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MODELLING THE GROUNDWATER DYNAMICS AS INFLUENCED BY WATER MANAGEMENT IN HETAO IRRIGATION DISTRICT, UPPER YELLOW RIVER BASIN, AND PREDICTING IMPACTS OF FORESEEN WATER USE AND SAVINGS

XU XU[1,2], GUANHUA HUANG[1,2], ZHONGYI QU[3], LUIS S. PEREIRA[4]

1 Chinese-Israeli International Center for Research and Training in Agriculture, China Agricultural University, Beijing 100083, P. R. China, xushengwu@cau.edu.cn
2 Center for Agricultural Water Research, China Agricultural University, Beijing 100083, P. R. China, ghuang@cau.edu.cn
3 College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot, 010018, P. R. China, quzhongyi68@sohu.com
4 CEER - Biosystems Engineering, Institute of Agronomy, Technical University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal, lspereira@isa.utl.pt

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ABSTRACT The upstream irrigation districts of the Yellow River basin are the highly productive agricultural area in North China. Due to the severe water scarcity, application of water-saving practices at both farm and district level is required for the sustainable agricultural development. An integrated methodology was developed on the basis of loose coupling the groundwater flow model (MODFLOW) and ArcInfo Geographic Information System to assess the impacts of irrigation water-saving practices and groundwater abstraction on the groundwater dynamics of the Jiefangzha Irrigation System in Hetao Irrigation District, upper Yellow River basin. The model was calibrated and validated with datasets of years 2004 and 2005, respectively. The model and corresponding methodology were then used to simulate the groundwater dynamics of the study area for various water-saving practices considering the groundwater abstraction foreseen for the year of 2020. Results showed that water-saving practices with 60% of canal lining and upgrading hydraulic structures, and upgraded irrigation technology in 50% of the area are feasible and it is a reasonable solution. Their implementation would reduce groundwater evaporation by 37 mm and the total diversions from the Yellow River by 208 mm.

Keywords: Groundwater table, MODFLOW, Geographic Information System, water-saving practices, irrigation district

INTRODUCTION The Yellow River is the second largest river in China. It supplies water for about 130 million people in nine Provinces in the Northwest and North China. The Yellow River basin is an area with severe water scarcity. Agricultural irrigation is the main water use in the basin, accounting for 81% of the total water use. The water demand is continuously increasing for industrial, domestic and hydroelectric power uses, which exacerbates water scarcity. Forecasted scenarios on water resources allocation and use in the basin point out the need to reduce irrigation water use (Xu et al., 2002). Therefore, the need for sustainable use of water and land resources in the basin dictates that water conservation and water-saving measures and practices should be implemented for coping with water scarcity (Pereira et al., 2003).

Excess water diversions from the river and poor irrigation and drainage management practices have caused severe water logging and salinity in the upstream irrigation districts (Wang et al., 1993). Diverse water-saving measures have been taken in irrigation districts in the upper reaches of the Yellow River to improve both water conveyance and farm water use. Application of water-saving practices (WSPs) will cause lowering the groundwater table, thus leading to better controlling water logging and salinity. However, an excessive lowering of the groundwater table may result in negative impacts on the fragile ecological environment due to reduced capillary rise (Ruan et al., 2008). Additionally, the increase of groundwater abstraction for municipal and industry will accelerate the decline of the groundwater table. It is therefore important to investigate the impact of human activities on the groundwater dynamics in the upstream irrigation districts. In this study, Jiefangzha Irrigation System (JFIS) of Hetao Irrigation District (Hetao) was considered as a typical example.

Groundwater flow models are appropriate tools to assess the effect of foreseen future human activities on groundwater dynamics. Most of these data vary both in space and time, thus adopting a Geographic Information System (GIS) in association with a model is helpful. Coupling GIS technology with a groundwater model may ease hydrogeological and hydrologic system conceptualization and characterization (Kolm, 1996). Strategies for GIS and model integration can be categorized as loose coupling, close coupling and embedded coupling. The advantage of loose coupling is that it eases future changes in the model, which are performed independently. In close coupling, changes in the model imply changes in its coupling with GIS. Embedded coupling and closing coupling require a significant investment in programming contrarily to loose coupling. Both approaches impose more constraints when changes are needed (Gogu et al., 2001). Thus, loose coupling was selected for this study. Various examples confirm the appropriateness of coupling a groundwater flow model with GIS in groundwater hydrology (Jha et al, 2007). They show that most strategies and methods for this coupling method are specific to the study area. In this study, the main objectives are to develop an integrated methodology based on loose coupling of the groundwater flow model MODFLOW and ArcInfo to assess the impacts of various irrigation WSPs and groundwater abstraction on the groundwater dynamics in the JFIS of Hetao, in the upstream reaches of the Yellow River basin.

STUDY AREA

The Hetao, located in the arid upper reaches of the Yellow River, is one of the three largest irrigation districts of China. The JFIS is the second largest system in the Hetao, with a total area of 215,700 ha, of which 66% is irrigated. The main part of JFIS is located southeast of the main drainage ditch and northwest of the main canal (Fig. 1), with a gradient of 1/5000 from southeast to northwest. The study area has a typically arid continental climate. The mean annual precipitation for the period of 1986-2004 is only 155 mm. The mean annual temperature is 7 ºC, with monthly averages of -10.1 and 23.8 ºC in January and July, respectively. The mean annual evaporation is about 2000 mm. Due to the climatic conditions in the region, irrigation is essential during the entire crop growing season. Irrigation water is mainly diverted from the Yellow River. Groundwater is mainly exploited for domestic and industrial purposes. Canal seepage and field percolation cause the rising of the groundwater table. Groundwater is either used by the crops through capillary rise or, due to the poor drainage system, is discharged by evaporation. The latter one results in severe problems of soil secondary saline-alkalization (Wang et al., 1993). The most appropriate target groundwater table depth in the crop growth period is 1.5-2.0 m.

The basin is underlain by Quaternary sediments, mainly lake sediments and alluvial deposits of the Yellow River. The deposition properties for Q4 are mainly clay-sand in the south and clay with interlayers of silt sand in the north, while the deposition properties for Q3 consist of fine-medium sand, fine sand and silt sand with clay interlayers. The upper layer of Q2 (Q_2^2) is underlain as a layer of stable muddy clay with a thickness of 20-40 m, which acts as a relatively low permeable layer preventing vertical flow.

METHODOLOGY

Model description The modular finite-difference groundwater flow model MODFLOW-2000, developed by the US Geological Survey (Harbaugh et al., 2000), was selected to simulate the behavior of groundwater flow in the study area because it is a well-documented and extensively tested model, which can be readily incorporated into future studies for optimal water resources management. The packages Recharge (RCH), Well (WEL), River (RIV), Drainage (DRN) and Evapotranspiration (EVT) were used in this study. The Visual MODFLOW version 4.2, which is a powerful MODFLOW pre/post processor (Waterloo Hydrogeologic Inc., 2006), was used to simulate three-dimension unsteady groundwater flow in this study.

Aquifer discretization, initial and boundary conditions The first aquifer system was discretized into the first and the second sub-aquifers. The second sub-aquifer was assumed to have uniform hydrogeological parameter values and was divided into 3 layers with uniform spacing. Thus, the aquifer system could be vertically discretized into four layers. A uniform rectangular grid of 435 rows and 425 columns with square cells of 200 m was adopted. The first layer representing the Q4 is a low-permeable layer with a thickness varying from 6 to 25 m from south to north, while layers 2 to 4 refer to the Q3 aquifer and have higher permeability, with thickness varying from 12 to 80 m from south to north for each.

It is assumed that the aquifer is horizontally isotropic with its horizontal hydraulic conductivity being 10 times larger than the vertical one. The property zones for hydrogeological parameters were determined based on digitized hydrogeological maps. The horizontal hydraulic conductivity for the first layer varies 0.3-1.0 m d^{-1} in the N-S direction and the specific yield ranges 0.02-0.08. The layers 2 to 4 have the same hydraulic conductivity, which ranges 4-18 m d^{-1} in the N-S direction; their corresponding specific yield and storage coefficient vary respectively 0.06-0.13 in the N-S direction and 0.00028-0.0038.

Initial values of groundwater levels in the first sub-aquifer were obtained by using the interpolation technique applied to the observation data of 56 wells for May 1, 2004 and May 1, 2005. However, because there is not enough data about the groundwater head in the second sub-aquifer; due to the recharge from melt water in the upper soil layer by April, the value of the groundwater level in the first sub-aquifer was assumed to be close to that of the groundwater head in the second sub-aquifer by those dates. Thus, the initial heads of layers 2 to 4 were assumed equal to the ones of layer 1.

In the southeast boundary, the main canal is not lined; thus a river boundary in the first layer was simulated using the RIV package during the irrigation period. Differently, no flow boundary conditions were defined for the layers 2 to 4 for southeast boundary during the irrigation period. During the non-irrigation period, based on the long term monitoring data available from Bameng Survey (1994), the recharge water from the Yellow River is estimated using the WEL Package. In the northwest, the main drainage ditch was considered as a drain boundary for the first layer. In the southwest, the first sub-main drainage ditch and the upper reaches of the Wulahe sub-main canal form the southwest boundary of the study area (Fig. 1). They were simulated using a drain boundary and a flux boundary for the first layer, respectively. Non-flow boundary conditions were considered for the lower layers because the horizontal groundwater flow direction approximately parallels these boundaries as show in Fig. 1. The conductance per unit length was assumed to be 0.4 m d^{-1}. The east boundary consists of the fourth sub-main drainage ditch and the upper reaches of the Yongji sub-main canal (Fig. 1). A drain boundary and a flux boundary were therefore considered for the first layer. For the lower layer, a non-flux boundary was considered because the horizontal groundwater flow direction approximately parallels this boundary (Bameng Survey, 1994). The conductance per unit length was assumed to be 0.5 m d^{-1}.

Sink and source terms The recharge due to canal seepage assigned to the cells through which the canal water is flowing was computed with the RCH Package. Recharge from field percolation, rainfall, melt water, and distributor ditches was combined into a single effective recharge R_e, also using the RCH Package.

The evaporation from the groundwater was estimated by using the EVT Package. The maximum rate of evaporation was estimated as the product of the rate of evaporation from an open water surface by an empirical coefficient obtained experimentally (IWC-IM, 1999). During the soil frozen period, the evaporation from the groundwater is mainly affected by temperature and the groundwater table depth (Wang et al., 1993). It was estimated as the product of S_y by the changes in water table.

The groundwater abstraction for industrial, domestic and livestock uses was estimated with the WEL Package with appropriate spatial distribution. Only the main and sub-main drainage ditches were considered for estimating the groundwater natural discharge using DRN Package.

Data processing using GIS The ArcInfo version 9.2 (Environmental Systems Research Institute, ESRI) with Access databases (Microsoft) was used to construct the GIS database, which can efficiently improve the groundwater modeling of the study area. The pre- and post-processing of MODFLOW data were efficiently operated using various ArcInfo GIS tools. It may easy to handle data for conceptualization and characterization of groundwater flow system.

GIS database development The data collected from different sources are in disparate formats and scales, and then were converted into digital formats and processed to form a GIS database (Fig. 2). The Gauss-Krueger projection and the Beijing 1954 Coordinate System were selected to integrate different spatial data. All spatial data of JFIS were integrated and stored in the geodatabase. The topology, subtype and domain were created for accurately processing the spatial data for MODFLOW use. The geodatabase was connected with a database management system (DBMS) from Microsoft Access for efficient management of the GIS database.

GIS data processing for MODFLOW Physical and hydrogeological data were used to develop a conceptual model by using the available ArcInfo tools. Fig. 2 shows the flow chart to develop the groundwater flow model of JFIS. The data for the aquifer-system stress factors (i.e., for the RCH, EVT, RIV, DRN, and WEL packages) were processed using the ArcInfo and Excel VBA programs. Then the input files for stress factors could be constructed for MODFLOW. The spatial distribution of the groundwater table depths was analyzed with Spatial Analysis tools and 3D Analyst tools.

RESULTS AND DISCUSSION

Model calibration and validation Groundwater level data from twelve observation wells (Fig. 1) were used for model calibration relative to the period from May 1, 2004 to April 30, 2005. This period was divided into twelve stress periods and computations relative to the groundwater head were performed using a one-day time step. During the irrigation season, from May to October, each stress period has a month duration, while out of this season the stress periods ranged from 10 to 60 days according to specific boundary conditions. A trial and error method was used in the calibration process. The root mean square error (RMSE) and the model efficiency (EFF) were used as indicators of modeling fitting. Results for this regression show that there is a good agreement between the measured and the simulated data. RMSE and EFF are 0.21 m and 0.98, respectively.

The model was validated with data of six different observation wells, whose locations are given in Fig. 1, for the period from May 1, 2005 to April 30, 2006. The same twelve stress periods defined for calibration were used for validation. A good agreement between the observed and simulated data is also shown by the values of RMSE = 0.24 m and EFF = 0.98 obtained for the validation. The results of calibration and validation allow to explore MODFLOW for predictions of the groundwater dynamics for various scenarios.

Predicting impacts of water-saving and groundwater use According to the planning of Hetao (IWC-IM, 1999), WSPs will increasingly be implemented in the study area. The canal system improvement is expected to reduce water conveyance losses, thus increasing the conveyance ratio (*a*) of canal system, and decreasing the seepage ratio (*b*). The application efficiency will be increased following the referred application of water-saving technologies at farm. Therefore five scenario alternatives are considered as shown in Table 1, corresponding to the combination of different values of the canal conveyance ratio (*a*), the field percolation ratio (*c*) and the amount of groundwater abstraction by the year 2020.

Groundwater table depth changes Results indicate that the groundwater table will decline progressively with the further application of WSPs and the increase of groundwater abstractions. The areas for different groundwater table depths (Fig. 3) were calculated for the crop growing period, i.e. from June to August, without considering the residential areas and those occupied by infrastructures. The area with a groundwater table depth smaller than 1.5 m is 53%, 49% and 43% of the total area in June, July and August in 2004, respectively. This indicates that the groundwater table in those areas is close to the root zone. The application of WSPs and the increase of abstractions may reduce the area where the groundwater table depth is less than 1.5 m to 36%, 28% and 21% in June, July and August, respectively, for alternative 5 (Figs. 3a, 3c, and 3e). These results indicate that conditions favoring salinity control are foreseen but the groundwater contribution for the vegetation is reduced. Conversely, for alternative 5, the area with groundwater table depth larger than 2.0 m becomes the main part of the area, increasing by more than 1/3 relative to the present situation, which indicates that the groundwater table is expected to significantly decline after the application of the considered alternatives. This decline will be associated to a decrease of groundwater evaporation and groundwater contribution for the crops.

The area where the target groundwater table depth is achieved, i.e. between 1.5 m and 2.0 m for the crop growth season, is nearly constant for June (Fig. 3b). The decline trend for August is more pronounced, when that area will decrease from 21 to 16.7% of the total area from alternative 1 to 5. Contrarily, the percentage of area with depths larger than 3 m, is about 6% in 2004, will increase for alternative 5 up to 14.4 and 23.1% respectively for June and July. The resulting reduction on the groundwater contribution for crops consumptive use may require additional irrigation water.

Groundwater balance The recharge from irrigation water and groundwater evaporation, including through plant roots uptake, are the main factors influencing the variations of the groundwater levels. A reduction of the evaporation from the groundwater of 18 to 59 mm is predicted for alternatives 1 to 5 when compared with the present situation. It implies that the application of WSPs can contribute to control of evaporation induced salinity. However, the contribution of capillary rise for crops water use also decreases. Simultaneously, the recharge from the irrigation water is expected to decrease by 29 to 136 mm for alternatives 1 to 5, thus by 12 to 55% relative to present. The proportion of groundwater abstraction to the total discharge is expected to increase markedly, from 5.5 to 19%. This indicates that groundwater pumping for industrial, domestic and livestock uses will play a more important role in the groundwater dynamics in the future. Alternatives 1 to 5 correspond to various time and space steps for the implementation of water-saving measures, with alternative 5 representing the maximum attainable area, irrigation water savings shall progressively decrease in proportion to the area where these measures are implemented. However, it is likely that upgraded crop husbandry and new varieties of crops will be considered together with the water-saving measures. Then, crop consumptive water use may increase relatively to present while non-beneficial water uses are expected to decrease. It may result in that crop water uses foreseen will be different and that those decreases will be less drastic than current forecasts.

CONCLUSION Coupling the groundwater flow model MODFLOW with GIS technologies allowed to simulate the groundwater dynamics in the Jiefangzha Irrigation System, Hetao Irrigation District, in the arid upper Yellow River basin. After the model calibration and validation, the model and corresponding methodology were then used to simulate the groundwater dynamics of the study area for various WSPs with considering the groundwater abstraction foreseen for the year of 2020. Several scenarios were created, and the results showed that the WSPs with 60% of canal lining and upgrading hydraulic structures, and upgraded irrigation technology in 50% of the area are feasible and reasonable solution. Their implementation would lead to reduce groundwater evaporation by 37 mm and the total diversions from the Yellow River by 208 mm. Spatialized results show that the application of water-saving practices and the increase of groundwater abstractions will result in the decline of the groundwater table. In some areas this decline could be excessive since it leads to a large decrease of the groundwater contribution to the vegetation consumptive water use.

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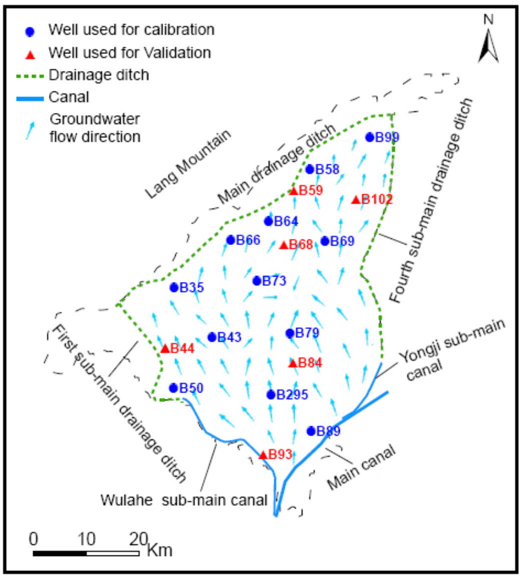

Figure 1. Locations of observation wells used for model calibration and validation, and groundwater flow directions relative to the first aquifer group.

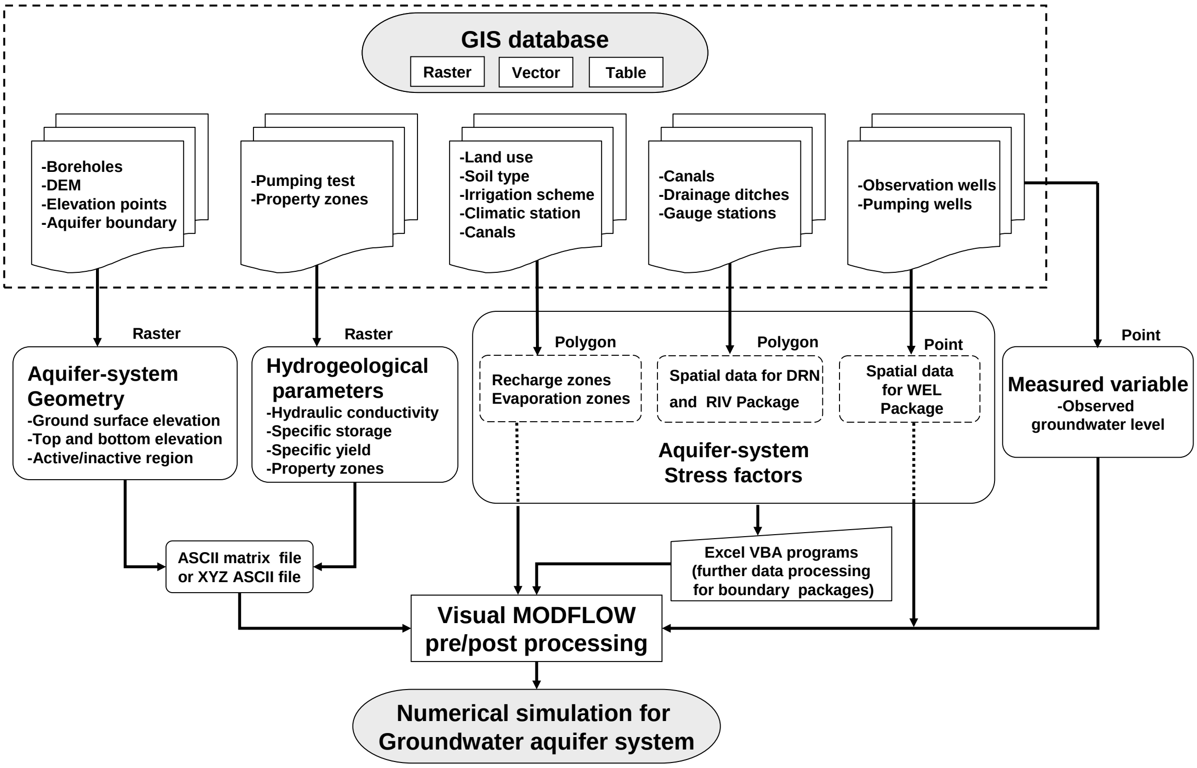

Figure 2. Schematic representation of the procedures used for GIS data processing and construction of the databases for the groundwater flow model.

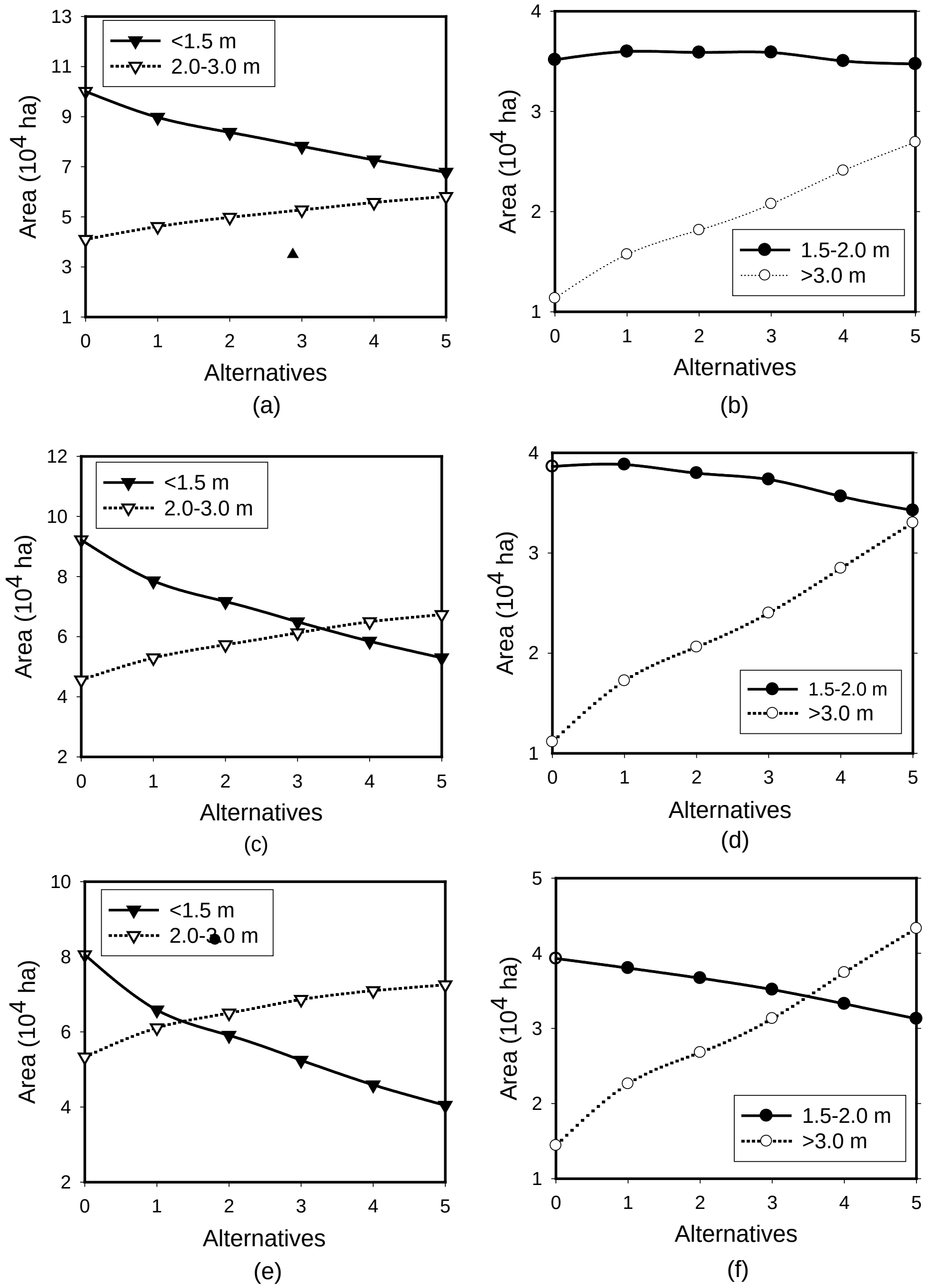

Figure. 3. Predicted areas having different groundwater table depths following the application of the various water-saving alternatives in June (a and b), July (c and d), and August (e and f); the alternative 0 refers to the present condition.

Table 1 Present situation of 2004 and five scenarios for different water use and saving in the JFIS and their corresponding parameters

Scenario alternatives	Water-saving practices	Ratio of outflow to inflow for the canal system	Ratio c_1 of percolation water to total irrigation water relative to the crop growing period	Ratio c_2 of percolation water to total irrigation water relative to the autumn irrigation period	Groundwater abstraction (10^4 m^3 a^{-1})
Present situation	Present situation	0.50	0.29	0.41	1633
1	Canal system improvement (20%) and upgraded irrigation technology in 20% of the area	0.54	0.25	0.38	4436
2	Canal system improvement (40%) and upgraded irrigation technology in 35% of the area	0.57	0.21	0.35	4436
3	Canal system improvement (60%) and upgraded irrigation technology in 50% of the area)	0.63	0.18	0.31	4436
4	Canal system improvement (80%) and upgraded irrigation technology in 65% of the area	0.69	0.15	0.28	4436
5	Canal system improvement (95%) and upgraded irrigation technology in 80% of the area	0.75	0.12	0.25	4436