ABSTRACT

For this study the Plaichumpol Irrigation Project (PIP) which is an area that relies heavily on conjunctive water use was selected to study water demand, supply and actual use for the purpose of providing possible guidelines for optimal water exploitation. Groundwater models are applied to the study area to mimic the interaction between farmer’s irrigation behaviour and hydrological process. Agricultural water allocation schemes are examined by the models to fit the local weather conditions and the regional management rules. The simulation provides adaptation guidelines of conjunctive water use, according to optimal water utilization and based on proper management. The seasonal interaction indicates that the irrigation canals recharge water to the aquifer during the wet and dry seasons, but only during the wet season the latter contributes small amounts of water to the canals. The relationship between canal recharge and water level is significant for the understanding of the rise of the groundwater table in dry seasons, and it should be developed further for use in canal water regulations to keep up the groundwater levels. This study puts forward the groundwater potential in the conjunctive use which farmers have available during periods of shortage so that, eventually, the water assurance is increased and more annual crops are possible.

Keywords: conjunctive use, irrigation, groundwater model, river-aquifer interaction

1. INTRODUCTION

The export of agricultural products, namely rice, is bringing in a large portion of the national revenue of Thailand. The recent world food crisis has boosted rice production and led the Thai government to an active policy to develop more irrigation projects and agricultural cash crop schemes to support the local farmers, namely in the upper part of the Central Plain of Thailand. This region is usually very suitable for agriculture, as water resources are normally plentiful. However, with the active price policy mentioned, farmers nowadays tend to grow rice more frequently putting more pressure on the available water resources there, with the need for more irrigation using both surface and groundwater. The classical method to augment water to agricultural areas during dry seasons or drought periods has been the use of irrigation water supplied through canals. If the latter falls short of the needs, then groundwater pumping is another alternative for farmers to mitigate the deficit. Naturally, such a situation puts more pressure on the overall water resources in the region which has led to several political “rumbles” among the various stakeholders involved in recent years.

Because of this, in the long run, precarious water-availability situation in central Thailand which, moreover, will be most likely exacerbated by imminent climate change in that region
of the world, in particular (IPCC, 2007; Koch, 2008), the improved management of existing surface water and groundwater resources is of utmost importance to guarantee the future food supply from irrigated agriculture (Rosegrant et al., 2002). One approach to this regard is the use of techniques of so-called conjunctive management which is a management tool, similar to Integrated Water Resources Management-IWRM (GWP, 2000), but with the emphasis on the combined use of both surface- and subsurface waters to meet the total water demand. More specifically, conjunctive water use management attempts the optimal operation of surface water allocation and groundwater use. The use of groundwater in conjunction with surface water can indeed increase agricultural output in many instances (Bredehoeft and Young, 1983), namely in drought periods, when the use groundwater resources allows for a buffer against the uncertainties of surface water supplies (Tsur, 1990), which means that the benefits of conjunctive use management are particularly high during such dry seasons.

Mathematical and/or numerical modeling is a decision support tool for planning and management in water resources. To derive management alternatives or to evaluate alternatives for integrated management over long periods of time, efficient simulation methods for surface and groundwater systems are indispensable (Andreu and Sahuquillo, 1987). With the advent of numerical, namely, finite difference models some four decades ago, numerous modeling studies have been carried whereby the integrated coupling of the surface – groundwater system - crucial for a reliable simulation of conjunctive use pattern and management strategies - has always been of a particular conceptual and numerical challenge. The first studies of this kind have been by Chun et al. (1964) who used a stream-aquifer model to evaluate a conjunctive use system and by Pinder and Sauer (1971) who studied in particular the interaction between river - and groundwater storage. A Green’s function approach was used by Koch and Cekirge (1995) to study stream-aquifer interaction and its effect on possible groundwater pollution in an industrial river in central Florida, US...

More recent technical advances in conjunctive water management include the use of optimization techniques (Belaineh et al, 1999), although this study appears to be hampered by the fact that details of the physical system, including the water demand, are not properly taken care of. Another approach has been the use of stochastic modeling in irrigation water demand calculations (Azaiez and Hariga, 2001); although in this study the entire water supply and the behavior of the water movement are not clarified. A physically more precise formulation of the complicated relationship between streamflow and groundwater storage has been set up and implemented into a surface-groundwater interaction model by Orhan and Aral (2004). Bejranonda et al. (2006) used a groundwater model for conjunctive use patterns investigation in the upper central plain of Thailand, whereas Bejranonda et al. (2007) developed a physically more pertinent semi-coupled model by combining the SWAT surface water- and the MODFLOW groundwater model and applied it to the upper Chao Phraya surface- groundwater system. The calibration results from this semi-coupled model turned out to be much better than those of the two uncoupled, individual models.

As many irrigation projects in upper part of central plain of Thailand are not capable to provide sufficient surface water for farmers, the Thai RID (Royal Irrigation Department) initiated a feasibility study of conjunctive use schemes for the improvement of the irrigation system in the Phitsanulok area (RID, 2005; Koontanakulvong et al, 2008). The research focused on water use and allocation in an irrigation area from both canals and local shallow wells (cf. Bejranonda et al, 2006). In this study, conjunctive use scheme and its application were investigated inside a selected irrigation area. The research focused on the water use and its allocation in an irrigation area there from both canals and local shallow wells. As part of this study, conjunctive use schemes were investigated. Plaichumpol Irrigation Project, a
service area of the Royal Irrigation Department located in upper part of the Central Plain, was selected to study water use patterns and interaction between surface water and groundwater determining the potential of conjunctive use. Surface water and groundwater models have been used to estimate water balance managing and allocating the irrigation water. Because of the intertwined interaction, a comprehensive water supply study is necessary to understand the surface and the subsurface water resources. Both of which are prerequisites for a conjunctive use analysis. Beforehand it is necessary to understand the present conjunctive use-pattern, the proportion of local agricultural demand as a function of the use conditions of surface water and groundwater. These use patterns have been investigated 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 behavior of the underneath groundwater system and to come up, eventually, with sustainable conjunctive water use patterns for the future.

2. STUDY AREA

The Plaichumpol Irrigation Project (Fig.1), located in the Upper Great Chao Phraya Plain of Thailand, covers about 440 km² / 273,000 Rai (20 km x 70 km) of the Phitsanulok and the Phichit Provinces, with a total population of about 16,000 households. The main land-use is 80% agricultural, with 25% of the area intensively irrigated. The irrigation service area is divided into 3 divisions, with a total of 396 service units. The main surface water basin is dissected by the Yom and Nan rivers which drain the catchment in southern direction. Irrigation water is diverted from the Nan River at the Naresuan Diversion Dam. The groundwater aquifer developed from the depositional flood plain and slopes from north to southeast. Mountains of volcanic rocks form the western boundary of the aquifer. More than 3,000 groundwater wells exist in the region. The elevation of topography is 40-60 m MSL. The 900 - 1,450 mm annual rainfall, with an average 1,336 mm/year, is apportioned to 81 % in the wet (May.-Oct.) and 19 % in the dry season (Nov.-Apr.).

3. CONJUNCTIVE USE STUDY

3.1 Methodology and Data Collection

There are three sources of the agricultural water used in the study area; rainfall, irrigation water and groundwater. The Plaichumpol Irrigation Project (PIP) selected here for the study of the water use pattern provided data for rainfall, irrigation supply and groundwater extraction during the year 2006-2007, covering both wet and dry seasons. Groundwater use is a key input parameter in this study. 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 compared with the agricultural demand.

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 of the wells. Groundwater use, surface water allocation, river and canal properties, hydrogeology, surface water and groundwater level data were collected to investigate the relationship between surface water flow and groundwater movement. Groundwater levels and movements in the study area are simulated with the MODFLOW groundwater flow model. The modeling approach follows the usual steps of building the conceptual model, model design, calibration and verification/prediction (Anderson and Woessner, 1992).
The calibrated groundwater model was applied to evaluate the groundwater amount that farmers can extract maximally by their own pump for use in their agricultural field. The available groundwater potential to compensate water shortage and irrigation water supply were eventually carried out the conjunctive use applicability area and estimated ratio between surface and subsurface water use compared this with the actual water demand. An overview scheme of the methodology is depicted in Fig. 2.

3.2 Aquifer Simulation

The groundwater conceptual model, 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 set up 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 (Fig. 3). The 3-D block-centered grid model representing the groundwater basin has a grid-size ranging between 0.5 to 2 km, resulting in 2,934 elements in the upper and 2,934 elements in the lower layer (Fig. 3).
The eastern and western boundaries of the groundwater model are made up by the Nan and Yom rivers, respectively, and are defined hydraulically as head boundaries using the corresponding river gage elevations. The north-eastern boundary of the model is set up as a flow boundary whereby the inflow has been computed with a previously developed regional groundwater flow model (Bejranonda et al. 2006). 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 estimated from rainfall and/or with an assumed infiltration rate (Chulalongkorn, 2006). Over 100 questionnaires were distributed inside the PIP to survey information on the existing shallow wells and the actual water-use pattern.

Model calibration and verification/prediction were performed in steady-state and in transient state. Following the seasonal crop pattern, the seasonal stress period was used in the calibration of the two years (1996-1997) of recorded groundwater levels. The early water level data were obtained from registered wells that recorded water levels during well construction in this region. Local groundwater levels were obtained from 35 observed wells inside and around the irrigation project, providing continuous data from 1998 to 2000 and 2006 to 2007. The last updated observed well records are biweekly groundwater levels from 2006 to 2007. Since the groundwater use during 1998 was almost stable, due to a constant availability of surface water, the average water level during the dry season of 1998 was selected to be the representative steady-state water level for the calibration. 12 groups of the hydraulic conductivity were adjusted during the steady-state calibration process.

Calibration in transient state was carried out, using the 1998-2000 historical water levels, whereby groups of the specific storage were calibrated (Fig. 4). During the transient-state calibration, the pumping rates were fine-tuned, as these are often not well reported or prone to errors. Model verification was performed with updated water levels of years 2006-2007. However, Fig. (4) indicates some discrepancy between computed and measured heads for the later verification period which is most likely due to the fact that actual pumping in years 2003-2005, which have been defined as dry years by RID (as historical storages of the Bhumiphol and Sirikit Reservoirs were rather low during those years), might have been higher than assumed in the model. In summary, the mean square error is 0.36 m for the steady-state model and 5.46 m in transient mode. The results of the calibrated groundwater model indicated that the average groundwater use in a normal water year is 134.4 million m$^3$/year which is apportioned by 40% and 60% to the wet and dry season, respectively.
3.3 Surface Water – Groundwater Interaction

The groundwater flow simulations indicate that the water levels are, on average, about 5-11 m below surface in the wet season, but drop to 8-16 m in the dry season. The groundwater balance listed in Table 1 illustrates that the recharge from the main irrigation canal amounts to 3% of the total inflow. The seasonal budgets indicate that the main irrigation canal contributes water into the aquifer which amounts to an average of 27% of the local recharge for the wet and dry season, and to 64% for the dry season alone. Thus, canal water plays an important role in the recharge of the aquifer, as well as for its groundwater levels during the dry season. As the groundwater use increases and the surface water supply decreases during this time-period, the river-aquifer interaction too declines (Bejranonda et al, 2007).

Table 1: Water balance of upper aquifer beneath Plaichumpol in normal water situation

<table>
<thead>
<tr>
<th>season</th>
<th>Flow</th>
<th>discharge (million m$^3$/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In</td>
</tr>
<tr>
<td>Wet</td>
<td>Pumps from lower aquifer</td>
<td>-9.2</td>
</tr>
<tr>
<td></td>
<td>from irrigation canal</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>surface recharge</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>lateral flow</td>
<td>69.8</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-34.6</td>
</tr>
<tr>
<td>Dry</td>
<td>Pumps from lower aquifer</td>
<td>-13.2</td>
</tr>
<tr>
<td></td>
<td>from irrigation canal</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>surface recharge</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>lateral flow</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-3.3</td>
</tr>
</tbody>
</table>

3.4 Conjunctive Water Use in the Study Area

For the PIP with its very intensive rice farming (2.5 crops/year), the irrigation water demand as well as the irrigation water supply were explored in detail. Obviously, in a wet water year the irrigation supply of 341.7 million m$^3$/year is not sufficient for effective farming when compared with the average irrigation demand of 520.4 million m$^3$/year (RID, 2007). In the
irrigation area itself, water is allocated by a rotation rule, whereby farmers obtain irrigation water only during one week out of three, with the consequence that farmers tend to pump groundwater in between their turns. Even when irrigation water was allocated to farms, it was collected in ponds or ditches along the canal that caused the total water use to be much higher than required by the demand. Based on these pumping strategies and the overall water consumption, Table 2 was set up. It lists the ratios of surface and groundwater used, relative to the irrigation water demand. One notes that the extra amounts of groundwater extracted for agricultural use range from about 27% of the total irrigation water demand for a wet year to 68% in an extremely dry (drought) year.

Table 2: Average conjunctive water use and their ratios during the dry season in Plaichumpol

<table>
<thead>
<tr>
<th>water situation</th>
<th>Irrigation demand</th>
<th>act. surface water supply</th>
<th>groundw. extraction</th>
<th>percentage to irrigation demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>wet</td>
<td>275</td>
<td>135</td>
<td>74</td>
<td>100% 49% 27%</td>
</tr>
<tr>
<td>normal</td>
<td>268</td>
<td>86</td>
<td>96</td>
<td>100% 32% 36%</td>
</tr>
<tr>
<td>dry</td>
<td>300</td>
<td>141</td>
<td>156</td>
<td>100% 47% 52%</td>
</tr>
<tr>
<td>drought</td>
<td>266</td>
<td>167</td>
<td>181</td>
<td>100% 63% 68%</td>
</tr>
</tbody>
</table>

4. CONJUNCTIVE WATER USE DEVELOPMENT

There are two distinguished categories of integrated management models (Gorelick, 1983): 1) hydraulic management models which deal with the management of water flows and heads, and, 2) policy evaluation/allocation models which simulate the economically efficient allocation of surface and groundwater resources. In an ordinary irrigation area, the surface water allocation is operated by the national reservoir operation rules. On the other hand, a local groundwater basin is a manageable resource when considering the “safe yield” which can be considered as the maximum amount of extracted (pumped) groundwater under the constraint of a maximally allowed range of water level fluctuations (Hall and Dracup, 1970; Arlai et al, 2007). In the PIP area, an engineering approach that deals with the hydraulic management is about to be enacted. A future step will be the set-up of appropriate policy evaluation/allocation management models, as these await further data on farmer’s cultivation preferences and other economic indicators, such as energy consumption and rice price.

Naturally, the maximum amount of conjunctive water in the study area is set by the maximally available water supply. Surface irrigation water is the first choice, but it is almost always inadequate and, moreover, exacerbated sometimes by inefficient water routing through the irrigation canals, namely to remote paddies. On the other hand, groundwater can be reached everywhere; however, its extraction is often limited by inadequate pumping equipment. Using their own pumps, farmers can access groundwater down to 15 m below ground surface (Chulalongkorn, 2006). For this reason, the amount of groundwater eventually available for conjunctive use was confined to that depth, which then also serves as the criterion for determining the groundwater potential of the PIP using the numerical model.

The results of these groundwater simulations are listed in Table 3 and they indicate that the recent (year 2007) monthly groundwater use is only 43% of its potential of 27.48 million m³/month, i.e. there is still much room for further development of this resource. Based on these results, one can conclude that groundwater as part of the conjunctive use strategy is
enough to satisfy the agricultural needs of the farmer in the Plaichumpol project area overall, through there are significant differences for the three divisions that make up the project area. Thus Table 3 shows that the groundwater use in division 3 was close to its potential for the time period considered. Groundwater levels in the dry season - limiting the groundwater potential there - fluctuate more in remote areas on the west-side of the PIP (see PCP-19 in Fig. 4) than in the east-side near the main irrigation canal.

The groundwater use guideline for conjunctive use planning in the irrigation project is based on the farmer’s water use behavior, the existing irrigation system, the groundwater-well structures and the local groundwater potential. Average irrigation water supply was estimated from water use per area, and the average groundwater use from the well density. Fig. 5 shows that for a normal water year the ratio of the amount of groundwater extracted from the aquifer to that of the surface water supply ranges between 0 - 140% with an average of 28%. Almost all heavy groundwater users (ratio >25%) are located at the end of irrigation canals or in remote areas where irrigation water is less available.

Table 3: Groundwater use and its potential in 3 irrigation divisions

<table>
<thead>
<tr>
<th>Irrigation division</th>
<th>Groundwater use 2007 (mil. m³/month)</th>
<th>Groundwater potential (mil. m³/month)</th>
<th>Groundwater use : potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.10</td>
<td>3.49</td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>5.05</td>
<td>18.46</td>
<td>27%</td>
</tr>
<tr>
<td>3</td>
<td>4.77</td>
<td>5.53</td>
<td>86%</td>
</tr>
<tr>
<td>Total</td>
<td>11.93</td>
<td>27.48</td>
<td>43%</td>
</tr>
</tbody>
</table>

Figure 5: Annual groundwater-use guideline for conjunctive-use planning in case of normal water situation at the Plaichumpol Irrigation Project (PIP).

5. CONCLUSIONS

The seasonal interaction indicates that the irrigation canals recharge water to the aquifer during the wet and dry seasons, but only during the wet season the latter contributes small amounts of water to the canals. The relationship between canal recharge and water level has an important effect on the rise of the groundwater level in the dry season, and it should thus be developed further for use in the regulation of the canal irrigation water to keep the groundwater levels up. Due to the high fluctuations of the groundwater table and the need of sustainable management, water allocation in the PIP area requires the combination of surface-water and subsurface-water supply. This study puts forward the groundwater potential in the conjunctive use which farmers have available during periods of shortage so that, eventually,
the water assurance is increased and more annual crops are possible. The unused water during
the transition period between the wet (flood) and dry season could be applied for aquifer
recharge and so increase the groundwater potential in the PIP area. Thus, while groundwater
turns out to be an indispensable factor in the conjunctive water use scheme in the PIP region,
its precise apportioning could only be quantified through the application of the
comprehensive integrated surface water- irrigation-groundwater modeling approach, as done
in the present study.

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