td>1:0.93:0.07</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aquifer types</th>
<th>Pump yield m³/hr</th>
<th>Average ratio of GW use to water demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood deposits</td>
<td>10–20</td>
<td>17%</td>
</tr>
<tr>
<td>Low terrace deposits</td>
<td>5–12</td>
<td>7%</td>
</tr>
<tr>
<td>High terrace deposits</td>
<td>1–10</td>
<td>2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water situation</th>
<th>Water demand: SW:GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>1:0.49:0.27</td>
</tr>
<tr>
<td>Normal</td>
<td>1:0.32:0.36</td>
</tr>
<tr>
<td>Dry</td>
<td>1:0.47:0.52</td>
</tr>
<tr>
<td>Drought</td>
<td>1:0.63:0.68</td>
</tr>
</tbody>
</table>
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. Figure 10 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 climate, wet and dry season, and water situation, wet, drought etc., 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 are depicted in Fig. 10 and show the different water levels encountered with these three approaches. 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 the past. The simulation results for the groundwater level in the Mae Nam Yom basin, where groundwater is abundantly extracted, are illustrated in Fig. 11. One observes 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 fate of the groundwater table in the study ahead was predicted using the conjunctive use ratio. Figure 12 shows that in the year 2026, the water table will have declined by an average of 2–3 m in a dry season under a normal water situation, relative to that of the 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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