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Studying the Effects of an Irrigation/Drainage Network on Groundwater Table Fluctuations Using 3D Groundwater Flow Modeling

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ABSTRACT: The Miandarband plain is one of the most fertile plains of the Kermanshah province, Iran, as it is endowed by ample surface and groundwater resources. With the construction of irrigation/drainage networks and the reduced use of groundwater resources, the groundwater table has risen and caused water logging, followed by salinization of the arable soils in the plain. Environmental deterioration and economical losses have been the consequence. From this the importance of a study of the fluctuations of the water table levels in response to the construction of irrigation and drainage network in the Miandarband plain becomes clear. In this study the fluctuations of the groundwater table have been simulated in both steady-state and transient regimes using the 3D groundwater flow model MODFLOW within the GMS 6.5 environment. For the set-up of the conceptual model, the meteorological, geological, hydrological and hydrogeological parameters, pertinent to the Miandarband area, were studied and implemented into the model. Based on the geological composition of drilling log cores, the aquifer is divided vertically into 11 horizontal layers. The groundwater surface measured in April 2007 is used to carry out the steady-state calibration and employed, at the same time, as initial condition for transient simulation with head measurements taken between May, 2007 and March, 2009. For model verification the heads measured in the subsequent month, April, 2009 is used. A very good agreement between simulated and observed groundwater heads with a coefficient of determination R^2 of 0.99 is obtained. In the next step the transient effects of the operation of the irrigation and drainage network on the ground water table is analyzed, whereby the simulations are started with initial conditions as they have existed prior to the operation of the irrigation/drainage network. In addition, to satisfy the needs of the proposed cropping pattern with the recommended surface irrigation, an annual water volume of 176.2 MCM is transferred from the Gavshan dam to the Miandarband irrigation and drainage network. It is assumed that 25% of this irrigation water infiltrates into the aquifer as recharge. With these parameters ground water levels for times of 1, 5 and 10 years after the start of the network operation are calculated. The results show that after 1 year the groundwater table in the center of the plain has risen about 1.8 m, but going up to 3.2 and 5.2 m for 5 and 10 years, respectively. Moreover, after 1 year, 6.59% of the plain's areas are waterlogged, a value which goes up to 37.91% and 56.28% after 5 and 10 years, respectively. In conclusion, by using a transient groundwater flow model it is possible to control the ground water levels and, so, to prevent the occurrence of detrimental water logging events in irrigated agricultural areas

Keywords: Miandarband plain, Groundwater, Irrigation/drainage network, MODFLOW, Water logging

1 INTRODUCTION

Changing hydrological conditions occurring, for example, in the wake of future climate change (IPCC, 2007) by alterations of temperatures and precipitation will have detrimental effects on the surface and groundwater resources in many areas of the world (e.g. Koch, 2008; Fink and Koch, 2010). This holds particularly for regions and countries which are already nowadays affected by water scarcity, such as the Middle Eastern region, including Iran. There, responding also to the needs of a strongly increasing population, rising water withdrawals have already caused drastic changes in the surface flow regimes as well as severe drops in groundwater levels in many basins of that country. Responding to all these water demands and converting weak points and threats to new capabilities and opportunities necessitates the use of appropriate water resources management strategies more than ever before. Therefore, finding suitable methods and models for conjunctive use of surface water and groundwater resources, that have maximum efficiency, is one main priority in water resources management. (Bejranonda *et al.*, 2009)

One particularly water-affected region in the west of Iran is the Miandarband plain, where groundwater serves as the main source of agricultural irrigation. The construction of the Gavoshan Dam's irrigation and drainage network is a national project in Miandarband plain that is supposed to be realized in the near future. Although the main goal of this project is the agricultural development in the basin, some of its effects could also be undesirable, due to a lack of effective water resources management. In fact, after the construction of such a modern irrigation/drainage network, the groundwater withdrawal could be reduced significantly, so that the groundwater table level could rise, and water logging may occur subsequently. The phenomenon of water logging is prevalent in many artificially irrigated, agricultural areas in arid regions across the globe, where it then causes numerous economic and environmental losses, for instance, among other factors, increasing soil salinity (Rhoades and Loveday, 1990). Therefore, one key to understand water logging and to develop measures, to prevent it, such as proper drainage (Ritzema, 1994), is an analysis of the groundwater table fluctuations in the region affected. This can be done efficiently by the use of numerical groundwater flow models (Mahmudian Shoushtari, 2010).

In recent years, groundwater simulation models such as the well-known MODFLOW groundwater model (McDonald and Harbaugh, 1988) have been widely employed in general groundwater flow studies and, namely, in applications of conjunctive water use, which is often the cause for the named water-logging problems in irrigation command areas (Bejranonda *et al.*, 2009; Dafny *et al.*, 2010; Xu *et al.*, 2011; Koch *et al.*, 2012). For example, Kim and Soltan (2006) simulated the impacts of an irrigation and drainage network on the Nubian aquifer's, Egypt, groundwater resources using MODFLOW. The authors showed that, in order to prevent waterlogging problems in the floodplain, an effective water resources management strategy must be applied. Kumar *et al.* (2009) simulated groundwater flow in a section of the Western Yamuna Canal (WYC) in Haryana state (India) during May 1985– May 2004 by Visual-MODFLOW. Their results indicated a long-term water table drop in the central, north and along the River Yamuna, whereas in the south of the model region, water levels rose by 5–10 m, i.e. waterlogging conditions had been created there. These authors showed further that with such a rate of groundwater pumping a further future deterioration of the groundwater situation would occur, with the groundwater table declining further in the already afflicted area, with no changes to be anticipated in the waterlogged areas. Several groundwater modeling studies deal with groundwater flow in regions of Northern China, where many areas are facing water resources shortages and/or the named pollution problems which, eventually, have already adversely affected the agricultural productivity there (e.g. Wang *et al,* 2008; Xu *et al.*, 2011 Xu *et al.*, 2012). Groundwater resources problems in Thailand, where regularly interchanging periods of droughts and flooding are often leading to large fluctuations of the groundwater table, have been numerically analyzed by Bejranonda *et al.* (2009) and Koch *et al.* (2012), both of which indicated the need for more elaborated approaches for optimal conjunctive water uses in such extreme situations.

In the present paper, the effects of the construction of the Gavoshan Dam's irrigation and drainage network on the groundwater resources in the region will be simulated, using the MODFLOW groundwater flow model in the GMS 6.5 environment (USACE, 2008).

2 STUDY AREA

The Irrigation and drainage network of Gavoshan Dam will be constructed in Miandarband plain that located in western Iran, near the city of Kermanshah. This region is geographically limited in the North by the Gharal and Baluch mountains and in the South by the Gharsu River and has a surface area of about 280km^2 (see Figure 1). Surface water in the study area occurs in the form of springs and stream flow, with the major river being the Razavar River (Anonymous, 2010).

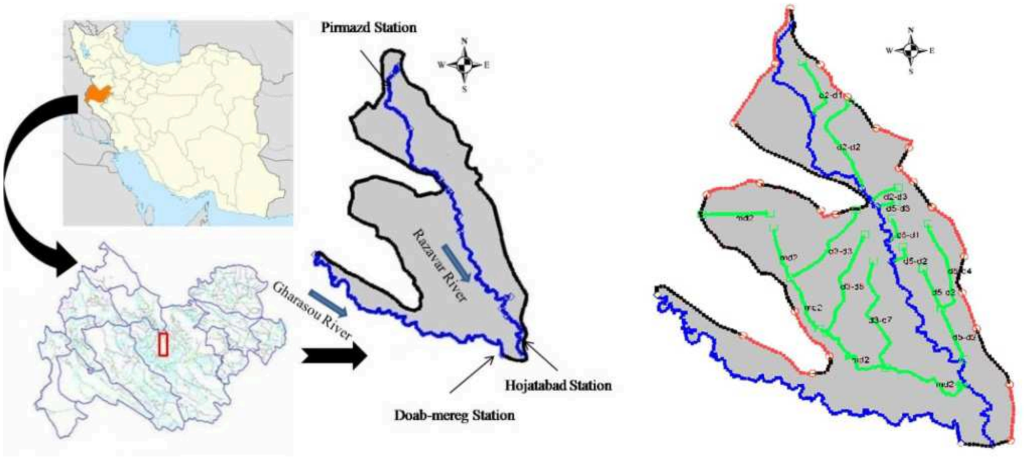


Figure 1. Left Panel: Miandarband plain groundwater study area in western Iran; Right Panel: Gavoshan Dam's planned and partly constructed irrigation and drainage network

3 MATERIALS AND METHODS

3.1 *Hydro-meteorological and hydrogeological data*

Meteorological as well as hydrological data are required for the development and calibration of a mathematical and/or numerical groundwater model. In the present study data recorded over a period of 35 years (the long-term monthly means of the meteorological variables precipitation, potential evapotranspiration and temperature) are employed, whereas Table 1 shows the long-term averages of the monthly inflow and outflow discharge data at the three gauging stations used in the analysis. More specifically, the Pirmazd and Hojatabad hydrometer stations discharge data are used to specify inflow and outflow boundary conditions, respectively, for water the budget estimations in the plain. This data is augmented by discharge measurements at the Doab-mereg station at the Gharasu River.

With regard to hydrogeological data, there are 1,160 wells and 7 springs in the study area. According to the water statistics for year 2003, agriculture used 151.928 MCM/year of groundwater reservoir which corresponds to an average pumping rate of 4.15L/s for each well (Gamasiab, 2007)

Table 1. Miandarband plain's average of annual monthly long-term inflow (station Pirmazd), outflow (station Hojatabad) as well as the discharge at the station Doab-mereg at the Gharasu river (see Figure 1) (in m^3/s)

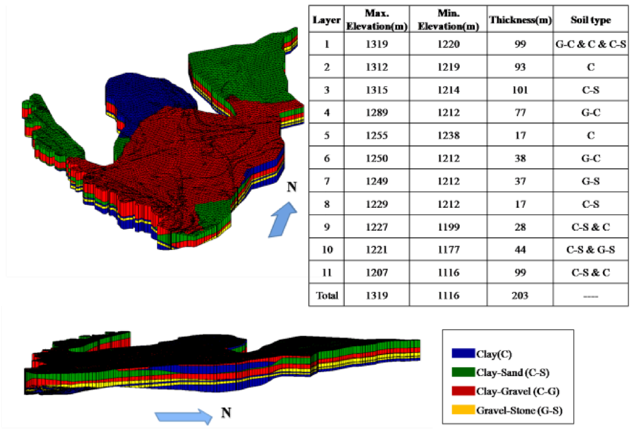
Station	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
Pirmazd	22.41	10.24	1.71	0.42	0.16	0.1	0.17	1.26	4.92	4.94	9.6	60.72	5.93
Hojatabad	22.49	13.93	4.66	2.29	1.59	1.36	1.46	2.71	5.36	7.08	12.19	19.15	7.86
Doab-mereg	15.23	8.6	3.05	1.84	1.16	0.95	1.19	2.27	3.95	4.22	6.33	13.06	5.15

3.2 *Stratigraphy*

Based on the geological information inferred from the drilling log cores at the 8 well locations (Table 2), the groundwater aquifer is divided vertically into 11 horizontal layers, as shown in Figure 2. These layers are made of the following soils/soil-mixtures: 1. clay, 2. clay-sand, 3. clay-gravel, and 4. gravel-stone. Each of these soil materials has certain permeability or, more important for groundwater modeling studies, a hydraulic conductivity *K*, which will be used and refined in the later model calibration task. Suffice to say here that the clay as well as the lower gravel-stone (consisting mostly of compacted marl) layers are acting essentially as aquitards.

Table 2. Drilling log core data from 8 wells, with well depths, estimated values of transmissivity and storativity, as well as the inferred bed rock lithology (adapted from Gamasiab, 2007)

Location of well	UTM (x)	UTM (y)	Depth (m)	Transmissivity T (m^2/sec) and Storativity S	Rock type
Ahmad abad	677470	3824210	240	T= 1750	Conglomerate & Radiolarit
Tappe afshar	682929	3825318	198	not measured	Conglomerate
Hashilan	672807	3826753	156	T = 1200, S=0.004	Marl
Sartip abad	675660	3831210	132	T=10000	----
Ahmadvand	686850	3815500	82	T=607, S=0.025	Conglomerate
Pirhayati	686753	3811278	71	T= 1570	Radiolarit
Koorbalagh	668552	3815506	86	not measured	Lime stone
Nazarabad	681770	3811661	209	T = 750, S=0.0003	Shale



Layer	Max. Elevation(m)	Min. Elevation(m)	Thickness(m)	Soil type
1	1319	1220	99	G-C & C & C-S
2	1312	1219	93	C
3	1315	1214	101	C-S
4	1289	1212	77	G-C
5	1255	1238	17	C
6	1250	1212	38	G-C
7	1249	1212	37	G-S
8	1229	1212	17	C-S
9	1227	1199	28	C-S & C
10	1221	1177	44	C-S & G-S
11	1207	1116	99	C-S & C
Total	1319	1116	203	----

Figure 2. Stratigraphic sub-surface layering of the study area as shown in two directions, together with a table of the attribution of the soils to the various layers. The vertical extension of the stratigraphic plot is 203 m.

3.3 *Groundwater characteristics of the Miandarband plain*

Groundwater flow direction, recharge and discharge areas, hydraulic interaction of surface-groundwater resources and other hydrogeological characteristics of the Miandarband plain have been obtained from piezometric head data recorded on a monthly base at 24 wells during the time period 1991-2008. The locations of these wells and the piezometric isolines generated from the point measurements made in April 2006 using an inverse distance weighting (IDW) interpolation are shown in the left and right panels of Figure 3, respectively. One may clearly notice from the figure that the groundwater table follows pretty much the topography of the Miandarband plain.

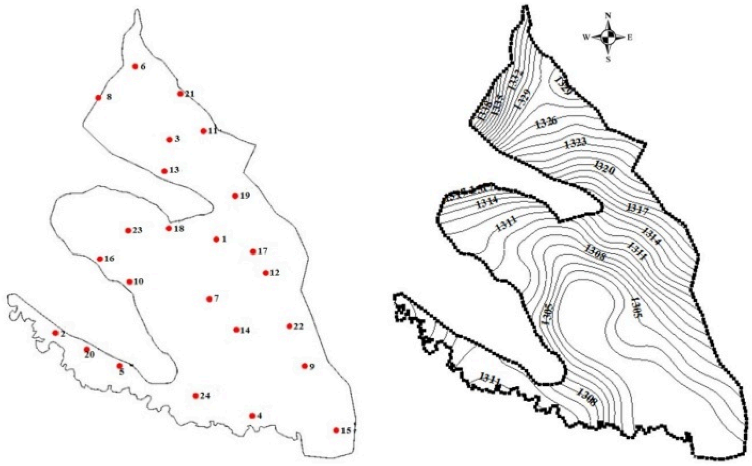


Figure 3. Locations of the piezometers (left panel) and head contours (in m ASL) for April 2006 data (right panel).

3.4 *Development and setup of a groundwater flow model for the Miandarband aquifer system*

The conceptual model

The first step in setting up a numerical groundwater flow model is the build-up of an appropriate conceptual model, in order to assess the groundwater system in its simplest form. Since the complete setup of the field system is difficult and almost impossible, simplifications of difficult issues need to be made during the model development task (Anderson and Woessner, 1991). The development of the conceptual model requires a thorough understanding of the general hydrology, hydrogeology, as well as the dynamics of the ground water flow in and around the study area. The result of this primordial task is then usually a computerized database as well as simplified digital maps and cross sections that will be used later in the final set-up of the numerical model. In order to develop this conceptual model, some field visits into the study area were undertaken and different hydrogeology-, hydrology- and drilling log core (see Table 2) reports related to the Miandarband plain were used. Eventually, a schematic plan of the system was developed using data from observation wells, flow discharge, and infiltration resulting from precipitation and as well as calculations of water balances.

Finite difference grid discretization of the model domain

Based on the results of the geological (see Table 2) and various other geophysical investigations (Anonymous, 2010), and following the ensuing stratigraphy plot (Figure 2), the Miandarband model aquifer has been set up as unconfined/confined mixed aquifer with 11 layers, whereby the upper aquifer layer is considered as unconfined and all layers below are allowed to convert from confined to unconfined and vice versa, depending on the computed head elevations in a layer under question. With this information a 3D finite difference grid of the model domain has been created in the GMS- environment, consisting of 100x100 cells in the horizontal-, and 11 layers in the vertical direction. The overall dimensions of the model in x, y and z directions are 22000, 30000 and 203 meters, respectively. Figure 4 shows the 3D-model grid created in this way, with the various colored lines marking sections, where different packages for inflow/outflow and/or stresses on the groundwater system in MODFLOW are activated.

Boundary conditions

The specification of the appropriate boundary conditions is another challenge in groundwater modeling studies. Boundary conditions are necessary to represent the groundwater system's interaction with the surrounding area (e.g. Ahmed and Umar, 2009). Two kinds of boundary conditions (BC) were formulated at the boundaries of the model domain (see Figure 4, middle panel): (1) Neumann- (no flow) BC's along those segments of the domain which, because of the surface topography of the Miandarband plain, form some kind of a water divide and, (2) general head boundaries (GHB) where the inflow/outflow across the boundary is computed by $QB = Cond^*(h_{out} - h_{aquif})$ (McDonald and Harbaugh, 1988), where h_{out} is a specified head outside the domain, h_{aquif} is the unknown (simulated) head next to the boundary inside the aquifer and Cond (m^2/s) is the conductance of the soil in the boundary segment. There are 11 GBH-segments along the whole model boundary which are indicated in Figure 4. As vindicated by the later model computations for h_{aquif} and the ensuing signs in the equation for QB above, all, but #11 of the numbered GHB segments are inflow boundaries, with only the latter being an outflow boundary. As for the boundary conductance C, it will be estimated and fine-tuned during the calibration process.

Sources and sinks in the aquifer system

In addition to the mentioned in- and outflows across the boundaries of the model, the Miandarband aquifer system gains inflow from infiltration through precipitation (recharge), and some streambed infiltration from the Gharasoo River. Apart from the afore-mentioned groundwater outflow across the downstream boundaries of the model domain, most of the aquifer's water loss is due to the pumping from the 1,160 wells and the discharge through the 7 springs (see Figure 4, right). It should be noted here that since the installation specifications of the wells, namely, their depths were not always known (many of them were drilled most likely without proper legal authorization), their penetration lengths have been limited in the model to the depth of the bottom of first layer.

The river–aquifer interaction was simulated using the river boundary package of MODFLOW. There is a seasonal (ephemeral) river (Razavar River) in the study area that acts more or less like a drainage system for the Miandarband plain, i.e. acts as a sink to the aquifer system, even during the wet season, since the groundwater levels (due to water logging) during that period are still higher than the stream levels.

All of these named aquifer losses (in addition to the gains and losses across the domain boundaries) are conveniently combined in the GMS-environment by the source&sink layer menu. Figure 4 (right) shows the upper source&sink layer #1 which is the only layer where losses from springs, wells and river drainage or gains from the rivers occur.

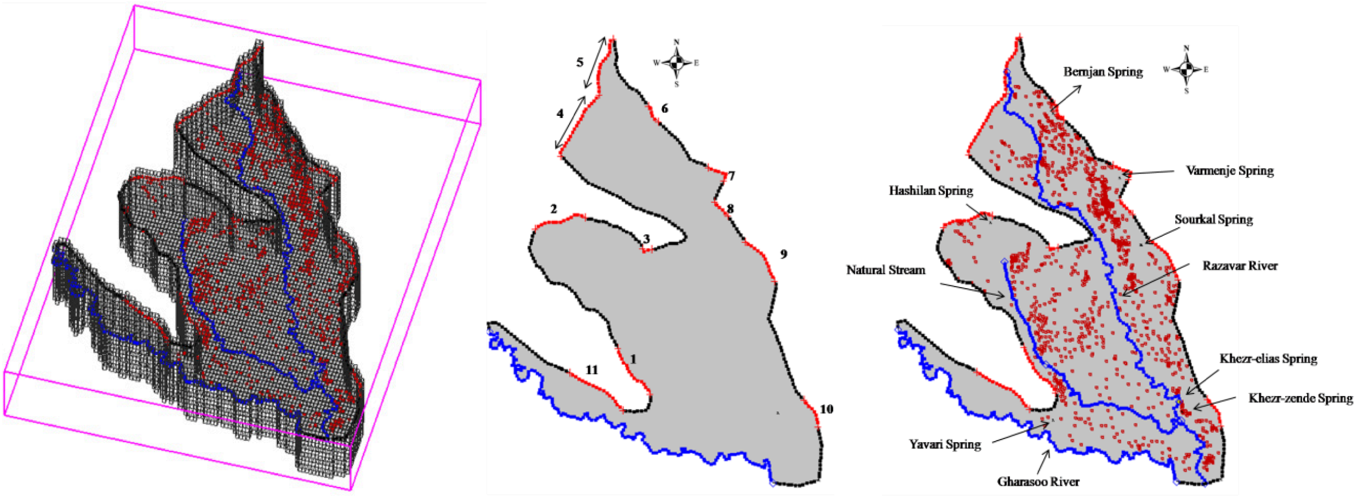


Figure 4. Left panel: FD grid of the model domain with blue and red lines delineating river- and GHB- sections, respectively, where the corresponding MODFLOW packages are activated. The points mark the locations of the wells. Middle panel: Outline of the boundary of the model domain with segments of different types of boundary conditions used. Numbered red-line segments are general head boundaries, black-line segments are no-flow boundaries and the blue line marks the course of the Gharasoo River with a river boundary condition. Right panel: Source&Sink layer 1 of the GMS6.5 menu, which comprises sources of water from lateral inflow, streambed infiltration and losses through lateral outflow as well as by springs and well pumping in the upper layer of the model.

4 RESULTS AND DISCUSSION

4.1 *Model calibration and verification*

An important part of groundwater modeling task is the model calibration process. In order for a groundwater model to be used in any type of predictive role, it must be demonstrated that the model can successfully simulate the observed aquifer behavior. Calibration is the process, wherein certain parameters of the model such as recharge, hydraulic conductivity and, - for transient models- , the specific yield, and other specific aquifer parameters are altered in a systematic fashion, and the model is run repeatedly, until the computed solution matches field-observed values within an acceptable level of accuracy (USACE, 2008).

The model has been calibrated in both steady-state and transient mode, whereby the hydraulic conductivity K has been calibrated for steady-state conditions, and the specific yield S_y and the two conductances *Cond* used in the general head boundary condition (C_{GHB}) and for the streambed in the river package (C_{RIV}) have been calibrated in the transient simulation mode (Zare and Koch, 2014).

To certify the results of both steady state and transient simulation, the coefficient of determination R^2 of the linear regression between the MODFLOW simulated heads and the observed ones at the 24 piezometers has been computed. Figure 5 shows the corresponding points and the regression line for all months of the transient simulation period April 2007 to March 2008. The high value of R^2=0.997 hints of a very good fit of the simulated to the observed heads.

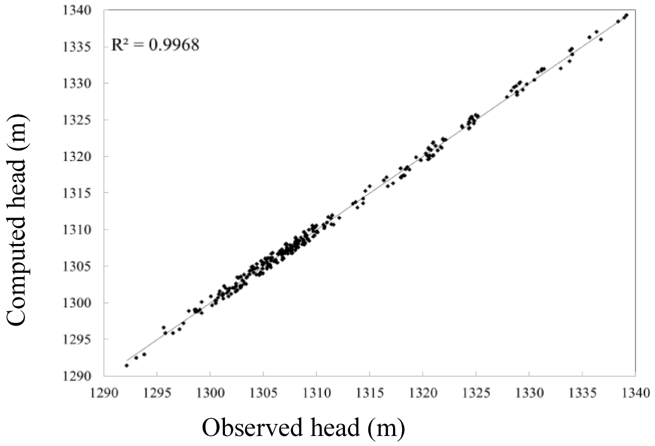


Figure 5. Simulated versus observed heads at the 24 piezometric wells for all months of the April 2007 - March 2008 transient simulation (after Zare and Koch 2014).

Model verification serves to check if the calibrated model is able to predict observed hydraulic heads for later time periods not yet used in the calibration process. As the transient calibration was performed for the May 2007 - March 2008- period, for verification the heads measured in the subsequent month, April 2008, is used. As results shows, a very good agreement between simulated and observed groundwater heads, with a coefficient of determination R^2= 0.99, is also obtained for this month of verification (Zare and Koch, 2014).

4.2 *Effects of the construction of an irrigation & drainage network on the groundwater table*

As mentioned earlier, the construction of the Gavoshan Dam's irrigation and drainage network across the Miandarband plain is currently underway. The courses of the canals already constructed or being planned have been delineated in Figure 1(right panel). It is expected that this irrigation & drainage network will convey about 176.2 MCM/year of surface water from the Gavoshan Dam into the Miandarband plain, where it will be used for agricultural irrigation. It is expected that the future use of groundwater will then be reduced or even stopped, so that the groundwater table may rise and waterlogging conditions may occur.

Before simulating the future effects of this irrigation & drainage network on the groundwater system, an estimate of the additional recharge to the groundwater aquifer due to canal losses but, more importantly, due to direct irrigation must be made. For the former, the kind of lining of the canals plays an important role. Thus, whereas the major feeding canals are lined by concrete, most of the secondary canals are unlined. The results of lysimeter experiments show that about 25% of the irrigation water infiltrates into the aquifer. With a total amount of water of 176.2 MCM/year conveyed from the dam to the plain, this means that 44.05 MCM/year will infiltrate into the aquifer.

Applying this amount of aquifer recharge uniformly across the recharge layer in GMS, its effects on the groundwater table after 1, 5 and 10 years after the start of the network operation were simulated, whereby the irrigation canals were incorporated into the MODFLOW model using the drain package.

The results of these simulations are shown in Figure 6. From the upper panel-row of this figure once can notice the absolute rise of the groundwater levels, with steep gradients near the drainage canals and from the lower panel row, where the relative changes to the April 2006 observations (see Figure 3) are shown, that already after 1 year the groundwater table in the center of the plain has risen by 1.8 m which goes up to 3.2m and 5.2 m after 5 and 10 years, respectively. The results indicate further that after 1, 5 and 10 years of the irrigation operation 6.59%, 37.91% and 56.28%, respectively, of the plain's surface area will be waterlogged.

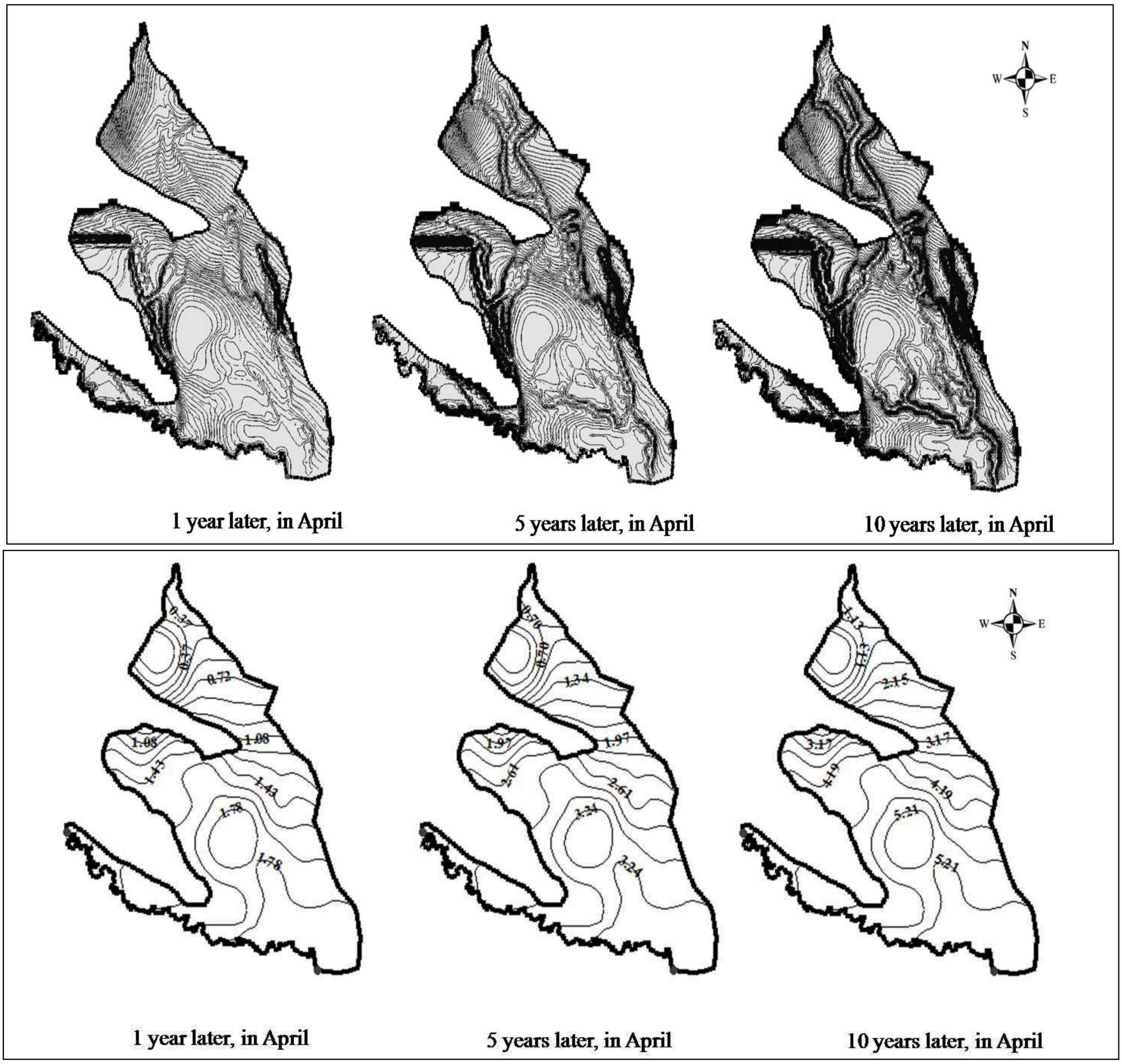


Figure 6. Top row: Simulated piezometric isolines after 1, 4 and 10 year of the operation of the irrigation network, Bottom row: Corresponding changes, relative to the observed heads for April 2006 (see Figure 3).

5 CONCLUSIONS

Water logging by rising groundwater levels, inducing the salinization of arable soils, has become an imminent problem in many irrigated agricultural areas in the world. Such has been the case for the Miandarband plain in the Kermanshah province, Iran. The adverse situation there is further accentuated by the ongoing construction of an irrigation/drainage network and the reduced use of ground water resources. To simulate the effects of the latter with regard to a possible groundwater table rise and the occurrence of subsequent detrimental water logging, the 3D groundwater flow model MODFLOW within the GMS 6.5 environment has been employed. After calibration and verification of the model, the possible effects of the future construction of the Gavoshan Dam's irrigation and drainage network on the groundwater table have been simulated. The results show that already after 10 years of irrigation operation, more than 50% of the plain's surface will be waterlogged. Therefore, an effective water resources management strategy is required to prevent this imminent waterlogging problem. One well-suited policy approach to that regard would be the application of optimally managed conjunctive surface-groundwater operations, the setup of which will, however, require further quantitative groundwater management simulations.

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