استخدام موديلات النمذجة الرياضية كأداة فعالة في إدارة الطبقات المائية الجوفية (حالات دراسية من سورية)

Using Groundwater Mathematical Modeling as an Essential Management Tool: Case Studies from Syria

Received 08 June 2010 / Accepted 09 February 2011

Mahmoud Al-Sibai

Acting Dean, Higher Institute for Water Management, Consultant, Water Resources Department, ACSAD.

المُلَخَّص

تُعَدُّ النمذجة الرياضية لحركة المياه الجوفية أداةَ فعالةً في تخطيط وإدارة الطبقات المائية الجوفية المعقدة، حيث تُؤمن هذه النماذج إطاراً لجمع البيانات الحقلية والمعلومات، واختباراً للأفكار والنظريات المختلفة عن كيفية عمل هذه الطبقات. يُمكن للنماذج أن تُحدد مناطق الضعف في المعلومات، التي تحتاج إلى تحرياتٍ ومعلومات أكثر، كما يمكنها أن تساعد في اختيار الحل الأمثل لاستثمار هذه الطبقات بشكل مستدام.

تمَّ خلال العقد الماضي تطوير العديد من النماذج الرياضية بهدف مساعدة الجهات المعنية في جهودها في إدارة هذه الأحواض الجوفية.

تعرض هذه الورقة ثلاث حالات دراسية من سورية، وتناقش كيفية الاستفادة منها و استعمالها كأداة لإدارة هذه الأحواض. ففي الجزء الشمالي من حوض الخابور، ساعد الأنموذج الرياضي في تحديد مواقع آبار الرصد، وأوضح تأثير الضخ المتزايد في الجريان الجوفي القادم من الحدود التركية، في حين ساعد الأنموذج الرياضي لسهل الزبداني على إظهار تأثير الضخ الإضافي من مواقع الآبار الجديدة في مناسيب المياه الجوفية وفي فحص تأثير التغيرات المناخية على الوضع المائي في السهل من خلال تصورات مختلفة، أما في منطقة حسياء، فقد أسهم الأنموذج الرياضي المطوَّر للمنطقة في تحديد مناطق التغذية لآبار الضخ وفحص تأثير تصورات الضخ المختلفة على مناسيب المياه الجوفية.

الكلمات المفتاحية: نمذجة حركة المياه الجوفية، إدارة الأحواض المائية الجوفية، أنظمة دعم اتخاذ القرار

Abstract

Groundwater mathematical models are efficient management and planning tool for complex aquifer systems. They provide a framework for synthesizing field information and for further understanding how the system works. They may identify areas where more field information is required. They also aid in selecting an optimum set of operating conditions to use the aquifer without endangering its sustainability.

In the last decade, several models were developed which aimed to help respective authorities in their efforts to manage groundwater resources.

This paper presents three case studies from Syria and discusses how they have been used as a management tool. In the Northern part of Khabour basin, the mathematical model helps in setting up new monitoring system and elaborates the effect of increasing groundwater pumping on lateral flow from Turkey. In Zabadani sub-basin the model predicts the influence of additional pumping from new sites and impact of climate change on water resources according to different scenarios. In Hasia sub-basin, the model delineated wellfield capture zones and tested the impact of different pumping scheme on groundwater level.

Keywords: Groundwater modeling, Aquifer management, Decision support system.

Introduction

Throughout the Arab region, the majority of countries suffer from imbalance between the constantly increasing demand for water and the available natural water resources. As the second largest source of fresh water, groundwater is under high pressure. Many countries are already using more water than their renewable water supply, and are in water deficit situation. In such situation many consequences of groundwater overexploitation are becoming increasingly evident. The most common symptom is secular decline in water tables (Droubi, 2006). In Syria most of the aquifers are suffering from overexploitation which caused sometimes severe decline in water tables (ESCWA, 2007, Al-Sibai, 2009). Groundwater use, particularly for irrigation has increased dramatically over the last two decades. Sixty percent of all irrigated area in Syria is currently irrigated by groundwater (FAO-MAAR, 2001). Most are privately developed and operated. In 2008-2009, the Groundwater usage for agriculture reached 7.5 Bm^3 while the total renewable volume of groundwater was 6.48 Bm^3 (Sayegh and Zakar, 2010). This gave a deficit of 1.03 Bm^3, which translated as water table decline in most of the Syrian basins (UNDP, 2009). This deficit is expected to increase as the water needs for all sectors are continue to increase.

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 schemes on the groundwater system. In addition, they can aid in understanding the overall behavior of a given aquifer system and may identify areas where more field information is required (Anderson and 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).

Methodology

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. Two commercial interface were used as an interface to Modflow, Proccessing Modflow[1] and GMS[2] (Groundwater Simulation System). The managerial outputs of these models will be discussed in this paper. More details about the modeling work itself can be found in the relative references (ACSAD; 2002, 2003, 2004).

Case Studies

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

Background:

The study area is located in the Northern part of the 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^{-1} (figure 1).

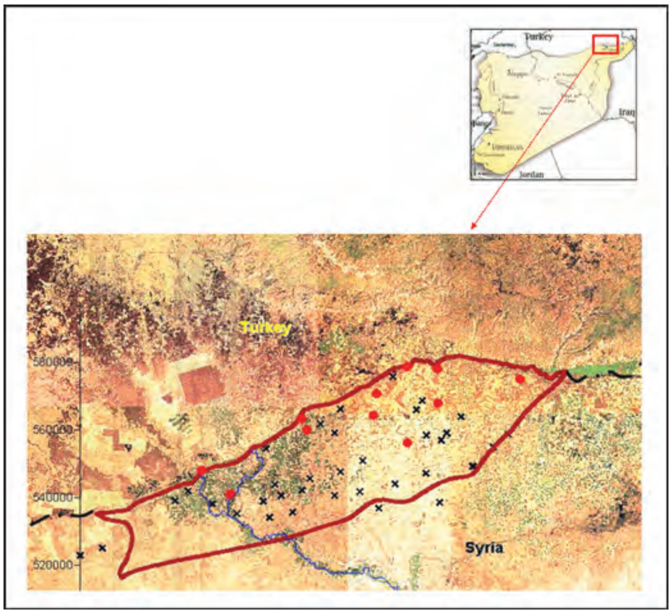


Fig. 1. Study area with the Khabour river (The locations of the observation wells are illustrated by dots for standard piezometeric wells and "x" for farmer's wells.

The main exploited aquifer is the confined aquifer 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 40 m^3.sec^{-1}. The spring flow decreased with time until it stopped to flow early this century. The hydraulic transmisitvity of this aquifer is very high especially in the area adjacent to the spring (from 100,000 to 500,000 m^2.day^{-1} in the area adjacent to springs) with good water quality (0.3-0.5 g.l^{-1}). 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).

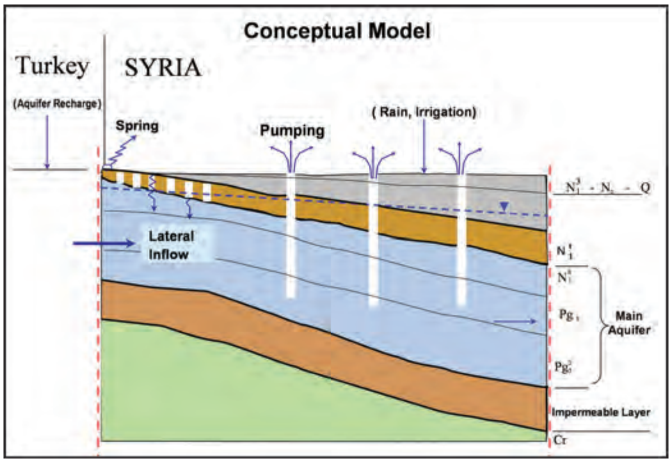


Figure 2. North-South schematic cross-section of the conceptual model of the studied aquifer (Helvetian-Eocene).

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 farmers' 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 $^{-1}$, reaching up to10 m.year^{-1} in some areas. Facing this problem, the Syrian authority asked for a tool to best managing groundwater resources.

---

[1] 1: PMWIN, version 5.3.0

[2] 2: GMS, version 5

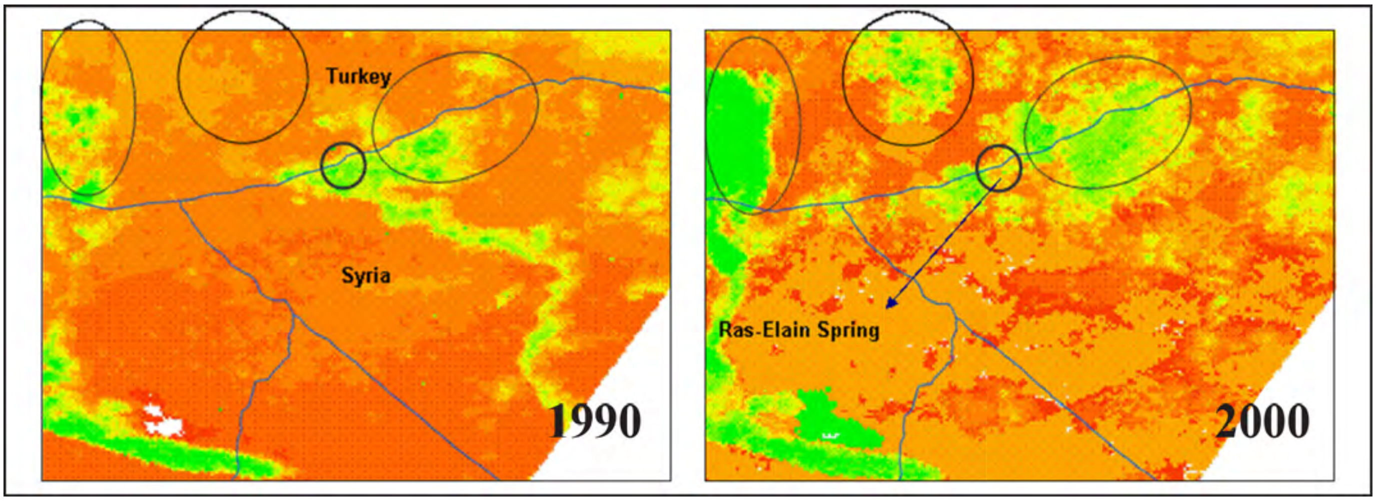


Figure 3. NDVI * values derived from NOAA ** data (1 Km resolution) of the area. The figure illustrates the expansion of irrigated areas (green color) between 1990-2000 in both sides of the basin (Syria and Turkey). The circles highlight these areas. (*): Normalized Difference Vegetation Index. (**): National Oceanic and Atmospheric Administration. United State Department of Commerce.

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 farmers' 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 built:

1- Layer to present the confidence in the readings of the observation wells.

2- Layer to present distribution of current observation wells.

3- Layer to present areas with special interest.

The observation wells were grouped according to the hydrogeological properties. A weighted average representative hydrograph (giving 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 due to 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 new pumping stations are operating) where the water authority wanted to have more detailed information (Figure 4b).

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.

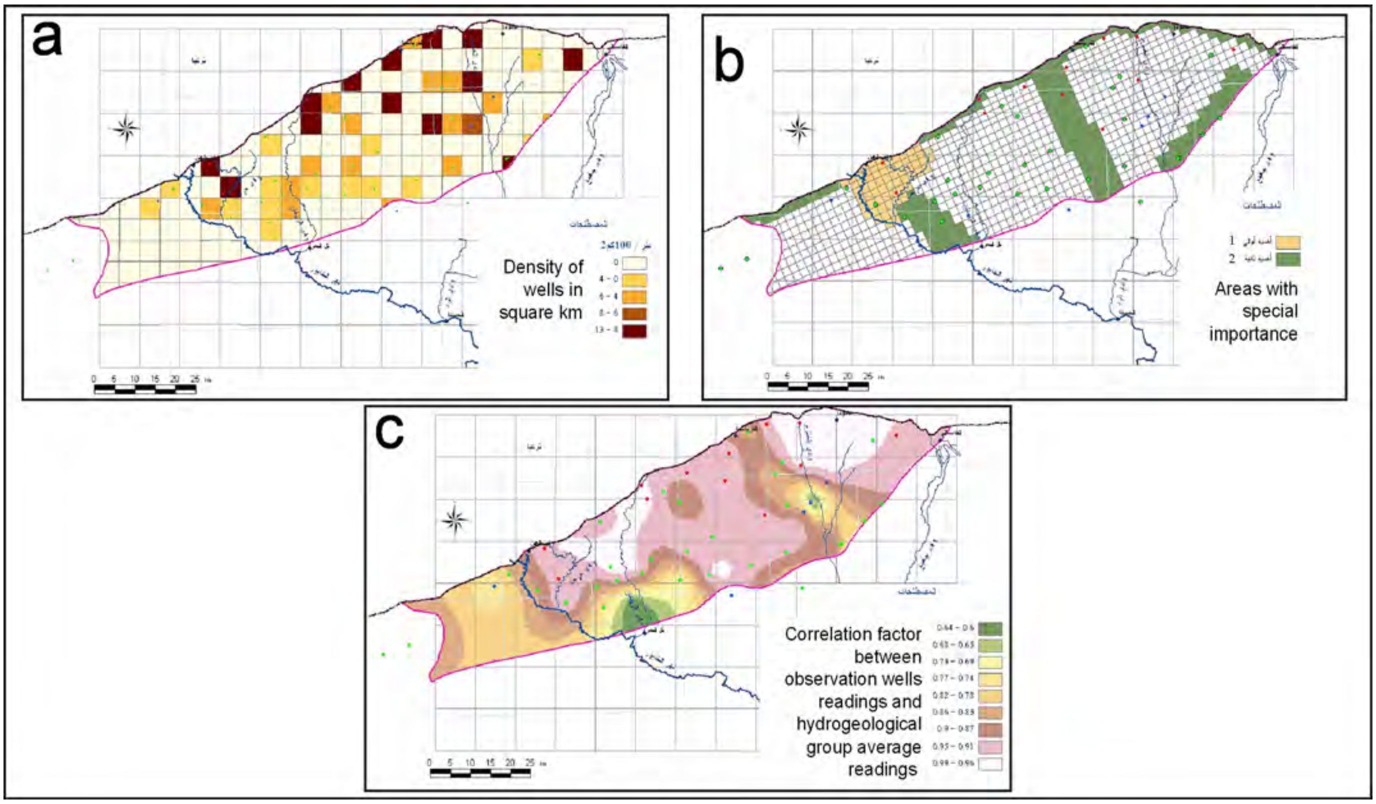


Figure 4. Information used in defining the important locations for new sets of piezometric wells (Al-Sibai, 2005).

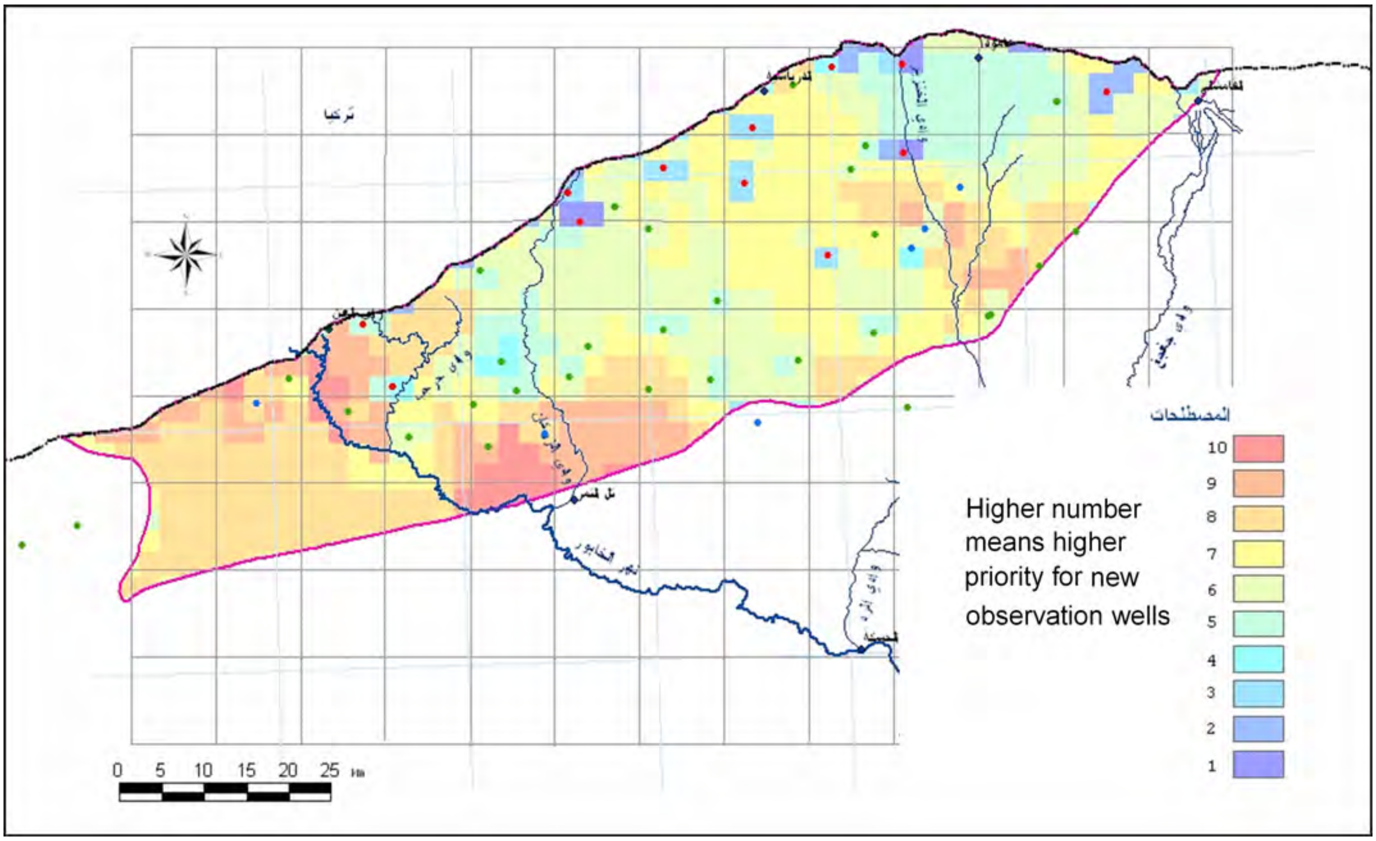


Figure 5. Important locations for constructing a new set of piezometric wells.

- Elaborate the effect of increasing groundwater pumping on lateral flow

Shared aquifers should have a shared management for sustainable use. Groundwater pumping from downstream side will induce more lateral inflow from upstream side. However; with time, and as both sides overexploit the aquifer, this induction will decrease despite the increase in pumping as shown in figure 6. The figure shows the quantity of groundwater abstraction and the lateral inflow from upstream toward the study area. It is clear that during the period of increasing abstraction (more than a threshold of 100 mm^3.month^{-1}), an increase in lateral inflow is observed. However, the model shows that this increase inflow is still smaller than the abstraction increase which resulted in higher deficit as shown in the columns in figure 6. This analysis should encourage the respected countries to start collaborative management of their shared aquifer.

2- Zabadani sub-basin (ACSAD, 2002; ACSAD-BGR, 2007)

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^{-1} (Figure 7).

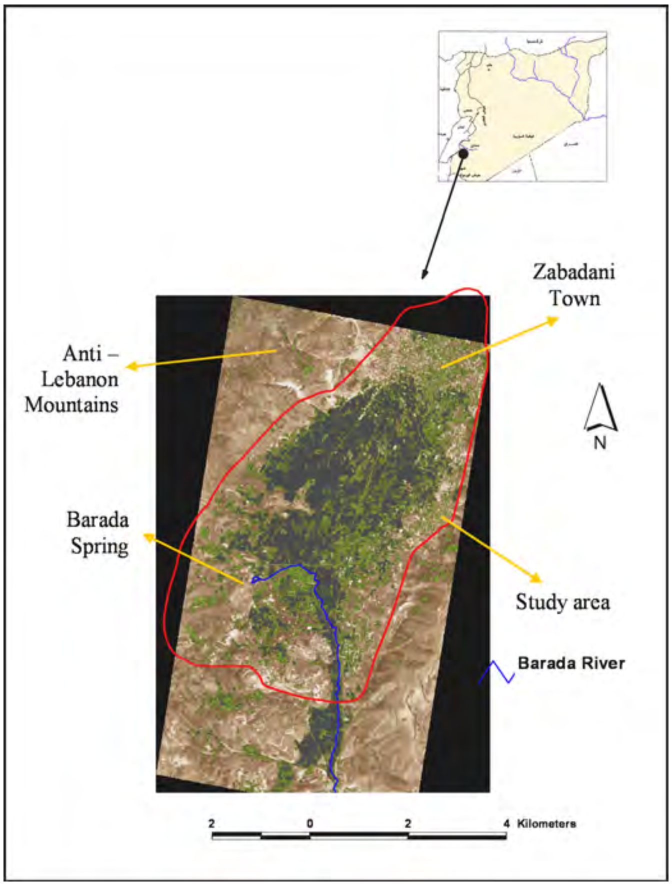


Figure 7. Satellite image of the Zabadani area.

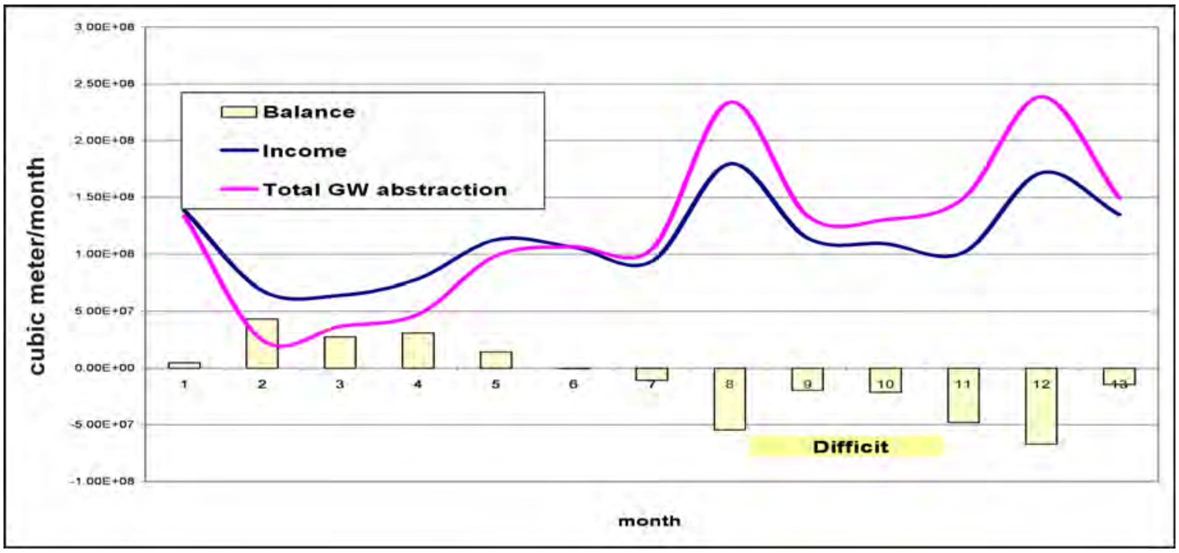


Figure 6. The red line shows the monthly quantity of groundwater abstraction and the blue line shows the monthly lateral inflow from upstream. Yellow columns depict the difference between both lines (deficit).

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 (Technoexport,1986). Figure 8 shows an east-west cross section of the model (Technoexport,1986).

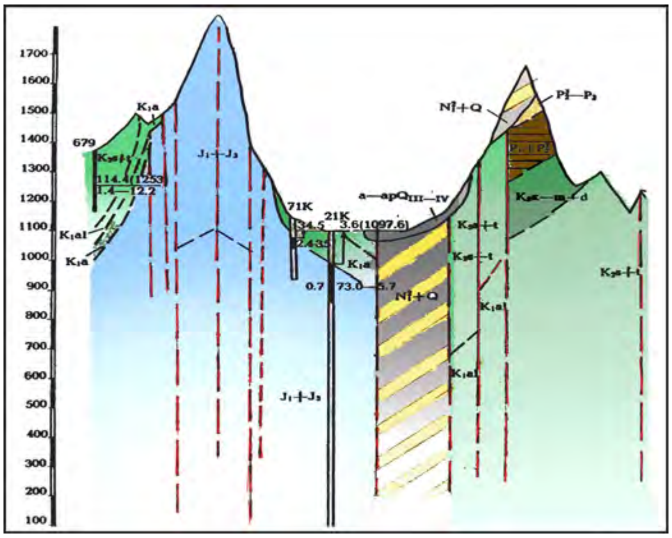


Figure 8. East-West Cross Section in the study area (Technoexport,1986).

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.

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 9. The model showed that under these conditions the Barada spring discharge will decrease by 36% after three years.

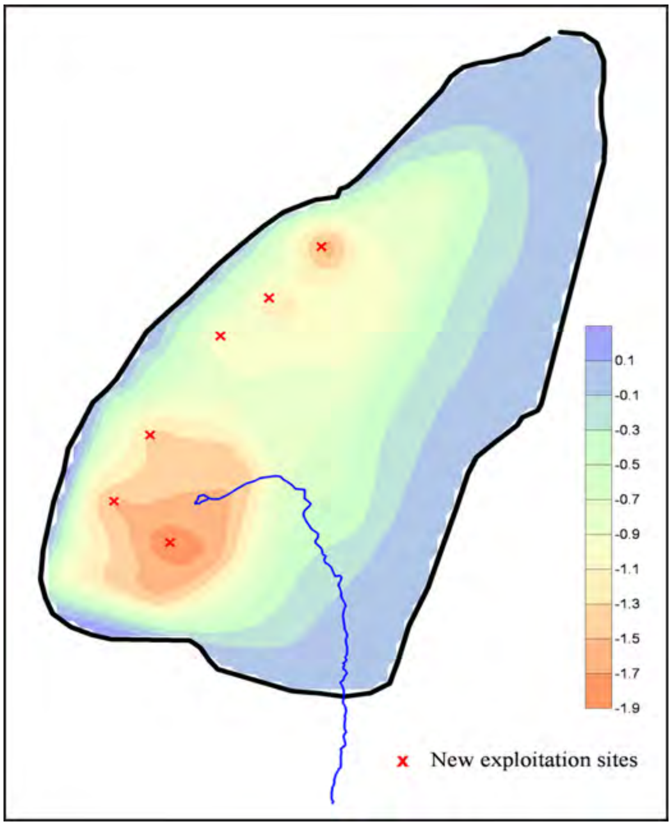


Figure 9. Groundwater drawdown at the end of the tested scenario.

- Integration of groundwater model with decision support system

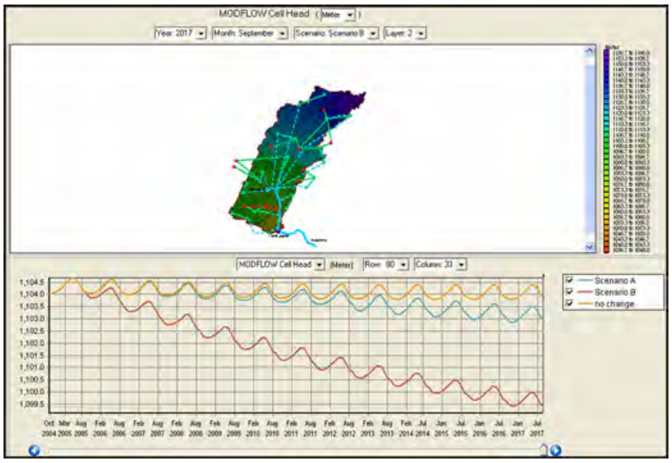
There is a high competition on the water resources in the area among different users. In addition to the irrigation, there is considerable water demand for drinking and environment. Tourism to this holiday destination also exerts a strain on the water resources of the area. To help the authorities to better manage the imbalance between water supplies and multiple water demands and environmental requirements, a Decision Support System (DSS) is developed (Droubi *et al.*, 2007). 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 DSS is a combination of two existing software products that are dynamically linked to and affecting each other. MODFLOW calculates groundwater heads, storage and flow whereas, WEAP3 calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. WEAP holds the Graphical User Interface for the DSS and acts as a "remote control" for MODFLOW, which is running in the background (Al-Sibai *et al.*, 2008). This linkage empowers both models and gives a chance to use the strength of WEAP to build different scenarios and the strength of MODFLOW to observe the impact of these scenarios on groundwater table.

Two short - term scenarios (2005/2017) (Droubi et al., 2007) were examined in order to see the impact of strong decreases in precipitation due to climate change:

Scenario A: A twenty percent decrease was applied to the amount of precipitation during the planning scenario

Scenario B: The historic precipitation measurements of Damascus station shows that there is roughly every thirteen years a "drought" year with less than half of the mean annual rainfall. Therefore , an additional planning scenario was created by reducing the average precipitation to 50% and calculating the impacts of consecutive drought years (Droubi *et al.*, 2007).

The hydraulic head fluctuations predicted by the model (Figure 10) showed that the most severe drawdown occur in scenario B. Similar impact has been observed in 2001 after three consecutive dry years. This decline in groundwater level will force the farmers to deepen their wells and will rise up the pumping costs.



MODFLOW Cell Head (Meter)

Year: 2017 | Month: September | Scenario: Scenario B | Layer: 2

MODFLOW Cell Head (Meter) | Row: 80 | Column: 33

Figure 10. Calculated hydraulic head for the planning scenarios. The window below shows the impacts of scenarios A & B on the water table at one of the selected Modflow cell.

A long term scenario was examined assuming a slight annual decrease in rainfall of 5.1% at 2040 (according to the result of MRI-96 projection model for Serghaya Station in the area, Syrian initial national communication report, 2009). The results showed a continuous decrease in groundwater storage in all sub-aquifer and a sum of 70 Mm^3 decrease in storage was expected at the end of 2039.

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 m $m^3.year^{-1}$. The study aimed to estimate the water budget in the area and

---

(3): WEAP, Water Evaluation and Planning System, www.weap 21.org predict the drawdown in water table as a result of the new exploitation plan.

The model area is about 2500 km^2 (Figure 11). The annual rainfall is between 100 and 300 mm.year^{-1} decreasing from west to east and from south to north.

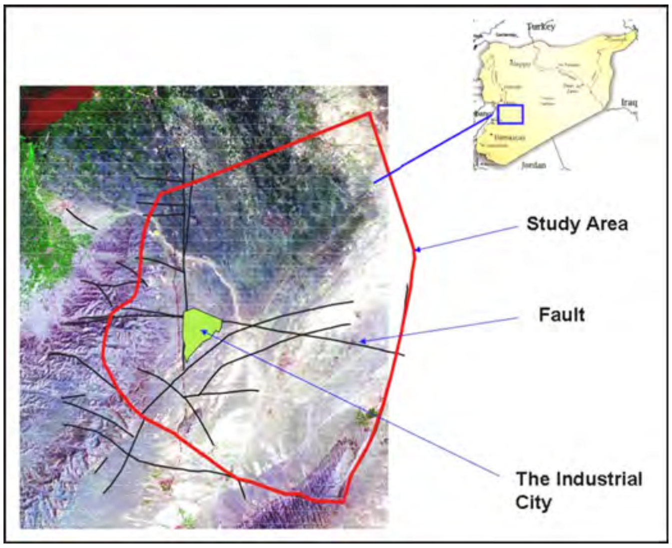


Figure 11. Location of the model area.

The surrounding area has a very complex structure (ACSAD, 2004) 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. 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).

Managerial output:

- Delineate wellfield capture zones

The other output of the model was the delineation of the wellfield capture zones for the different tested scenarios (Figure 12). This delineation will help the authority in 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

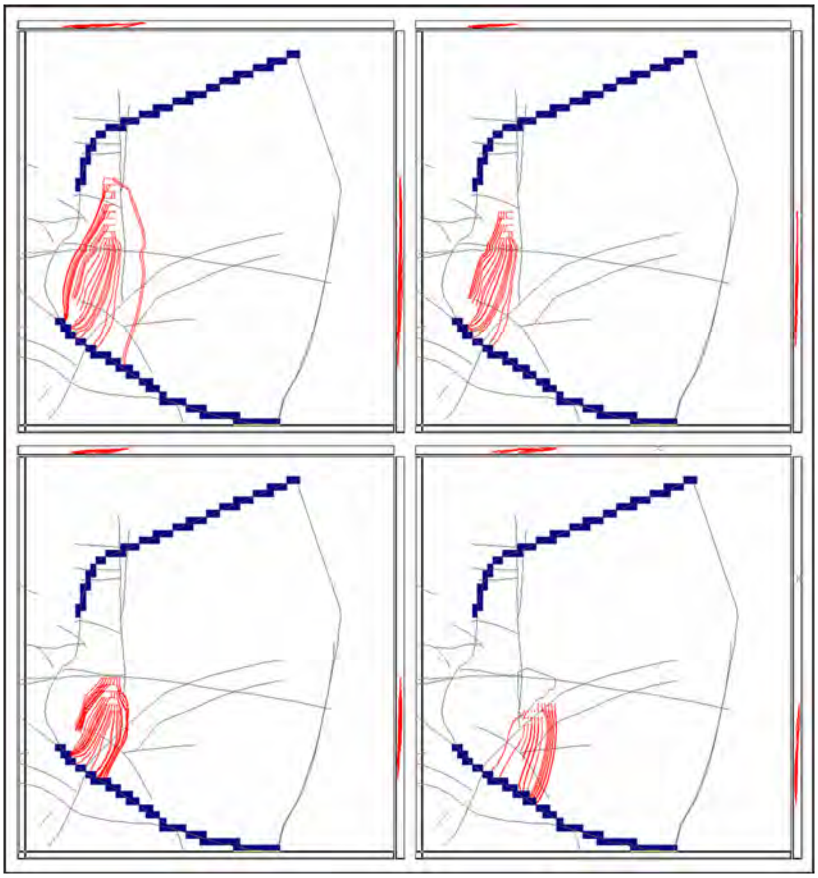


Figure 12. Capture zones for pumping wells according to the different scenarios.

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.

- *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 13). After that the model will be re-calibrated according to the new information.

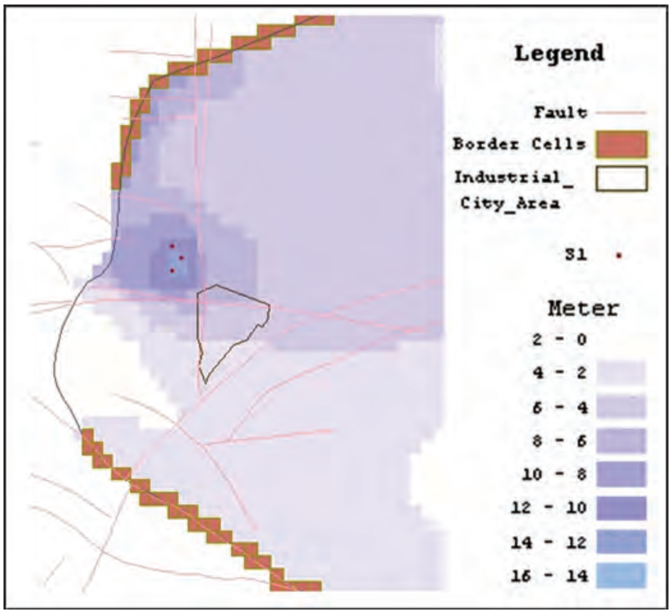


Figure 13. Water level drawdown according to recommended scenario. The maximum areal drawdown in the cells of pumping stations was 14 m.year^{-1}.

Conclusion

Groundwater mathematical models represent powerful tools for the assessment, development and management of groundwater resources. Case studies presented in this paper showed a wide range of applications according to the specific needs and conditions for each case, either in designing monitoring system (northern part of Khabour basin) or predicting the impact of climate change on groundwater storage (Zabadani sub-basin) or delineation of wellfield capture zones (Hasia sub-basin).

It is recommended that models should be a major component of any groundwater management study. Its predictive capacity makes it the most useful tool for planning, design, implementation and management of the groundwater resources.

The models 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 Project. 2007. Management, Protection and Sustainable Use of Groundwater and Soil Resources; Project report phase III, 01.04.2004 – 31.03.2008, Development and Application of a Decision Support System (DSS) for Water Resources Management (www.acsad-bgr.org).

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.

Al-Sibai, M., A. Droubi., A. Abdallah., S. Zahra., M. Obeissi., J. Wolfer., M. Huber., V. Hennings., K. Schelkes . 2008. Incorporate MODFLOW in a Decision Support System for Water Resources Management, Proceeding of Modflow and More international conference, Colorado, USA.

Al-Sibai, M. 2009. Vulnerability Assessment and Adaptation Measures of Water Resources (Modeling). Within Project: "Enabling activities for Preparation of Syria's Initial National Communication to UNFCCC".

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

Droubi, A. 2006. Integrated Water Resources Management is a tool for ensuring Arab water security The 2nd International Conf. on Water Resources & Arid Environment.

Droubi, A., M. Al-Sibai., A. Abdallah., S. Zahra., M. Obeissi., J. Wolfer., M. Huber., V. Hennings ., K. Schelkes. 2007. A Decision Support System (DSS) for Water Resources Management, Design and Results from a Pilot Study in SYRIA. In: Zereine F, Hötzl H (eds) Climatic Change and Water Resources in the Middle East and North Africa , Springer, Germany.

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.

ESCWA. 2007. State of water resources in the ESCWA region, Water development report 2. E/ESCWA/SDPD/2007/6.

FAO-MAAR. 2001. The Utilization of Water Resources for Agriculture in Syria. FAO Report GCP/SYR/006/ITA.

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

Sayegh R., B. Zakar . 2010. The Current Statues of the water Resources in Syria, In workshop on "Water reuse and desalination; Experience and opportunity", Damascus 28-28 Sep., Syria.

UNDP, 2009. Vulnerability Assessment and Possible Adaptation Measures of Water Resources. Syrian Initial National Communication to UNFCCC.