The 2nd International Conf. on Water Resources & Arid Environment (2006)

Managerial Outputs of Mathematical Groundwater Models: Case Studies.

Mahmoud Al-Sibai

Arab Center for the Studies of Arid Zones and Dry Lands, ACSAD, Damascus, Syria

Abstract

Throughout the Arab region, the majority of countries suffer from imbalance between the constantly increasing demand of water and the limited available natural water resources. As the second largest source of fresh water, groundwater is under high pressure. In such situation many consequences of groundwater overexploitation are becoming increasingly evident and a proper groundwater resources management is required.

Mathematical groundwater models are an efficient management and planning tool for complex aquifer systems. Models, if properly designed are useful to estimate the effects of future development/management schemes on the groundwater system. In addition, they can aid in understanding of the overall behavior of a given aquifer system and may identify areas where more field information is required. The computed result of an aquifer simulation is the potentiometric surface distribution of the aquifer and the salinity distribution in the aquifer or the concentration of a particular contaminant species, which are the critical factor in water resources management and planning.

Since the late seventies ACSAD started to apply computer simulation models for analyzing flow in groundwater systems. ACSAD has developed several models which aimed to help respective authorities in their efforts to manage groundwater resources. Some examples of these models and their managerial outputs will be discussed in this paper.

Key words*: Mathematical groundwater models, Groundwater management, Water resources management*

Introduction

In the management of a ground-water system in which decisions must be made with respect to water quality and water quantity, a tool is needed to provide the decision maker with information about the future response of the system to the effects of management decisions. Depending on the nature of the management problem, decision variables, objective functions, and constraints, the response may take the form of future spatial distributions of contaminant concentrations, water levels, etc. This tool is the model.

Numerical groundwater models are an efficient management and planning tool for the development of complex aquifer systems. Models, if properly designed are useful to estimate the effects of future development/management schemes on the groundwater system. In addition, they can aid in understanding of the overall behavior of a given aquifer system and may identify areas where more field information is required (Anderson & Woessner, 1992). The computed result of an aquifer simulation is the potentiometric surface distribution of the aquifer and the salinity distribution in the aquifer or the concentration of a particular contaminant species, which are the critical factor in water resources management and planning (ESCWA, 2005).

Since the late seventies ACSAD started to apply computer simulation models for analyzing flow in groundwater systems. Numerical groundwater flow models have been constructed to develop an understanding of the groundwater flowing systems, evaluate the effects of development on groundwater resources and support groundwater management. Some examples of these models and their managerial outputs will be discussed in this paper. More details about the modeling work itself can be found in the relative references.

Case Studies:

1- Northern part of Khabour basin (ACSAD, 2003)

Background:

The study area is located in the northern part of Syrian Khabour basin. The area is about 3600 km^2 and is suited within the Northern Fertile Crescent which has an average rainfall of 400 mm/year (figure 1).

The main exploited aquifer is the second one which is from Helvetian-Eocene age and consists of karst and fractured limestone (Figure 2). The famous spring (Ras El-Ein), located at the boundary between Syria and Turkey, was a natural outflow from this aquifer with an average discharge of 40m^3/sec. The spring flow decreased with time until it stopped to flow early this century. The hydraulic transmisitvity of this aquifer is very high especially in3 the area adjacent to the spring (up to 260000 m^2/day) with good water quality (0.3-0.5 g/l). This aquifer is shared by Syria and Turkey. It is confined in Syria and outcrops in Turkey where the recharge area is located (Figure 2). From analyzing geological maps, climatic data and satellite images, the recharge estimated to be at its maximum around 3.3 billion cubic meters per year according to the values of infiltration coefficients of different zones. The area is very fertile; thousands of farmer's wells are pumping the water for agriculture from both sides of the boundary (Figure 3). This overpumping of groundwater in both sides (Syrian and Turkish) has negative impacts on both sides of the aquifer. The impact appears in water table declining of more than 1 m/year, reaching up to10 m/year in some areas. Facing this problem, the Syrian authority asked for a tool to best managing groundwater resources.

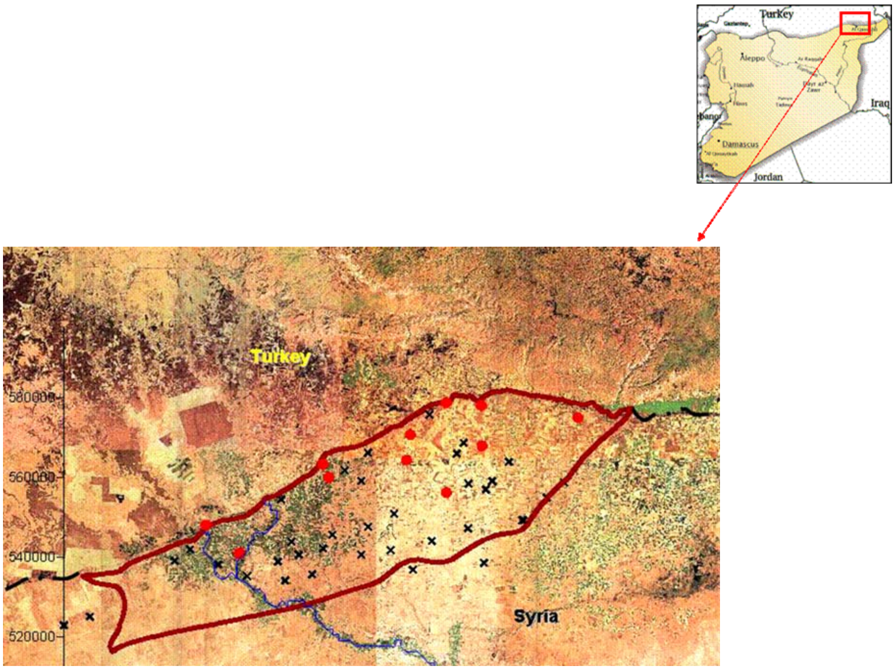

Figure 1: Study area with the Khabour river (blue). The locations of the observation wells are illustrated by red dots for standard piezometeric wells and black “x” for farmer's wells.

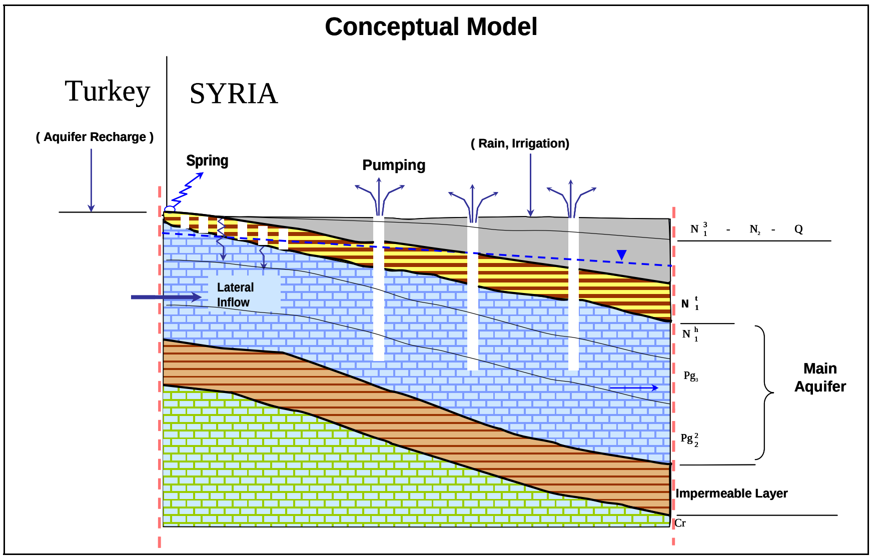

Figure 2: North-South schematic cross-section of the conceptual model of the studied aquifer

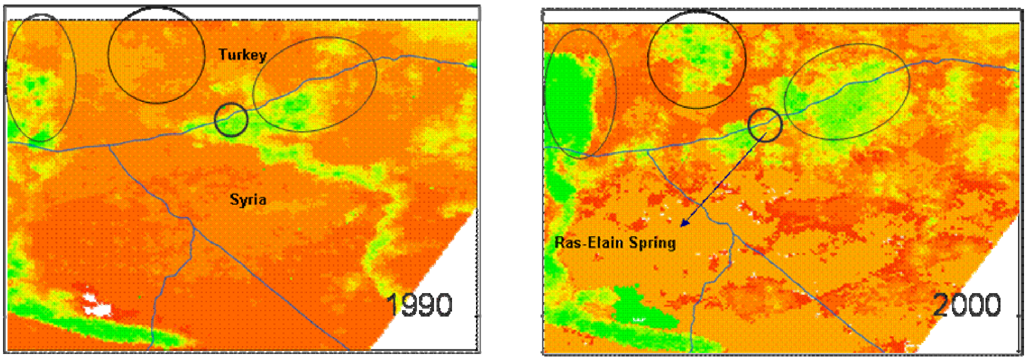

Figure 3: NDVI values derived from NOAA data (1 Km resolution) of the area. The figure illustrates the expansion of irrigated areas (green color) between 1990-2000 in both sides of the basin (Syria and Turkey). The circles highlight these areas.

Managerial output:

- **Setup new monitoring system**

In the model, developed for this confined aquifer, some of the used observation wells which reach the studied aquifer were farmer's wells. Most of these wells were not constructed with screens in the studied aquifer only. Even if the levels have correctly been measured, they were unrealistic for the aquifer under consideration. This is a very common problem in the region, because of the high cost of drilling piezometeric wells. Fortunately, there were several standard, well constructed, piezometeric wells in the area which could be used to correlate their readings with the hydrogeological conditions (Figure 1). One output of the study was setting up an optimum new monitoring network according to different considerations as it illustrated below. To do that three GIS layers were build:

1- Layer to present the confidence in the readings of the observation wells
2- Layer to present distribution of observation wells
3- Layer to present areas with special interest

Firstly, the observation wells were grouped according to the hydrogeological properties. An average representative hydrograph (with higher weights for piezometric wells) was derived for each hydrogeological unit. The correlation between this average hydrograph and hydrographs of each individual observation well was established. This was very helpful in defining which observation well has low correlation and therefore has lower confidence in measurements (unless if there were any noticed practices could lead to such uncorrelated measurements) (Figure 4c). The problem was worsened by the bad spatial distribution of the observation wells within the study area. Figure 4a shows the well density distribution. In addition, there were some important areas (e.g. surroundings of the spring) where the water authority wanted to have more detailed information (Figure 4b).

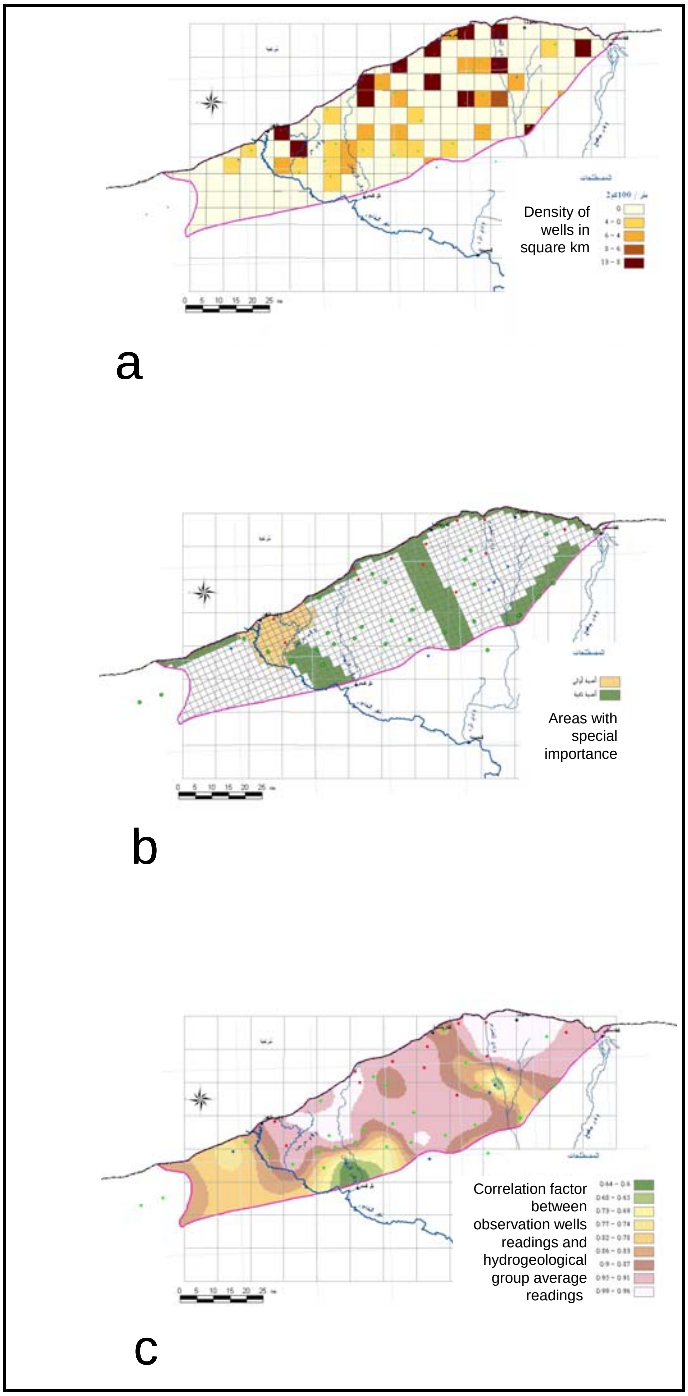

Figure 4: Information used in defining the important locations for new sets of piezometric wells (Al-Sibai, 2005).

By combining all above mentioned information using GIS tools, a figure is created which shows the water authority where are the most important locations to construct a new set of piezometric wells (Figure 5). These additional piezometric wells will improve the accuracy of groundwater level maps and enhance the groundwater monitoring in important areas

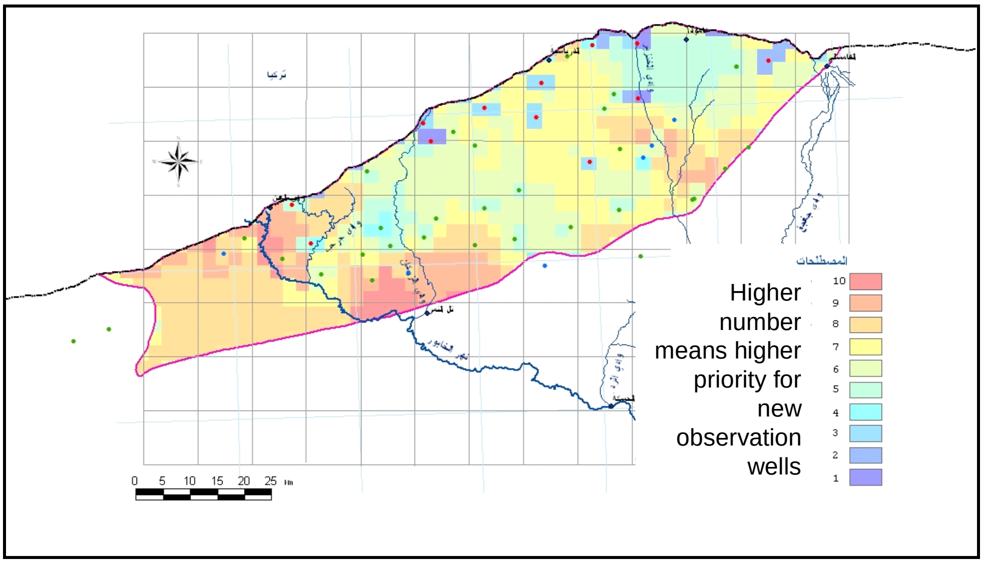

Figure 5: Important locations for constructing a new set of piezometric wells.

2- Zabadani sub-basin (ACSAD, 2002)

Background:

Zabadani plain is one of the most important inter-mountainous sub-basins in Syria. It is considered as a strategic groundwater source of drinking water supply for Damascus City. The historical Barada spring is flowing from this basin with an average rate of 3 m^3/sec (Figure 6).

The study area is about 47 km^2 with an average altitude of 1000 masl and average rainfall of 500 mm/year. There are two main groups of deposits in the area, the first one are the Cretaceous (*Cr)* & Jurassic (*Jr)* deposits which crop out in the west and east of the model area. The second one are the Quaternary-Neogene (*Q-N)* deposits which are located in the middle of the model area as graben sediment formed by the tectonic structure. Figure 7 shows an east-west cross section of the model (TECHNOEXPORT, 1986) .

This study aimed to build a mathematical model, to simulate the groundwater flow system and produce a tool for the decision maker to manage and set up proper plan for the basin water resources.

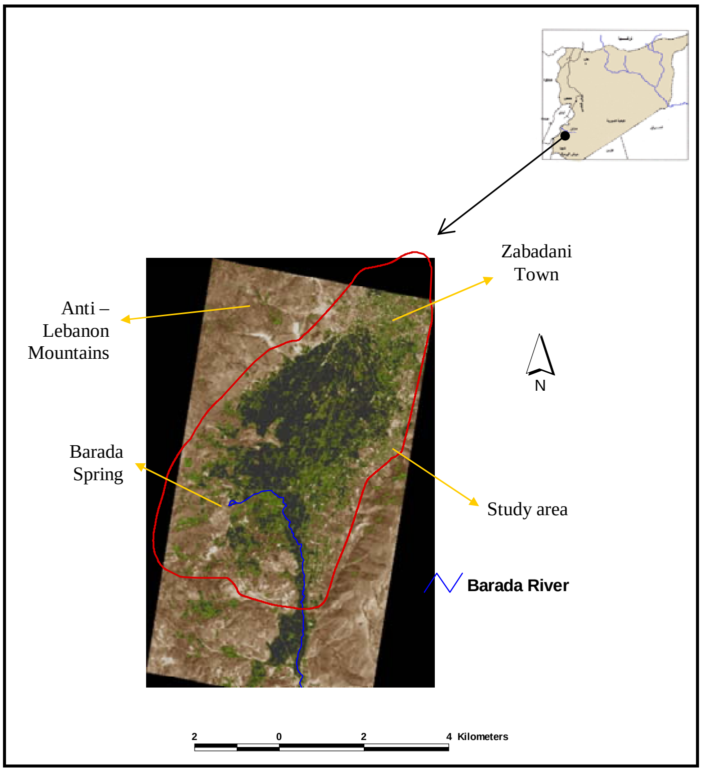

Figure 6: Satellite image of the Zabadani area.

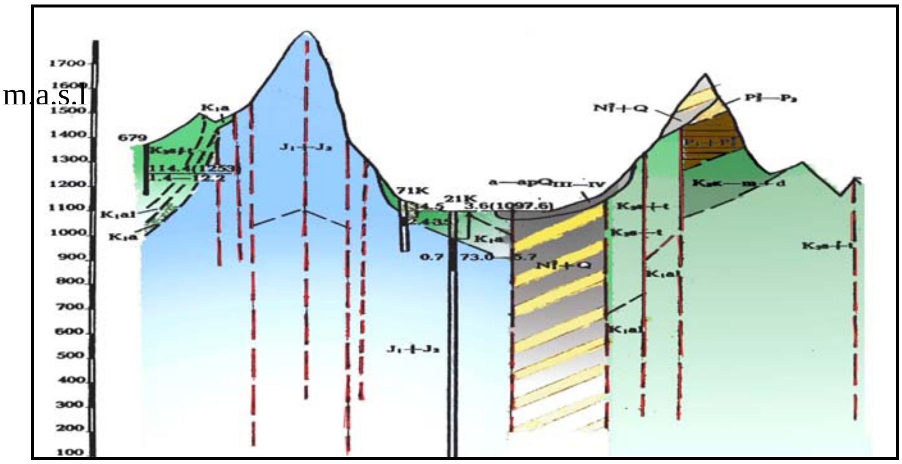

Figure 7: East-West Cross Section in the study area (TECHNOEXPORT,1986).

Managerial output:

- **Predict the influence of additional pumping from new sites:**

The calibrated year was the end of four dry years (1997-2001). One of the tested scenarios was to predict the influence of adding six new exploitation sites to pump additional drinking water to Damascus City when sort of steady state condition prevails in the basin in the next three years (i.e. no recovery of the aquifer). These additional sites were located according to the calibrated hydrogeological parameters of the aquifer. The pumped water was increased gradually by fifty percent each year and reached 56 Mm^3/year in the third year. The model predication showed that a maximum drawdown of two meters will appear after three years at the exploitation sites (Al-Sibai, *et al* 2003). The spatial distribution of this drawdown is shown in figure 8. The model showed that under these conditions the Barada spring discharge will decrease by 36% after three years.

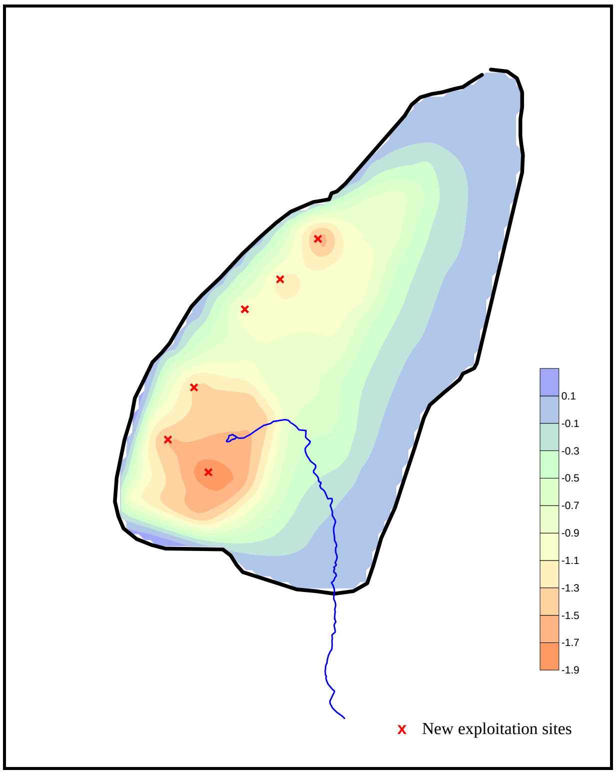

Figure 8: Groundwater drawdown at the end of the tested scenario.

- **The model will be one major component of a decision support system**

There is a high competition on the water resources in the area among different users. In addition to the irrigation, there is considerable water demand for drinking and environment. Tourism to this holiday destination also exerts a strain on the water resources of the area. To help the authorities to better manage the imbalance between water supplies and multiple water demands and environmental requirements, a Decision Support System (DSS) is developed now. The system is based on the concept of integrated water resources management which means that all the different uses of water resources are considered together and water allocations and management decisions consider the effects of each use on the others. The groundwater model will be linked to this system to calculate the effects of different water polices on water heads and to present the resulting drawdowns.

3- Hasia sub-basin (ACSAD, 2004)

Background

The Syrian government is planning to build an industrial city in this area. The expected maximum water requirement is about 35 Mm^3/year. The study aimed to estimate the water budget in the area and predicts the drawdown in water table as a result of the new exploitation plan.

The model area is about 2500 km^2 (figure 9). The annual rainfall is between 100 and 300 mm/year decreasing from west to east and from south to north.

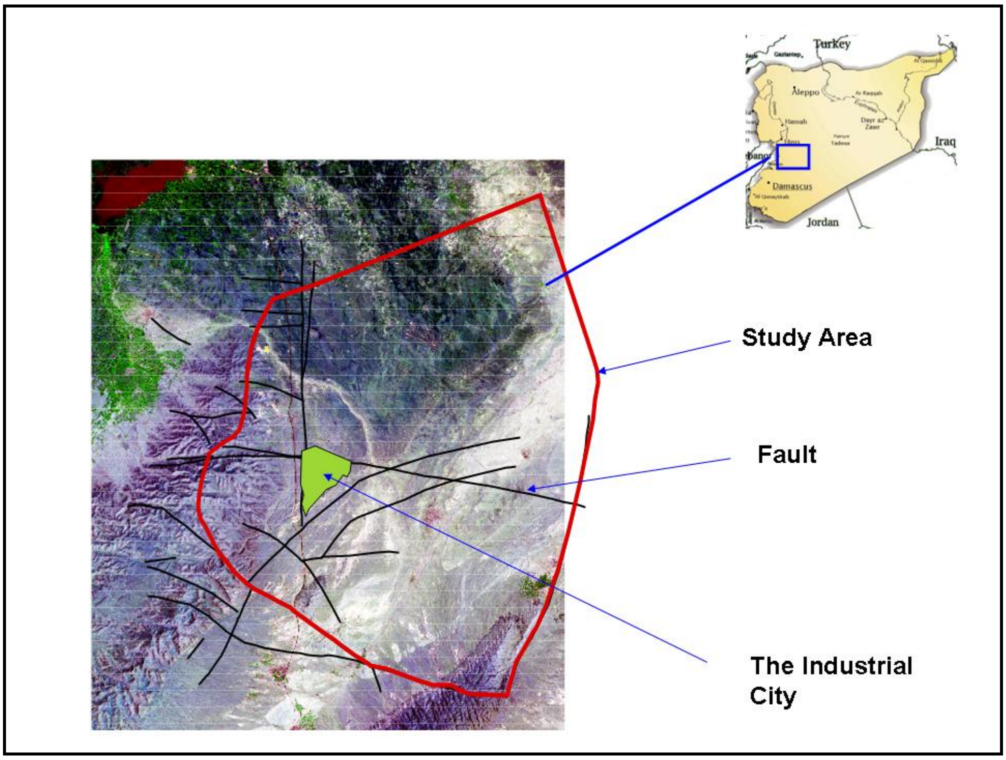

Figure 9: Location of the model area.

The surrounding area has a very complex tectonic structure and is affected by two major faults and several small lateral faults. The studied aquifer is the upper Cretaceous which crops out in the west and consists of fractured limestone (figure 10). This aquifer is dipping in the east where it overlaid by Quaternary-Neogene deposits. The aquifer is of good water quality in general (around 0.6 g/l).

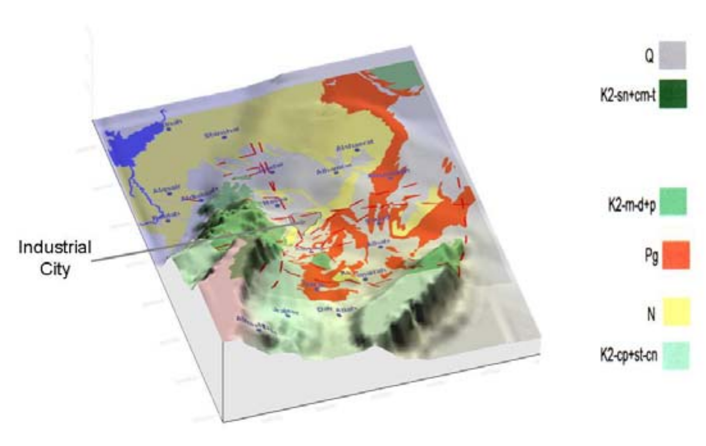

Figure 10: Geological map of the area**.**

Managerial output:

- **The critical aquifer parameters that should be measured**

The accurate representation of the hydraulic function of the faults was impeded by the low number of observation and exploratory wells. The industrial site was close to the conjoint point of the two major faults (figure 9). The cone of depression resulting from any additional groundwater withdrawal to meet the water demand of the site would definitely be affected by the hydraulic function of these faults. The model helped to show the authorities the importance of additional data and used to recommend locations where more observations are required.

- **Delineate wellfield capture zones**

The other output of the model was the delineation of the wellfield capture zones for the different tested scenarios (figure 11). This delineation will help the authority setting up restrictions for land use and human activities at these zones (groundwater protection zones).

The figures below show these zones for the different scenarios. The location of pumping stations and the pumping rate for each scenario are different. The red lines in the figures show the path-line of particles towards the pumping stations. This was done using Modpath (particle tracking code) model which works through Modflow (groundwater simulation code). The blue cells at the north and south are for time-variant specified head boundaries.

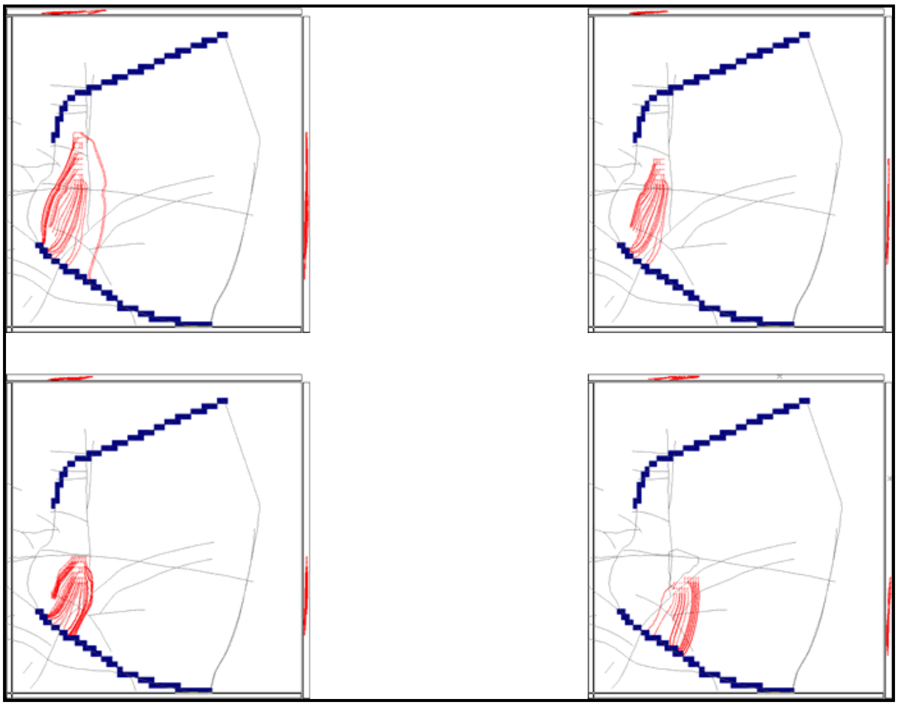

Figure 11: Capture zones for pumping stations according to the different scenarios.

- **Proposing a pumping scheme**

Four scenarios were tested according to the location of pumping stations and pumping rates. The resulting drawdown showed the authority the dangerous consequences of pumping the required amount of water and highlighted the importance of the acquisition more hydrogeological information. The study recommended a gradual increase in pumping while keeping monitoring water level for the coming three years (figure 12). After that the model will be re-calibrated according to the new information.

4- Bekaaa valley basin (ACSAD-BGR, 2004)

Background:

The Lebanese Beka'a valley is situated at an average elevation of 900 m between the western Lebanon and eastern Anti-Lebanon mountain ranges. The geology of the surrounding hills is characterized mainly by the Cretaceous sandstone and Jurassic limestone. The valley receives from the west torrential fan deposits and a mixture of colluvial and alluvial material. The valley comprises around 170 km in length, with a varying width between 20 km in the central part and 5 km near the southern tip. Due to intense agricultural activities in the valley, the Beka'a is of vital importance to the country's economy and food supply.

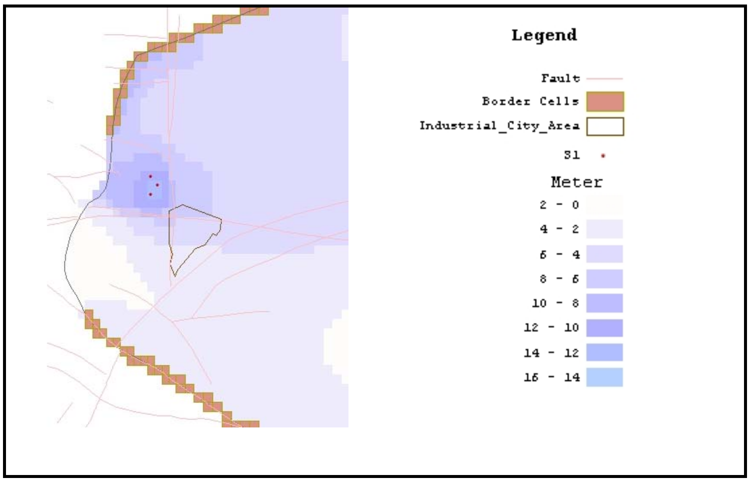

Figure 12 : Water level drawdown according to recommended scenario. The maximum areal drawdown in the cells of pumping stations was 14 m/year.

The study area lies in the central part of the Beka'a valley (figure 13). Including the city of Zahle and Berdaouni River in the eastern foothills of the Lebanon mountain chain, the study area further extends to the east across Litani River and towards the calcareous slopes of the Anti-Lebanon Range.

A groundwater model was build for the two aquifers of the area. A solute transport model was added to predict the pollutant transport from point source pollution from one planned waste dumps as well as from two existing waste dumps within the study area. Figure 14 shows the positions of the waste dumps within the area. While the two existing dumps are rather old and were never subjected to high environmental safety standards, the new waste dump is sealed with a lining to avoid ground-water contamination.

Managerial output:

- Prediction of the extend of pollutant plumes from waste dumps

Two scenarios were chosen to predict the extend of pollutant plumes from waste dumps, with the same initial and boundary conditions for all three waste dumps to investigate which waste dump is the least favorable with regard to its position in the groundwater flow field. A fresh water situation without any contamination was used as initial condition. A constant fictive infiltration of a contaminant having a concentration of 2000 ppm was assumed as boundary condition at each dump site. The flux rate was set equal to precipitation.

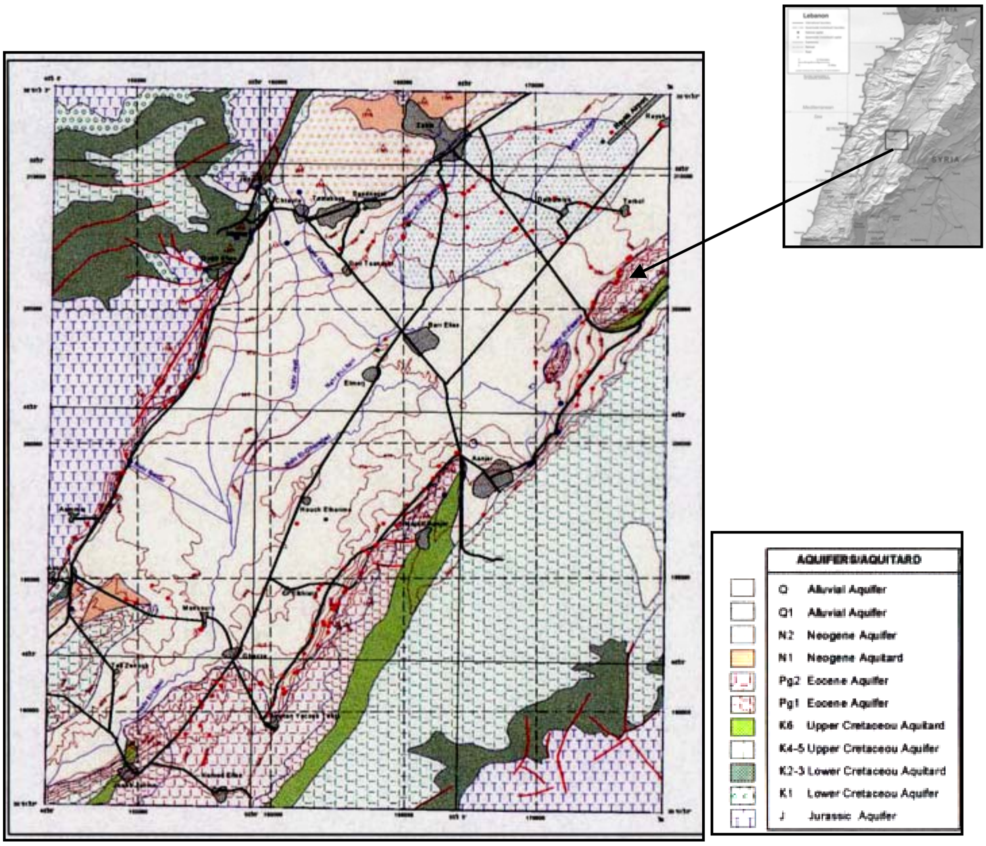

Figure 13: Hydrogeological units in the area

The difference in the two scenarios is the assumption that in the first scenario, the contaminant has a tracer behavior while in the second scenario it behaves like a sorbing substance. The position of the contaminant plumes for the first scenario after 13 years are shown in figure 14. It could be deduced from this map that the position of the northernmost waste dump is the most susceptible to a spreading of the contaminant. The same general trend was observed for sorbing solute, but is retarded by approximately 1000 days compared to the first scenario. The results highlighted the importance of proper constructing of landfill and alert the authorities to the movement directions of the pollutant plumes, especially that some of the wells in the area are used for drinking.

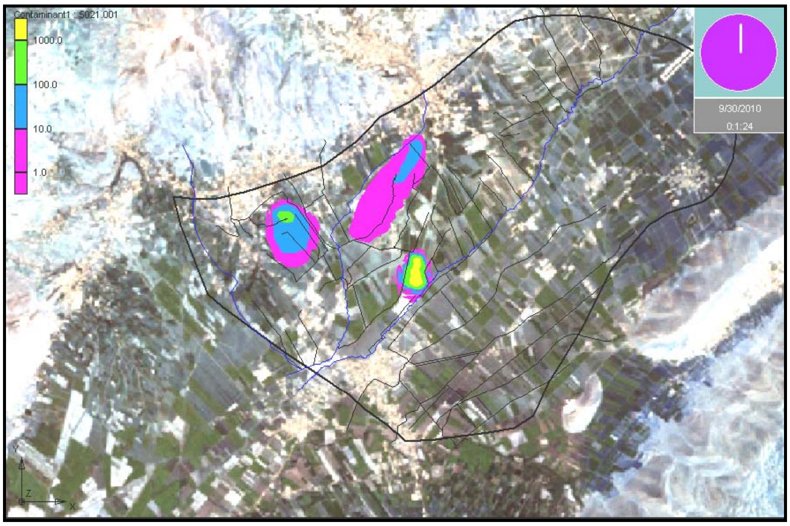

Figure 14: Position of the contaminant plumes of a nonsorbing nondegrading contaminant in the upper aquifer in the year 2010 following a contamination that began in 1997.

Conclusion

Groundwater mathematical models represent powerful tools for the assessment, development and management of groundwater resources.

This paper shows that models should be a major component of any groundwater study. The model can be started with simplified assumptions and modified step by step. The modeling work is continuous work and should be envisaged throughout the management process.

References

ACSAD .2002. Mathematical model of El-Zabadani basin, Water resources department, ACSAD/H.S/R156 (in Arabic).

ACSAD .2003. Mathematical model of the northern part of khabour basin, Water resources department, ACSAD/H.S/R160 (in Arabic).

ACSAD .2004. Mathematical model of Hasia basin, Water resources department, ACSAD/H.S/R172-B (in Arabic).

ACSAD-BGR Technical cooperation .2004. Groundwater modelling in the Beka'a valley, Lebanon, Technical report, internal publication.

Al-Sibai M., S. Zahra, N. Rofail. 2003. Water Resources Management of Al-Zabadani Basin; Proceedings of *WSTA Sixth Gulf Water Conference*,8-12 March 2003, Riydh.

Al-Sibai M. 2005. On Groundwater Models and the Need of Sufficient and Reliable Data, Examples, Dependencies and Interrelations, Proceedings of Seven Gulf water Conference, Kuwait, 19-23 November, 2005.

ESCWA .2005. Integrated Groundwater Resources Management, Module 12, Workshop on “Training of Trainers on the Application of IWRM Guidelines in the Arab Region” Kuwait, 14-18 May, E/ESCWA/SDPD/2005/WG.1/13.

Anderson, M.P., and Woessner, W.W. 1992. Applied groundwater modeling: Simulation of flow and advective transport, Academic press.

Holzbercher,E. 2002. Groundwater Modeling: Computer simulation of groundwater flow and pollution, An electronic book published and distributed by FiatLux Publications & EnviroComp Insititute.

Technoexport .1986. Hydrogeological and Geological Report of Barada and Auvage Basins, USSR.

التدابير الإدارية الناتجة عن استخدام النماذج الرياضية للأحواض المائية الجوفية: حالات دراسية

محمود السباعي

المركز العربي لدراسات المناطق الجافة و الأراضي القاحلة، أكساد، دمشق، سوريا

تعاني معظم أقطار الوطن العربي من عدم التوازن ما بين الازدياد المطرد في استهلاك المياه و ما بين الموارد المائية المحدودة المتاحة لديها. و باعتبار أن الموارد المائية الجوفية هي المصدر الأكبر الثاني للمياه العذبة فإنها تتعرض لضغوط كبيرة نتيجة لذلك. تحت مثل هذه الظروف تبدأ عواقب السحب الجائر للمياه الجوفية بالظهور و يصبح من الضروري وضع إدارة رشيدة للموارد المائية الجوفية.

تعتبر النماذج الرياضية للمياه الجوفية أداة فعالة في إدارة و تخطيط الحوامل المائية الجوفية. إن النماذج الرياضية، ذات التصميم الصحيح، مفيدة في تقدير تأثيرات الخطط التنموية المستقبلية على الحوامل المائية الجوفية بالإضافة إلى أنها يمكن أن تساعد في فهم السلوك العام لنظام حركة المياه الجوفية في الحوامل المائية و تحديد مواقع الضعف التي تحتاج إلى بيانات حقلية أكثر. تظهر النتائج الحسابية للنماذج على شكل أسطح توزع الضاغط المائي أو توزع قيم الملوحة في الحامل أو تغير تركيز ملوث محدد. هذه النتائج ذات أهمية كبيرة في إدارة الموارد المائية الجوفية و رسم السياسات الملائمة.

بدأ أكساد منذ نهاية السبعينات في استخدام هذه التقانة في دراسات الأنظمة المائية الجوفية. طور أكساد العديد من النماذج بهدف مساعدة الهيئات المعنية في جهودها نحو تحسين إدارة الموارد المائية الجوفية. سوف تناقش هذه الورقة بعض الأمثلة من هذه النماذج و تبرز الفوائد الإدارية لها.

الكلمات المفتاحية: النماذج الرياضية للمياه الجوفية، إدارة الموارد المائية الجوفية، إدارة الموارد المائية.