

## Using Modflow and MT3D Groundwater Flow and Transport Models As a Management Tool for the Azraq Groundwater System

Wa'il Y. Abu-El-Sha'r<sup>1)</sup> and Randa I. Hatamleh<sup>2)</sup>

<sup>1)</sup> Associate Professor, Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan, E-mail: [wail@just.edu.jo](mailto:wail@just.edu.jo)

<sup>2)</sup> PhD Student, Department of Civil Engineering, The Hashemite University, Zarqa, Jordan, E-mail: [rhatamleh@gmail.com](mailto:rhatamleh@gmail.com)

### ABSTRACT

Numerical modeling has emerged as an effective tool for managing groundwater resources and predicting future responses, especially when dealing with complex aquifers systems and heterogeneous formations. Among these models, MODFLOW and MT3D are the most commonly used simulators for groundwater flow and solute transport in subsurface systems, respectively. These models have been used herein as a management tool for the Azraq basin, one of the most important groundwater resources for domestic and agricultural sectors in Jordan. Groundwater extraction from this basin already exceeded the safe yield of the aquifer, and a sharp drop in the water table, a dry out of the springs at the center of the basin and the problem of increased salinity in many parts of the aquifers have been reported. Currently, more than 600 wells including governmental, private and unauthorized wells are operating within the basin boundary. In its attempts to restore and sustain the aquifer, the Ministry of Water and Irrigation (MWI), the official entity in charge of water resources in Jordan, is considering several scenarios of controlled pumping. In this study, five suggested scenarios of pumping with different abstraction rates for years 2005 through 2020 have been explored by using the three dimensional finite difference flow model [MODFLOW (PM5)] to simulate the flow system, and the solute transport model (MT3D) to predict the transport of total dissolved solids given in terms of Electric Conductivity (EC). These scenarios include: first, maintaining the current pumping rate of 57 MCM for the study period; second, reducing the current pumping rates by half; third, increasing the pumping rate by half; fourth, reducing the pumping rates in public wells by half and maintaining the current rates for other wells; and finally reducing the pumping rates by half for the farm wells (private) and maintaining the rates at the other wells. Results indicate that the first and fourth scenarios have similar effect on the drawdown. Also, the second and fifth scenarios have similar effects and provide the lowest drawdown values. The third scenario gives the worst drawdown. The transport of Total Dissolved Solids (TDS) given in terms of Electric Conductivity (EC), has also been explored. Different parameters including EC, recharge, model boundary and advection parameters were adjusted to run the model. Simulation results indicated that the effect of the different scenarios on the values of EC is less profound than the effects on the drawdown values. The third scenario caused a slight increase of EC values over the values simulated by other scenarios.

**Keywords:** Numerical Models, Modflow, MT3D, Groundwater Flow, Transport, Management Scenarios, Azraq Basin.

## INTRODUCTION

With nearly half the population of Jordan drawing its drinking water from groundwater resources, issues of groundwater flow and contaminant transport in subsurface systems have elicited considerable interest from both public and private sectors. Among the twelve groundwater basins in Jordan, Azraq basin is one of the most important since it provides the three main cities of Jordan, namely: Amman, Irbid and Zarqa with significant portions of its domestic water supplies. It consists of a three aquifer system, the upper (unconfined), middle and lower aquifers, separated by two confining formations. The water is mainly pumped from the upper aquifer and only few wells penetrated the middle aquifer and the deep aquifer, respectively.

In the beginning, water was pumped from the basin to supply the city of Irbid only, and the increased water demand due mainly to the explosive population growth in the cities of Amman and Zarqa, led to drill new well fields and draw groundwater at high rates. Furthermore, private wells in the basin increased dramatically in the past two decades; some of these wells are not even authorized. The total pumping from the basin was estimated to reach 57.7 MCM/yr in the year 2001 (Al-Hadidi and Subah, 2001), which is far beyond the safe yield of the basin (30 MCM/yr.). Absence of full control on private wells and its pumping rates in addition to pumping from the water authority well fields resulted in overexploitation of water storage and deterioration of groundwater quality in some parts of the aquifer.

The Azraq basin received great attention, and numerous studies were conducted for estimating the potential safe yield and for assessing current and potential future scenarios (Agrar and Hydrotechnick, 1977; Humphry and Sons, 1978 and 1982; Rimawi, 1985; Al-Momani, 1993; Al-Kharabsheh, 1995; Ayed, 1996; UNDP- Azraq Oasis Conservation Project, 1996; Jordanian Consulting Engineering, 1997; Al-Khatib, 1999; Hatamleh, 2001; Al-Hadidi and Subah, 2001; Rihani, 2003; Moqbel, 2004). All computer modeling studies of Azraq basin (except for Rihani, 2003 and

Moqbel, 2004) used the processing ModFlow and MT3D to come up with future scenarios for water management of the basin. For instance, the water budget obtained from the steady state simulation organized by the United Nations Development Program (UNDP) and the Azraq Oasis Conservation Project (1996) employed Processing ModFlow (PM3) to predict the behavior of the shallow aquifer for the years 2005, 2015 and 2025. These results formed the basis of the solute transport modeling study (via MT3D) organized by Jordanian Consulting Engineers (1997) which also included a hydrochemical evaluation of the basin.

Concerns about increasing salinity in the basin began to rise since the mid 1980s, and numerous studies were conducted to assess the severity of the situation and to determine the salinity characteristics of the groundwater at Azraq (Worzyk and Huser, 1987; Al-Waheidi, 1990; Al-kharabsheh, 1991; Rimawi, 1985; Ayed, 1996; Jordanian Consulting Engineering, 1997; Moqbel, 2004). Among the first of these was a study conducted by Worzyk and Huser (1987), which aimed at locating the fresh water/ salt water interface, especially at the Qa'a area and the well fields. The main conclusion of this study was that water quality deterioration in the upper aquifer is due to the full utilization and overpumping of the aquifer and would most likely originate at the center of the basin and then extend towards the north, northwest and northeast parts of the basin. Al-Waheidi (1990) showed that the saline zones extended to a maximum depth of 65m within the upper aquifer. However, two types of salinity were characterized in the upper aquifer (Al-Kharabsheh, 1991), namely; Na-HCO<sub>3</sub> in the north and NaCl in the south and southwest.

Rimawi (1985) conducted an isotope hydrology study and investigated the hydrochemical properties of the water at Azraq. Some of the groundwater stored in the basin was dated back to 20000 years ago. Recent waters (from the present) were also found to exist in the basin. Ayed (1996) studied the hydrological, hydrogeological and hydrogeochemical characteristics of the basin's three aquifer system. This study indicated that water from the upper aquifer system is potable in the Qa'a area (around

the middle of the aquifer) while water in the south flowing toward the north and west of Azraq has high TDS values.

All the above mentioned studies reported a general lack of data about the hydrogeologic system that exists at Azraq basin. For example, only four observation wells do exist for the upper aquifer and no observation is available for the middle and deep aquifers. Nevertheless, important decisions need to be made by the MWI in order to restore and sustain the aquifer systems. The study presented herein used Processing Modflow PM5 and the solute transport code (MT3D) to construct a groundwater flow model and to model contaminant transport in the basin. These models were then used as a management tool for assessing the current situation and forecasting future responses to assumed coming events. Five different future pumping scenarios have been considered.

## DESCRIPTION OF THE STUDY AREA

### Location

Azraq Basin is one of the largest basins in the northern parts of Jordan. According to the Palestine grid, the basin lies from 250 to 400 east and from 55 to 230 north as shown in Figure (1). It covers an area of approximately 12710 km<sup>2</sup>, of which 94 percent lies within Jordan and the reminder in Syria and Saudi Arabia. The area is bounded by Syria to the north, Hammad Basin to the east, Sirhan Basin to southeast, Mujib Basin to the south and Zarqa Dhuleil Basin to the west.

### Topography and Drainage

Azraq Basin is a depression surrounded by hilly relief. All the water courses within its boundary drain in the center of the basin, Qa'a Al-Azraq, which is the lowest point in the basin. The elevation of Qa'a Al-Azraq is about 503 to 512 m above mean sea level (a.m.s.l.). The elevation rises to 900 m (a.m.s.l.) in the eastern, southern and western parts of the basin. It increases sharply to 1550 m (a.m.s.l.) in the north.

### Geology

The outcropping formations in the Azraq Basin are

the Rijam and Wadi Shallala in the central and eastern part of the basin. The northern part of the Azraq Basin is dominated by Miocene to Pleistocene basalt, whereas to the west and south by the Rijam and Muwaqqar Formations of the Late Cretaceous (Early Tertiary) age. Cretaceous rocks in Jordan are subdivided into two main sequences; the Early and Late Cretaceous. The Early Cretaceous rocks are locally known as Kurnub, and the Late Cretaceous rocks are further subdivided into the Ajlun and Belqa Groups. There are two major fault systems in the Azraq Basin, one trending east to west and a second trending northwest to southeast.

### Hydrology

The climate of the Azraq Basin is characterized by two well-defined seasons, a hot and dry summer, and a wet and cold winter. Most of the study area is arid, while a small portion can be considered as semi-arid. The average annual minimum and maximum temperatures are 11.6°C and 26.6°C. The average relative humidity varies from 49.9% to 61% in summer and from 56% to 82% in winter. The wind direction is northwest in summer, shifting to southeast in the winter. The annual average wind speed is 11.6 km/hour, which ranges between 10 and 18 km/hour in the winter and from 7 to 12 km/hour in the summer. The average daily evaporation observed from a class A pan is 10.4 mm/day and varies from 5 to 19 mm/day in summer and from 3 to 12 mm/day in winter. The mean annual rainfall in the Azraq basin varies between 75 and 400 mm in a wet water year, and varies between 50 and 300 mm in a normal water year, whereas it ranges from 10 to 175 mm in dry conditions. It is clear that the mean annual rainfall decreases across the basin from northwest to southeast. A number of major wadi's drain into the central mud flat of Qa'a Azraq. These wadis are characterized by wide, shallow flow-beds with relatively low slopes.

## HYDROGEOLOGY

### Aquifer Systems

Groundwater aquifers in Jordan can be divided into

three main hydraulic complexes (Agrar and Hydrotechnick, 1977): (1) the Shallow Aquifer System (Upper Aquifer, B4/B5); (2) the Upper Cretaceous (Middle Aquifer System, B2/A7) Amman-Wadi Sir Hydraulic Complex; and (3) the Deep Sandstone (Lower Aquifer System), Kurnub and Disi Hydraulic Complex.

The Upper (Shallow) Aquifer and the Middle Aquifer Systems are separated by the Muwaqqar (aquiclude) formation (B3). Two major groups of springs existed in the central part of the Azraq Basin comprising the main discharge outlets of the Shallow (Upper) Phreatic Aquifer.

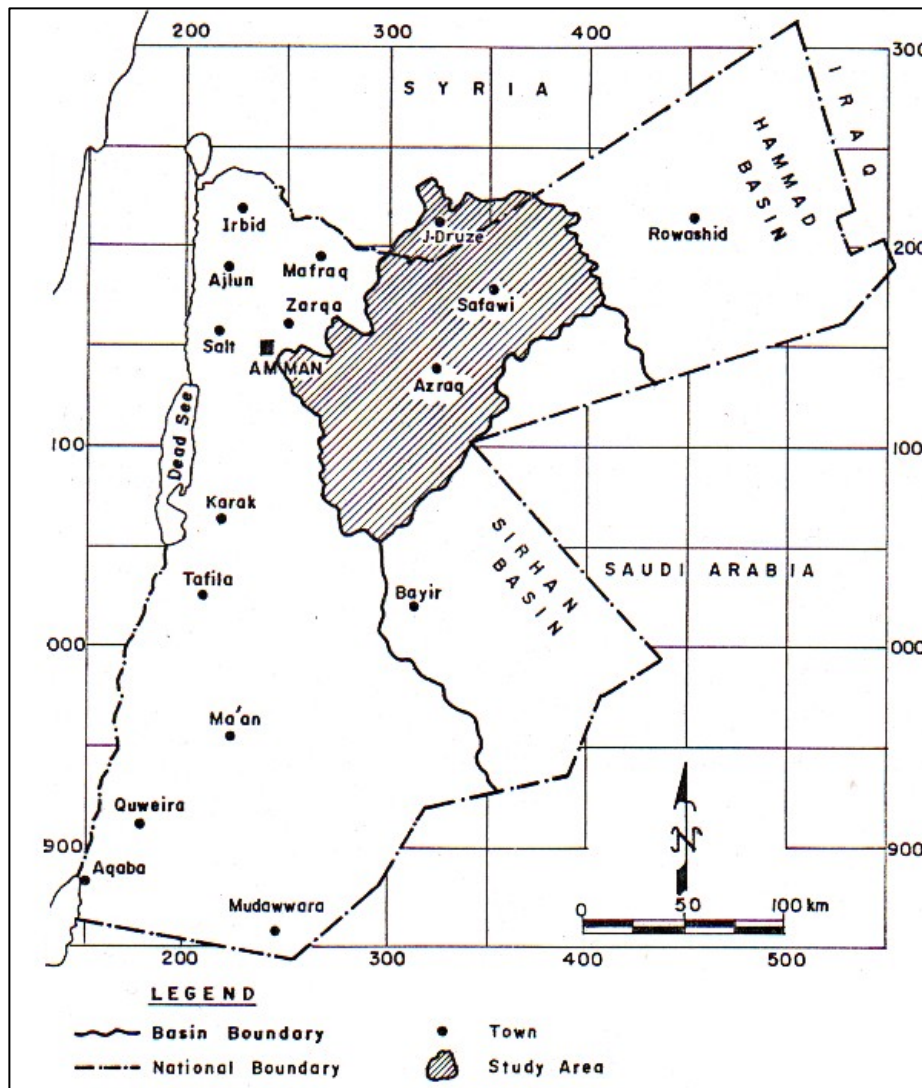


Figure 1: Map of Jordan showing the location of Azraq basin (Al-Hadidi and Subah, 2002).

The Upper Aquifer System is an unconfined aquifer except at the middle of the basin (Qa'a Azraq). The Qa'a Azraq deposits form a lens up to 15 meters thick overlying the aquifer and give rise to leaky artesian

conditions. Before the publicly owned well-field extraction to Amman began in 1982, this aquifer discharged as springs and seeps near Azraq Al-Shishan and Azraq Al-Doruz and as evaporation from the shallow

water table in the vicinity of the Qa'a Azraq.

The Middle Aquifer System is a confined aquifer due to the aquiclude, bituminous marl of the (B3) formation. This aquifer system underlies the Upper Aquifer System and outcrops in the western part of the basin. More than 15 water wells penetrating the B2/A7 Aquifer System were drilled in the Azraq Basin.

The Middle and Lower Aquifer Systems are separated by marl and marly limestone of the low-permeability Ajlun Group (A1/6). The Lower Aquifer System is a confined aquifer. There is only one well in the Azraq Basin completely penetrating the B2/A7 Aquifer System. It is only 40 m through the underlying Kurnub Sandstone (Lower Aquifer), with a total depth of about 1299 m. It was found that the Kurnub Group seems to be a promising ground source for future planning. The Middle and Lower Aquifer Systems occur at depths varying from 400 to 3000 m with brackish to saline water (Gibbs, 1993). The ground water exploited from the Middle and Lower Aquifer Systems have not been utilized to date.

The saturated thickness of the Upper Aquifer System in the Azraq basin varies from one place to another. The depth of the water table varies from a few meters in the center of the basin to more than 300 m in the north and northeast parts of the basin at the Basalt Plateau.

More than 1100 water wells have been drilled in the basin, most of which are located north and east of the Azraq Oasis. About 600 wells are in operation. The depths of these wells range from a few meters in the center of the basin to more than 400 m to the north and northeast of the basin (BGR/WAJ, 1996).

The yields of the wells are variable and range between 7 and 107 m<sup>3</sup>/hour in the B4/B5 aquifers, between 13 and 200 m<sup>3</sup>/hour in the Basalt aquifer and between 14 and 304 m<sup>3</sup>/hour in the Basalt/Rijam (B4) aquifer.

### **Groundwater Level Fluctuation**

The groundwater of the Upper Aquifer System generally occurs under unconfined conditions in the Azraq Basin. The water table is not stable and fluctuates according to wet and dry seasons and also according to

the withdrawal rate of groundwater. Four observation wells (F1022, F1043, F1060 and F1280) are used to monitor the water level fluctuations of the Upper Aquifer. These wells have total depths of 88, 255, 116 and 195 m, respectively. The F1060 borehole terminates in the basalt; the others penetrate both basalt and B4 limestone (BGR, WAJ, 1996).

### **Discharge**

Prior to the sixties, the Upper Aquifer System in the Azraq Basin was relatively undeveloped. Drilling activities started in the early sixties and the extensive drilling program accelerated in the 1980s. Until 1990, the discharge from the Upper Aquifer System occurred at springs in the center of the basin and water pumped from boreholes. Unfortunately, spring flow declined to zero by the end of 1990. Now, the total number of boreholes reached 1100 and the total annual groundwater extraction has continually increased.

### **Storage**

The evaluation of storage in the Upper Aquifer System of the Azraq Basin is estimated by the amount of water that can be released before the decline of the water table depth becomes the controlling factor of groundwater development in the area. The saturated area in the Azraq Basin is about 9900 km<sup>2</sup>, the average saturated thickness of the Upper Aquifer System is 150 m and the average specific yield is 0.015 (Ayed, 1996).

### **Recharge**

The average annual recharge to the upper aquifer of the Azraq Basin was estimated to be about 34 MCM (Al-Hadidi and Subah, 2001).

### **Hydrogeochemistry**

The historical hydrochemical data for the wells in Azraq Basin were collected from more than 960 samples collected from wells scattered all over the basin (UNDP and Azraq Oasis Conservation Project (1996)). These samples were subjected to correlation analysis in order to study the interrelation between the different parameters.

The high significant relationships are indicated between EC and Cl, Na, Mg, Ca and SO<sub>4</sub> in descending order and low significant relationships between EC and pH and CO<sub>3</sub>. The values of EC were calculated by multiplying the values of TDS (mg/L) by 0.64 (Jordanian Consulting Engineering, 1997).

## FLOW AND TRANSPORT MODEL

### Conceptual Model

The conceptual model for Azraq Basin adapted by this study consists of three hydrogeological layers, two aquifers and a confining layer. The top soil formation (B4/B5) of the unconfined aquifer is taken as the first layer, followed by the confining layer (B3) as the second layer. The third is the Middle aquifer (B2/A7). Interaction between the various aquifer systems is represented by leakage terms. These layers in addition to the surrounding boundaries are distinguished from each other by the hydraulic conductivity for each element in its field.

Sources and sinks of water in the basin (precipitation, baseflow, springs and recharge) are assigned to the corresponding grid blocks within the domain.

### Flow and Transport Governing Equation

A general form of the governing equation which describes the three dimensional movement of groundwater flow of constant density through the porous media is (Freeze and Cherry, 1979):

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) - w = S_s \frac{\partial h}{\partial t} \quad (1)$$

where:  $K_x$ ,  $K_y$ ,  $K_z$  are values of hydraulic conductivity along the  $x$ ,  $y$  and  $z$  coordinate axes (L/t);  $h$ : is the potentiometric head (L);  $w$ : is the volumetric flux per unit volume and represents sources and/or sinks of water per unit time (t<sup>-1</sup>);  $S_s$ : is the specific storage of the porous material (L<sup>-1</sup>); and  $t$ : is time (t).

The first part of this problem was run to get a steady state solution that takes the form:

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) - w = 0.0 \quad (2)$$

From the steady state solution, the hydraulic conductivity for model aquifers can be found. Then the equation is solved for transient case in order to solve for storage coefficient.

The partial differential equation for three-dimensional transport of contaminants in groundwater is (Freeze and Cherry, 1979):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left[ D_{ij} \frac{\partial C}{\partial x_i} \right] - \frac{\partial}{\partial x_i} (v_i C) + \frac{q_s}{\theta} C_s + \sum_{k=1}^N R_k \quad (3)$$

where:  $C$ : the concentration of contaminant dissolved in groundwater;  $t$ : time (t);  $x_i$  the distance along the respective Cartesian co-ordinate axis;  $D_{ij}$ : the hydrodynamic dispersion coefficient;  $v_i$ : the seepage or linear pore water velocity;  $q_s$ : the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative);  $C_s$ : the concentration of the sources or the sinks;  $\theta$ : the porosity of the porous medium; and  $R_k$ : chemical reaction term.

## FLOW MODEL

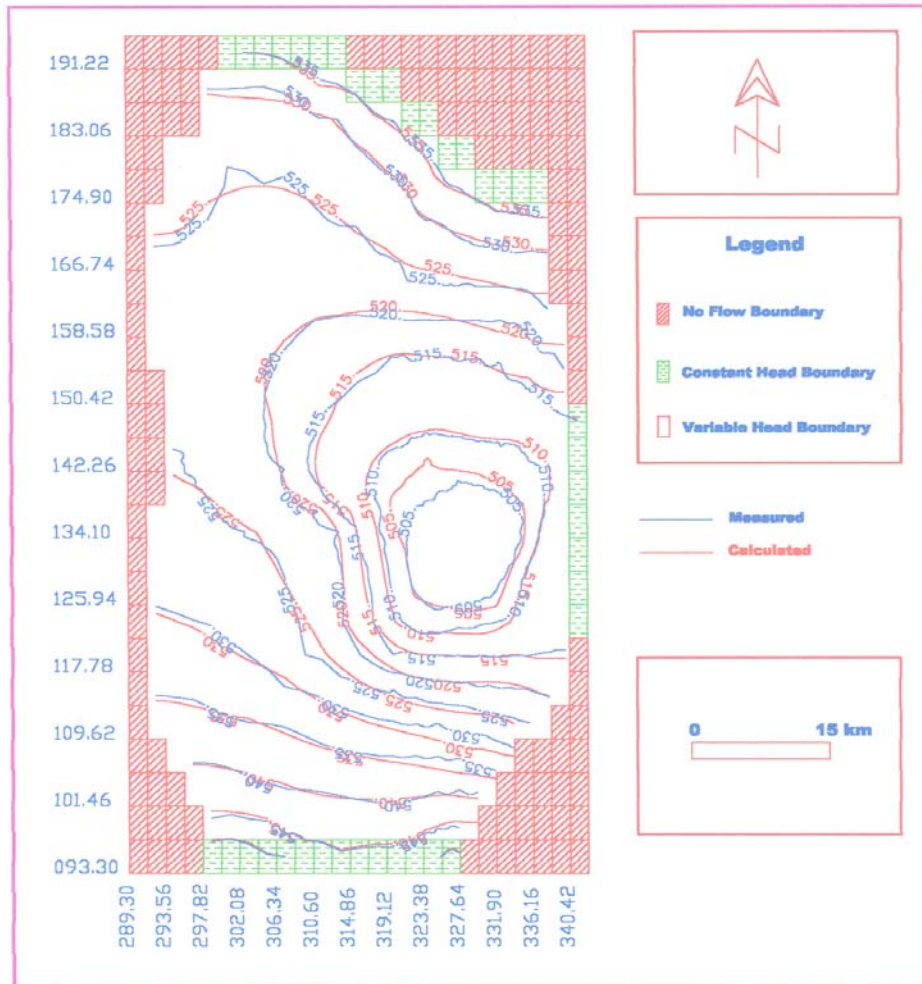
### Model Input

The model domain and grids used in this study are the same for both the flow and transport model. The model covered 5431.5 km<sup>2</sup> and the whole area is divided into 81 columns and 54 rows. The total number of cells is 4374 cells. The area of the largest cells is 8.69 km<sup>2</sup> and the area for the smallest cells is 0.14 km<sup>2</sup>. Similar grid sizes have been used by a previous groundwater flow study (Al-Khatib, 1999). The smallest cells are located in Qa'a Azraq where most of the wells exist. The boundary conditions of the upper aquifer (B4/5 and alluvium) are described in Figure (2). Constant head boundary is in the north, east and south of the domain. The topographic elevation of Jabel Al-Doruz in the north (a physical boundary) defined the constant head where flow comes from this side. No flow boundary conditions are in the

western, northwestern, southwestern, northeastern and southeastern parts of the domain. And the variable head boundary is in the middle.

For the middle aquifer (B2/A7 formation), the boundary conditions in the north, south and some

locations at the east and at the west of the domain are constant head as shown in Figure (3). No flow boundaries are in the cells where the stream flow lines are not perpendicular to water level contours.



**Figure 2: Steady state flow calibration matching map between calculated and measured water levels for the upper aquifer.**

### Steady State Calibration

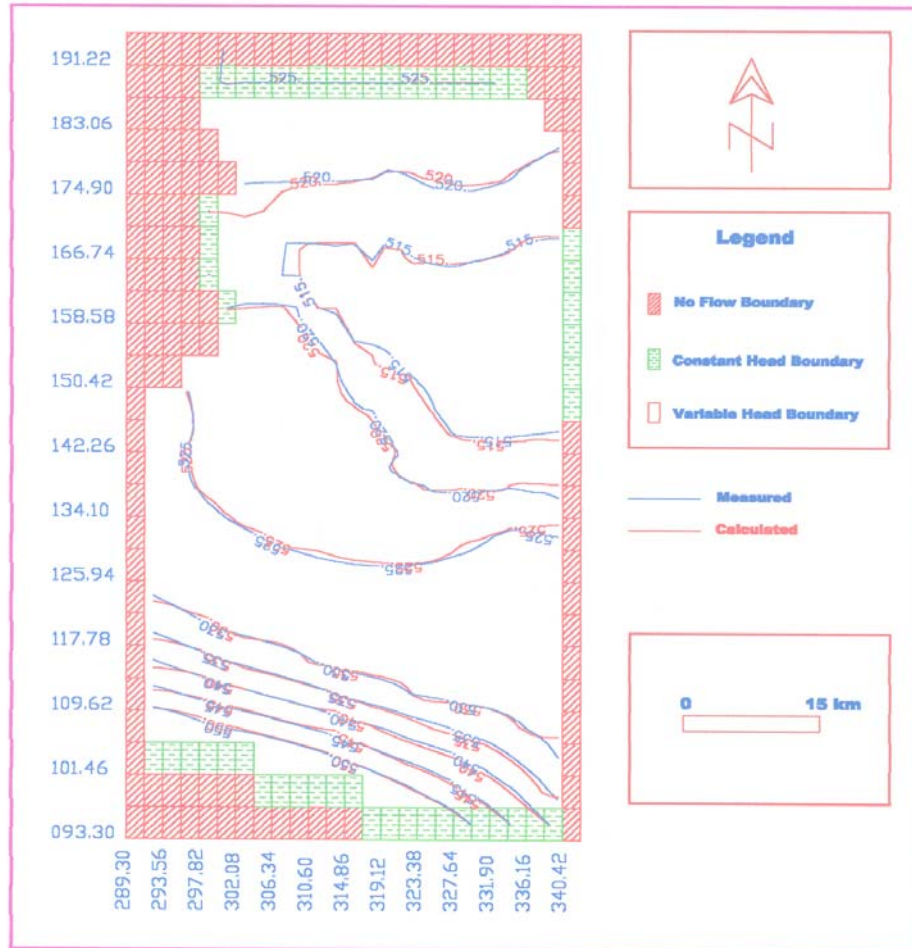
Steady state calibration for the flow model was achieved by comparing the hydraulic heads obtained from available groundwater level contour maps of the first and second model layer and the calculated hydraulic heads of the MODFLOW simulation in order to simulate the flow

lines of these layers. During calibration, horizontal and vertical hydraulic conductivities and recharge values were adjusted in sequential model runs to match the simulated heads and measured head. The comparison between measured and simulated water levels for the upper and middle aquifers is shown in Figures (2) and

(3), respectively.

As shown in Figure (4), the horizontal hydraulic conductivity values for the upper aquifer ranged from 0.10-90.00 m/ day for the first model layer (B4/B5),

8.4E-5 m/ day for aquitard (B3) formation; and the hydraulic conductivity values ranged from 0.001-30.00 m/ day for the middle aquifer (B2/A7) formations as Figure (5) shows.



**Figure 3: Steady state flow calibration matching map between calculated and measured water levels for the middle aquifer.**

### Transient Calibration

For transient simulation, the time was divided into fifteen-stress period. The first one started from the beginning of the 1970s to the end of 1984 with fifteen time steps. This period represented the steady state period where there was no significant drawdown in the water level. The second starts from the beginning of 1985 till the end of that year with one time step. And the

same will be for the next thirteen-stress periods with one time step for each. The data from 1970 to the end of 1994 were used for transient calibration and from 1995 to 1998 for verification. About 7 MCM was discharged each year for 1994 until 1998 from the upper aquifer through illegal wells. Abstraction from the two aquifers are only available from 1981 as total abstract without specifying the location of abstraction wells, so wells



discharge was randomly distributed. In the study area there are only four monitoring wells in the (B4/B5) formation. And there is no monitoring well for the middle aquifer. The available data were used to calibrate the transient state of the model. The first step of the calibration was to assign an initial value for storage coefficients and specific yield for each model

layer. These values were taken from previous studies. Calibration is done using trial and error procedure by changing the specific yield, storage coefficient, and with very limited range in the hydraulic conductivity values. Good performance of the model was observed through the transient simulation to fit between simulated and observed drawdown in the observation wells.

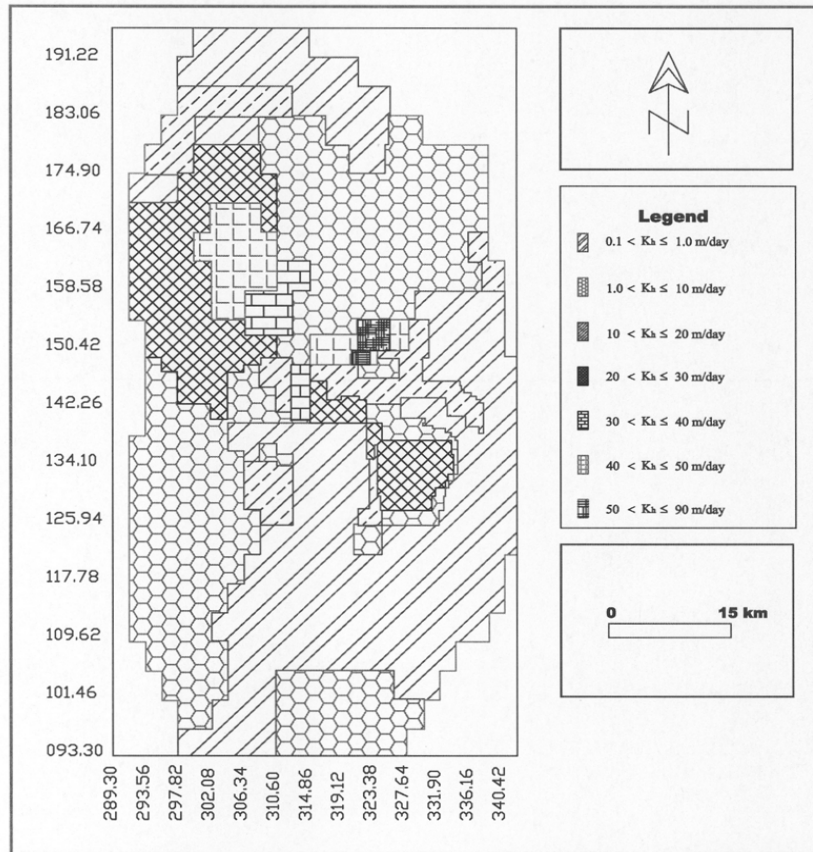


Figure 4: Calibrated hydraulic conductivity for the upper aquifer.

### Model Verification

Verification of the code was carried out to establish greater confidence in the model by using the set of calibrated parameter values and stresses to reproduce a second set of field data. Figures (6) to (9) present a comparison between the observed and the calculated drawdown in the observation wells F1022, F1043, F1060 and F1280, respectively. The results show good agreement between the observed and calculated drawdown for the government wells, while there is

noticeable difference between the observed and calculated drawdown in the farms wells. This conforms to the existence of illegal wells responsible for unrecorded discharge in the farm area.

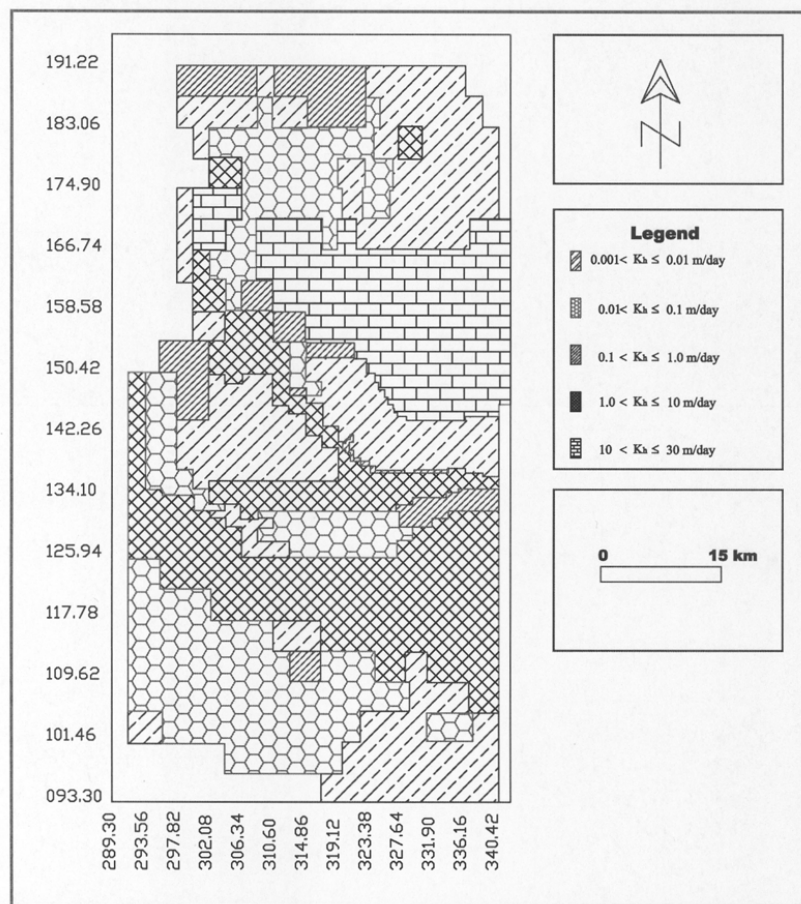


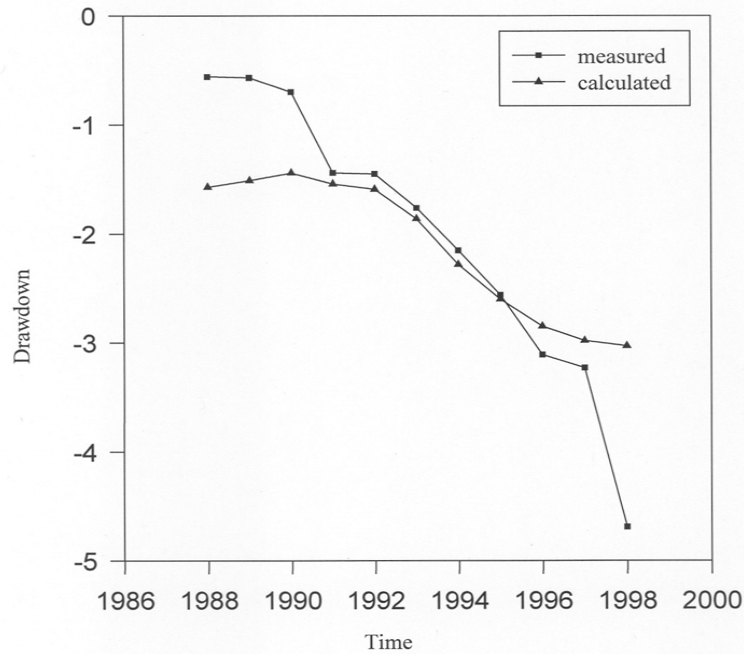
Figure 5: Calibrated hydraulic conductivity for the middle aquifer.

### SOLUTE TRANSPORT MODEL

Mass transport of total dissolved solids has been investigated by using MT3D, which is a computer model for simulation of advection, dispersion and chemical reactions of soluble contaminants in three-dimensional groundwater flow systems. Concentrations of the total dissolved solids are presented herein in terms of EC. Different parameters including EC, recharge, model boundaries, particle tracking algorithm and advection parameters and methods were adjusted to run the model by using methods of characteristics (MOD). Figure (10) shows the initial values of EC  $\mu\text{s}/\text{cm}$  at the beginning of 1985 for the upper aquifer system (JCE, 1997). The highest EC concentrations were found in the well field

area in the center and the north of the domain.

Transient simulation as well as flow calibration begin with the steady-state initial conditions with the same boundaries, parameters and methods of advection and ends before or when a new steady state is reached. Both the time and the stress period were divided into several steps. The first step started from the beginning of the 1970s till the end of 1984 with fifteen time steps. This represents the steady state period where there was no significant change in EC concentrations. While the simulation of transient conditions started in 1985 when a significant drawdown in water level occurred and caused an increase in the values of EC. Calibration was achieved by adjusting the advection parameters, and the amounts of recharge were also changed during the process of calibration.



**Figure 6: Comparison of observed and simulated draw for well F1022 (Farm well area).**

### MODEL PREDICTIONS

Model predictions have been conducted in order to evaluate the response of the model for five future scenarios. These scenarios vary in terms of pumpage rates for the different operating well groups in the basin and were developed jointly by the staff of the Ministry of Water and Irrigations as follows: the first scenario assumes that the current withdrawal rate of 57 MCM/year continues to be the same during the simulation period that starts in 2005 till 2020; the second scenario explores the effect of reducing the pumping rate by 50% (annual withdrawal rate 28.5 MCM) on the drawdown and EC values; in the third scenario, the effects of increasing all the pumping rates by 50% (annual withdrawal rate 85.5 MCM) during the period of 2005 to 2020 are examined. This situation might happen if the Azraq Basin is considered as an alternative for other water resources; the fourth scenario assumes that all the pumping rates of public wells have been reduced by 50% and pumping rates of private wells have been kept the same as in the year 2000 during the period of 2005 to

2020; the fifth scenario investigates the effects of reducing all the pumping rates of private wells by 50% while maintaining the public wells pumping rates at those of the year 2000 for the period of 2005 to 2020.

Simulation results of the first scenario, in which a total pumping rate of 57MCM is maintained during the period from 2005 till 2020, are summarized in Table (1).

As shown in this table, the maximum drawdown increased from 25.7m in year 2005 to 32.4m in year 2020 while the values of EC slightly varied for the same period (from 1882 to 1905  $\mu\text{s}$ ). The maximum drawdown values for all the scenarios considered are given in Table (2). These indicate that the first and fourth scenarios have similar effect on drawdown. Also, the second and fifth scenarios have similar effects and provide the lowest drawdown values. Among the five scenarios considered, the third scenario has the worst effect on drawdown values and especially for the year 2020. Figure (11) shows the simulated drawdown in the year 2020 for the upper aquifer (scenario one). Figure (12) shows the simulated values of EC in the year 2020 for the upper aquifer (scenario three).

**Table 1: Prediction results for the flow and transport model with the same current discharge 57 MCM/year (The first scenario).**

Year	Observation well	Max.	F1022	F1043	F1060	F1280
2005	Draw down (m)	25.7	5.3	13.6	11.1	11.7
	EC ( $\mu\text{s/cm}$ )	1882	1069	853	1776	820
2010	Draw down (m)	28.0	6.2	14.7	12.9	12.8
	EC ( $\mu\text{s/cm}$ )	1886	1099	867	1781	924
2020	Draw down (m)	32.4	7.8	16.8	15.9	15
	EC ( $\mu\text{s/cm}$ )	1905	1122	873	1804	929

**Table 2: Maximum simulated drawdown values for the five scenarios.**

Year	Max.	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
2005	Drown down (m)	25.7	20.3	30.6	25.8	20.2
2010	Drown down (m)	28.0	20.5	35.6	28.0	20.5
2020	Drown down (m)	32.4	20.8	43.7	32.4	20.8

The EC values for the year 2020 are shown for the first and third scenarios in Figures (13) and (14), respectively. There is no significant change in the values of EC through the different scenarios for the same year.

#### SENSITIVITY ANALYSIS

Sensitivity analysis was conducted herein to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of hydraulic conductivity, specific storage and the typical values of layer thickness, initial head and recharge. These parameters were systematically changed between -25% to +25% with increments of 5% from its base value to determine what effect these changes have on the predicted drawdown values and EC. Results indicated that for steady state conditions, the model is slightly more sensitive to changes in horizontal hydraulic conductivity than to changes in recharge values and not sensitive to specific yield. For transient conditions, it is not sensitive to horizontal hydraulic conductivity, slightly sensitive to recharge and

shows high sensitivity to specific yield at lower values rather than at higher ones. On the other hand, the transport model showed no response for the change of any parameter except for very long period of discharge.

#### CONCLUSION

The models used in this study, Modflow (PM5) and MT3D, provided an effective tool for managing Azraq Basin by evaluating the effect of the different alternatives under consideration by the Ministry of Water and Irrigation in Jordan. Simulation results indicate that increasing the current pumping rates by 50% caused the maximum drawdown and should be avoided. The first and fourth scenarios have similar effect on drawdown. Also, the second and fifth scenarios have similar effects and provide the lowest drawdown values. The effect of the different scenarios on the values of EC is less profound than the effects on the drawdown values. The third scenario caused a slight increase in EC values over the values simulated by other scenarios.

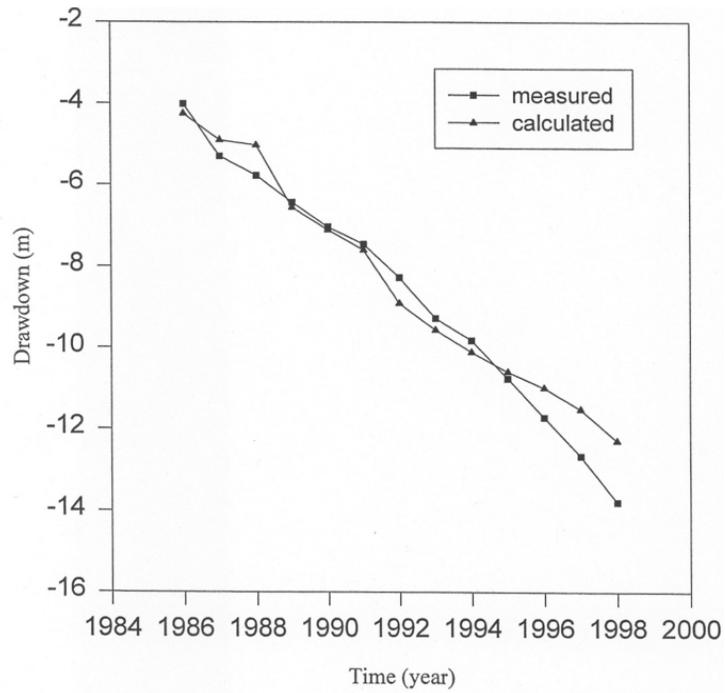


Figure 7: Comparison of observed and simulated drawdown for well F1043 (Governmental well area).

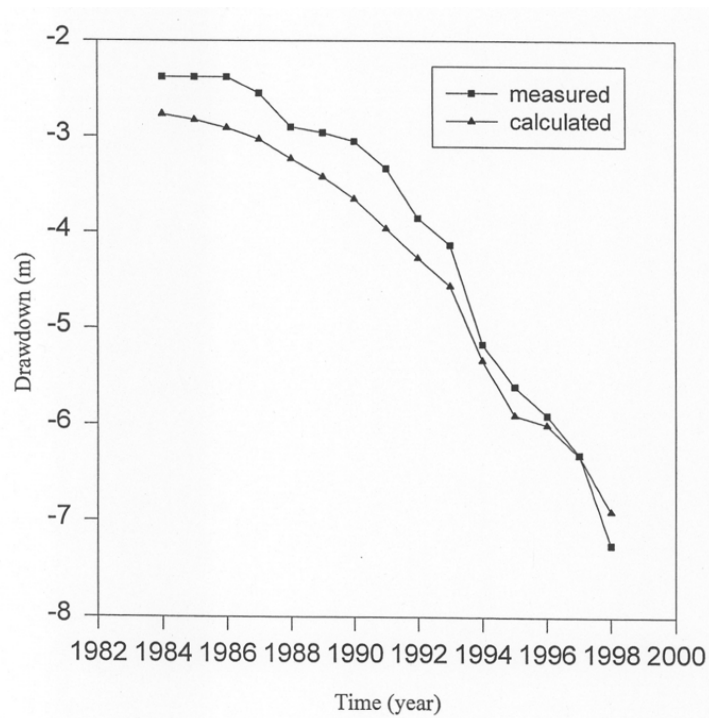
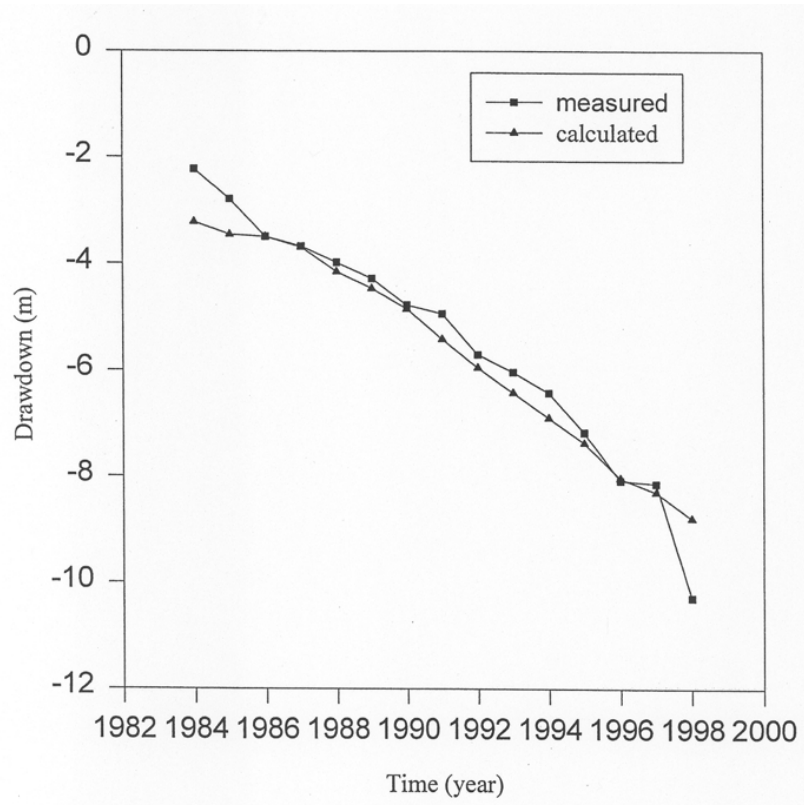


Figure 8: Comparison of observed and simulated drawdown for well F1060 (Farm well area).



**Figure 9: Comparison of observed and simulated drawdown for well F1280 (Governmental well area).**

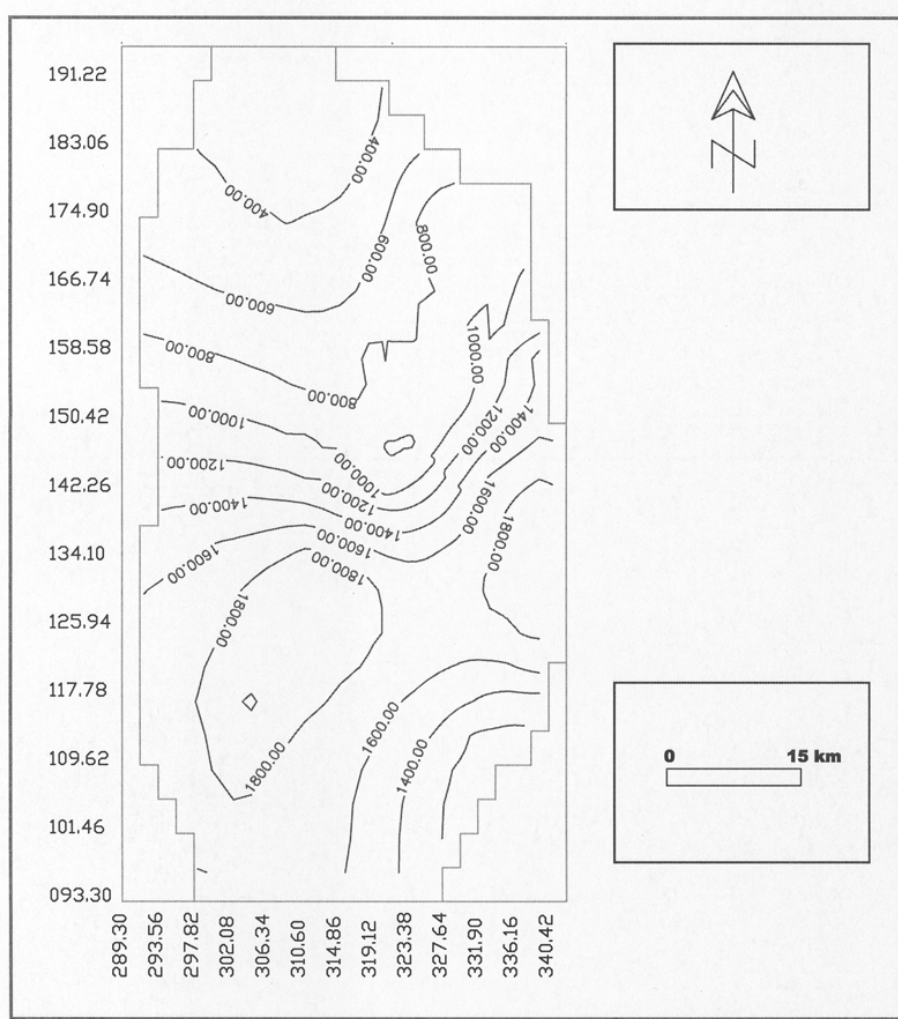
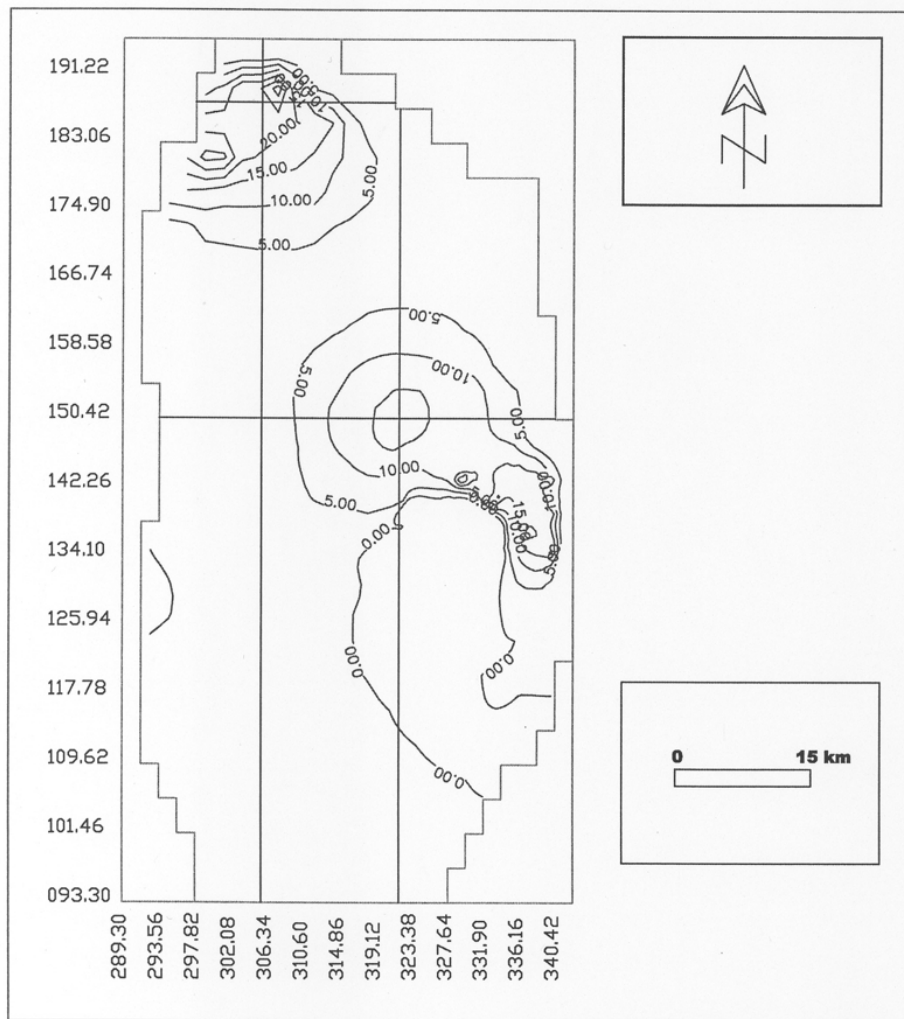
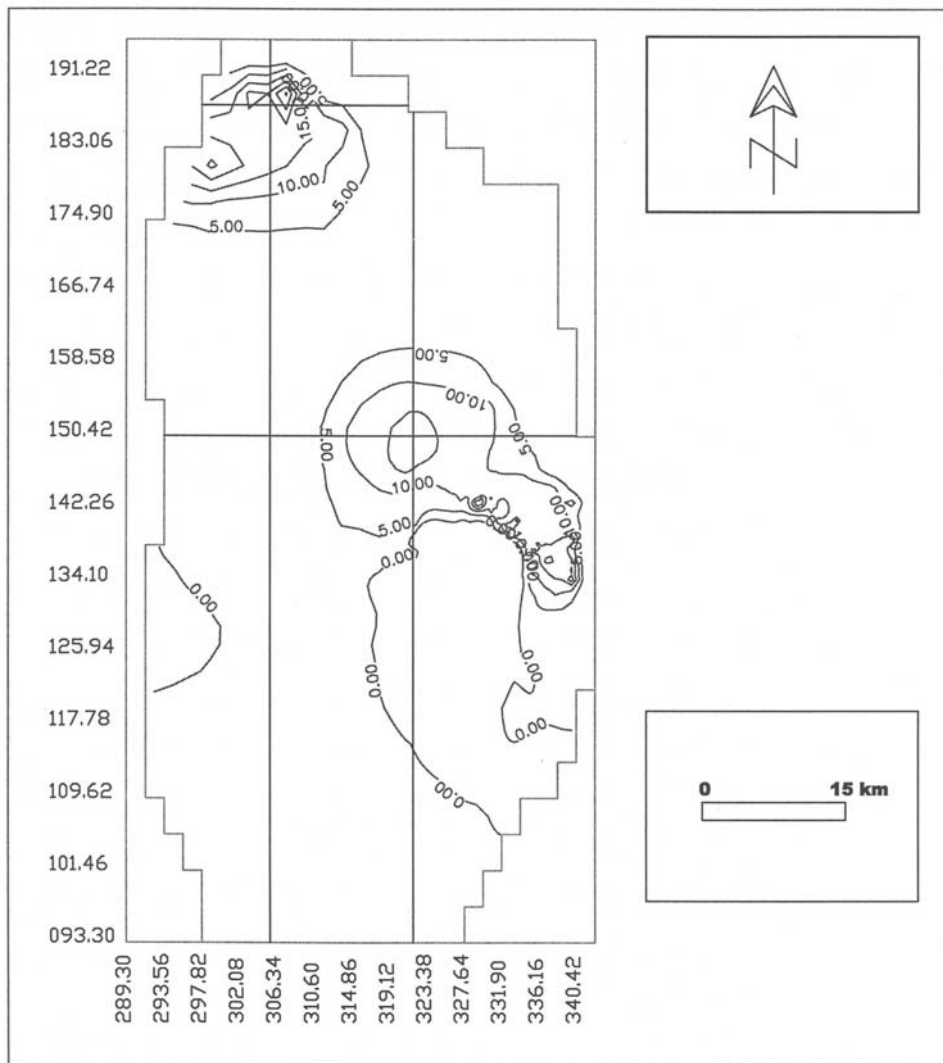


Figure 10: Measured iso-EC ( $\mu\text{S}/\text{cm}$ ) for the upper aquifer system (JCE, 1997).



**Figure 11: Simulated drawdown in the year 2020 for the upper aquifer (scenario one).**





**Figure 12: Simulated values of EC in the year 2020 for the upper aquifer (Third scenario).**

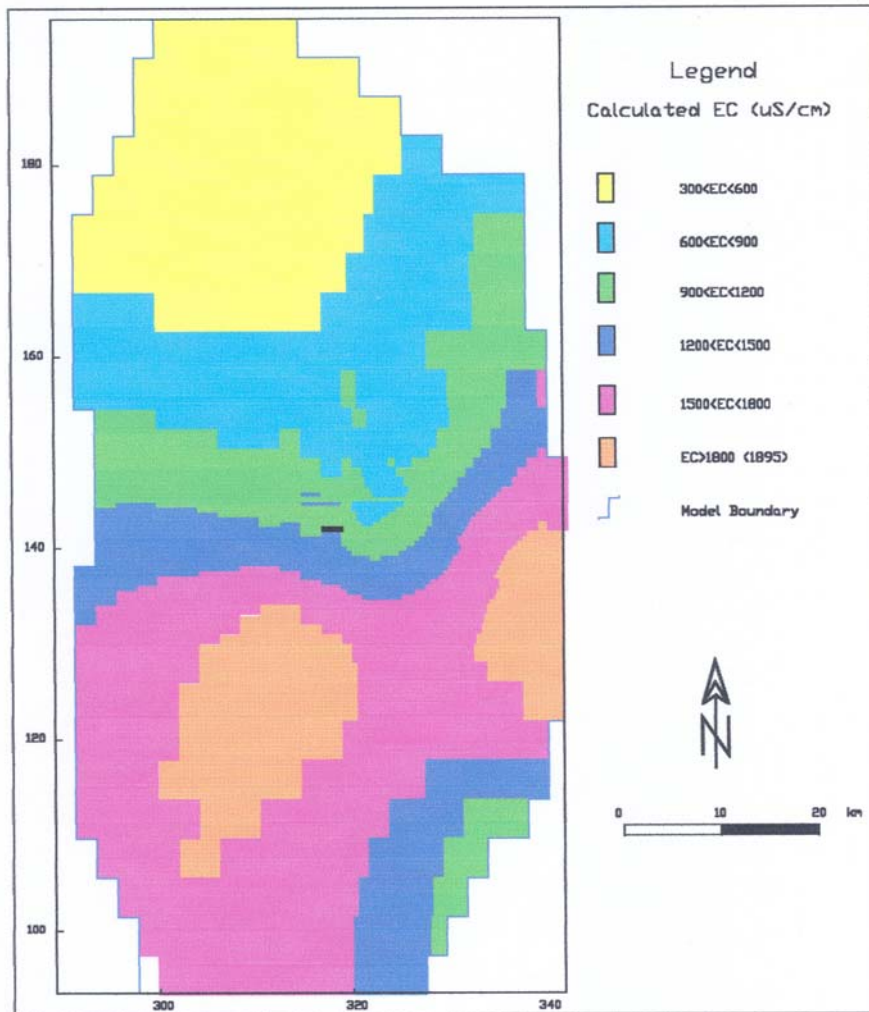


Figure 13: EC Values in the year 2020 for scenario one.

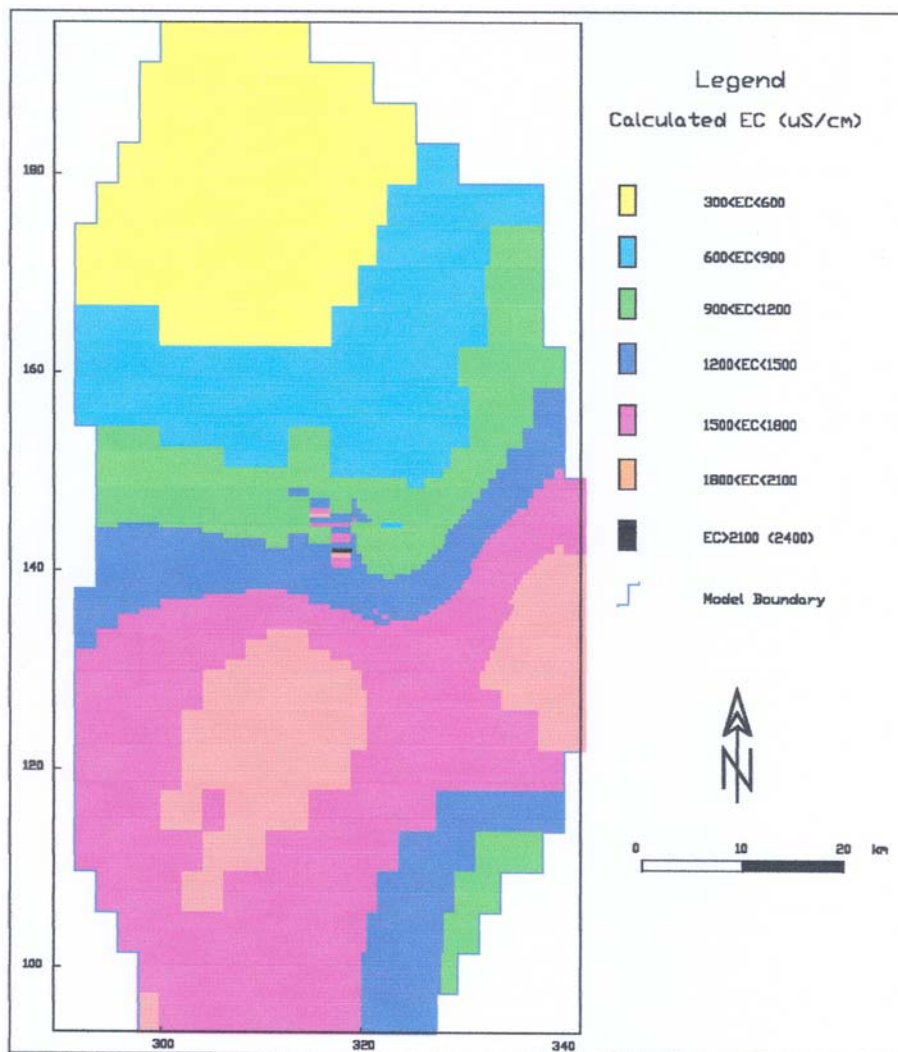


Figure 14: EC Values in the year 2020 for scenario three.

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