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Sustainable groundwater management in coastal aquifer of
Sinai using evolutionary algorithms

Hesham M. Bekhit\textsuperscript{a,*}

\textsuperscript{a}Irrigation and Hydraulics Department, Faculty of Engineering, Cairo University, Orman, Giza, 12613, Egypt

Abstract

Sinai Peninsula represents Egypt's strategic extension and historical link to its Arab neighbors. Owing to its important and critical location, the Egyptian Government budget for the coming year gives priority to a broad national development project in Sinai. However, the scarcity of freshwater in coastal arid regions of Sinai, coupled with the desired development and the ongoing population growth, makes optimal sustainable water management crucial. This paper is aiming at achieving the optimum groundwater management strategy in a pilot area at Sinai to support the sustainability of the development project. The evolutionary computational algorithms were used to achieve the abovementioned sustainable management strategy. The objective function of the developed management strategy aims to maximize the net benefit from groundwater withdrawal, while minimizing the invasion of saltwater front inside the aquifer. Also, to ensure sustainable development the objective function considers minimizing well interference effects. The results show that the developed framework can be effectively and efficiently used to achieve global solutions of the examined groundwater management problem.

Keywords: Sustainable management; Seawater intrusion; Evolutionary algorithms

1. Introduction

Water scarcity is considered one of the main challenges that are facing Egypt. Given its location in the belt of arid regions, Egypt is very sensitive towards limitations in the available water resources. Such shortage or scarcity of water is the main challenges that are facing the development in many regions in...
Egypt and more specifically for Sinai Peninsula. Owing to its important and critical location, the Egyptian Government budget for the coming year gives priority to a broad national development project in Sinai. Most of the development project in Sinai is relying on groundwater. Poor management or lack of management of groundwater leads to major problems. Of particular environmental importance are the problems related to the withdrawal from groundwater aquifers located in the coastal aquifers like the case of North Sinai region. In these aquifers, lack of groundwater withdrawal management leads to enhanced seawater intrusion. The proper management of such cases should aim at maximizing the benefits from the groundwater reservoir, guaranteeing sustainable resource utilization with minimizing decline in water level, and minimizing adverse environmental effects. Apparently, these objectives are conflicting thereby necessitating the use of an optimization framework. The complicity of the problem makes it practically very difficult and computationally very demanding to use traditional optimization techniques. Evolutionary computational algorithms provide an alternative that can efficiently deal with this optimization problem. Employing these techniques would result in an optimal solution that will result in maximum benefits and limited adverse environmental impacts.

The main objective of this study is to develop sustainable management scheme in the quaternary aquifer of Rafah. To achieve this objective, the presented paper integrates evolutionary methods along with groundwater simulation and solute transport models into a management tool for maximizing the benefit from groundwater resources while protecting the environment from seawater intrusion. In this study, SEAWAT model was employed within the framework of (GMS 9.2) as a simulation model to study the groundwater processes of the hydrogeological system of Rafah unconfined aquifer. Both neural network and genetic algorithm are used as soft computing techniques to improve computational efficiency of the optimization of management plan. Then the developed framework is used to manage and evaluate groundwater resources in the coastal aquifers of Northern Sinai.

2. Study Area and Model Domain

2.1. Hydrogeological formation

The study area is located at Rafah in North Sinai governorate, Egypt. Rafah is the eastern gateway to Egypt as shown in Fig 1. Rafah is located on the eastern Mediterranean coast of Egypt and it is divided into: (14) residential neighborhood and (11) villages. The number of population in Rafah is approximately 60 thousand capita. The people in Rafah rely on the groundwater to meet their municipal, agricultural and industrial water demands. The current domestic demand is 22,000 m$^3$/day which is abstracted from the shallow coastal aquifer. In addition, groundwater is used to secure irrigation requirement for the northern part of the center of Rafah.

Fig. 1. Location of the study area
Rafah aquifer is occupying the area from Rafah to El Shiekh Zuwyied. The climate of the study area is semi-arid to arid with irregular annual rainfall. The study area is covered by Quaternary deposits. The Quaternary deposits consist of old beach sand, sand dunes, and calcareous sandstone (which is known as Kurkar Formation). The aquifer thickness may reach about 80m to 100m. The aquifer is divided into three geological layers [1, 2, and 3]. The top layer consists of fine to coarse sand and intercalated with gravel and clayey layers. The bottom layer is consisting mainly from Kurkar formation. The Kurkar aquifer is confined by lenses of clays, where a confined aquifer conditions are developed. Although the clay layer occupies most part of the top of the bottom sandy layer, the hydraulic connection between the Kurkar aquifer and the overlying sandy aquifer is observed. The typical cross section of the area as obtained from borehole lithology logs of drilled water wells in the area is presented in Fig 2 (b).

2.2. Conceptual flow model

The areal extent of the model is shown in Fig 2(a). The model encompasses an area of approximately 242 Km². The model domain is making an angle of 25° anticlockwise with the north direction. The northern model boundary is assumed to be a specified head boundary which presents the Mediterranean Sea borders. The structural elements presented in Cairo University investigations [2] are used to define the eastern and the southern boundaries of the model. The south boundary of the model is corresponding to major fault \( F_1 \) (Fig 2(a)) which is considered to be permeable and can transfer water. Therefore, the southern boundary is simulated as general head boundary. The western boundary is also following another major fault \( F_2 \). The field investigations suggested that \( F_2 \) is impermeable and consequently the western boundary is taken as no flow boundary. Finally, the east boundary of the model is selected to be perpendicular to the head contour lines. Three hydrological layers are considered as explained above. A hydraulic connection is assumed to exist between the different model layers with normal gradient in the vertical direction. Data presenting heterogeneity in hydraulic properties is lacking and thus it is not warranted to incorporate heterogeneity in the modeled layers. Homogeneous conditions are assumed to prevail in each of the different formations modeled and the spatial.

![Fig. 2. (a) Model boundary; (b) geological section from west to east](image-url)
3. Numerical Flow and Transport Model

3.1. Model Description and Parameterization

As described earlier, the model consists of three main layers namely: the alluvial and sand dunes layer, clay layer, and the Kurkar layer. The depositions of sand extend from the land surface downward to the top of clay lenses with average thickness of 80m. The altitude of the base of the sandy aquifer is determined based on the lithology of different wells [4] and field measurements conducted through Cairo university investigations [2]. Following the same approach, the vertical extent of all layers is determined. The elevation of the top layer is obtained from the freely available SRTM data.

Two main sources for groundwater levels in the model are; 1) water levels inside 80 wells that are tapping the two formation of the study area [4], and 2) data collected through the field work conducted through Cairo University [2]. A complete inventory for water levels in all wells has been obtained during the period of 1988 to 1989. This inventory will be used in calibrating the steady state condition. Unfortunately, no rigorous data is available to estimate the net recharge in this area. However, several investigations have reported that the net recharge is ranging between zeros to maximum $3 \times 10^{-3}$ m/d. Thus, due to the uncertainty in the value of the net recharge, the value of the net recharge will be determined from the calibration process. Recharge is applied to the top model layer in the region of agricultural area and the alluvium deposition.

The salinity zonation map is obtained by using the salinity measurements that were reported in [5] together with the spatial distribution maps of salt concentration as adapted by El-Tablawi [6]. Both data sources were used to generate a map that presents the distribution of initial dissolved concentration of the study area before the development. The generated map is used to guide calibration of steady state case.

The work carried out by [4] presents results of 12 pumping tests that were conducted on selected wells. Data obtained from the pumping test analysis indicated that the alluvial deposits having wide range of transmissivity that ranges from 45 m$^2$/day to 1787 m$^2$/day while, the transmissivity of Kurkar aquifer shows low range of transmissivity that varies from 144 m$^2$/day to 390 m$^2$/day. However, values of the horizontal hydraulic conductivity in the two formations, in clay layer and vertical anisotropy are determined from calibration process guided by ranges of values obtained from the pumping tests results.

3.2. Implementation of numerical flow and transport model

Groundwater flow was simulated using the modular groundwater flow model MODFLOW-2000. The model domain is divided into a total of 3 layers. In the horizontal direction each of these layers is divided into grid cells with variable size $\Delta x$ and $\Delta y$ of 100 m at wells location and increased gradually with bias 1.1 to about 500 m. The total number of rows within the model domain is 76 rows and the total number of columns is 84 columns. The numerical model is constructed and calibrated in two stages (phases). The first stage is the steady state condition (base case) which represents the situation in the 1988-1989 where no development was considered and the well inventory of 1988 together with the salt distribution maps were used in the calibration. The second stage is the unsteady state which covers the time period from 1988 to 2005 where an increase of withdrawal is applied to simulate the current withdrawal as estimated by [7].

The increase in withdrawal was assumed to vary linearly from 1988 to 2005. Therefore, 17 stress periods are considered in the transient stage. The results of the second stage are used as an initial
condition for the management plan. It should be mentioned that all the simulations implemented variable density process using SEAWAT model.

4. Results and Discussions

4.1. Model calibration

The calibration of the steady state stage is conducted into two steps. In the first step the parameter estimation program PEST, which is a tool supported by GMS for automatic calibration, is used to calibrate the flow model. The process includes the use of a set of 51 points representing the observation data. GMS automatically interpolates the computed solution to the observation points, and the residual errors are calculated, the process is repeated till the minimum error is obtained. During this process the density variation is ignored and MODFLOW is executed alone. The second step is carried out manually, where the values of calibration parameters obtained by PEST are used as an initial guess. For each manual trial, a steady state groundwater heads and salt concentrations distributions were obtained by running a SEAWAT model for a very long time with steady state flow model. The computed heads and salt concentrations at the observation points are compared with the observed heads and concentrations. The locations of the observed head (shown as a target bar) and the calibrated model results are presented in Fig 3(a) which indicates very good agreement with the observed heads. Also, computed salt distribution Fig 3(b) is very similar to the measured concentrations reported by [6].

![Fig. 3. (a) Calibrated head model results of the base case; (b) calibrated salt concentration of the base case](image)

After achieving the calibration target in the steady state, the model has been used to conduct a forward run to simulate the aquifer performance from 1988 to 2005. The same model parameter structure that was obtained at the steady state calibration was used for the transient simulation. The only difference was the addition of storage coefficients, specific yields corresponding to each hydraulic conductivity zone, and increasing wells abstraction to match the increase in demand. The model results are compared with the available data at 2005 [7]. The transient calibration was achieved by adjusting only storage coefficients and specific yields and keeping all of the other parameter values from the steady state calibration. Fig 3(c) presents the heads distribution of 2005, whereas Fig 3 (d) presents the modeled salt distributions.
Fig. 3. (c) calibrated head model results of the unsteady simulation; (d) calibrated salt concentration of the unsteady simulation

4.2. Management framework

Fig 4 summarizes the management framework implemented in this study. The first step in the framework is obtaining the calibrated model of the groundwater system in Rafah as described above. All wells in the calibrated models are clustered based on the spatial location of each well into 8 well fields. The calibrated model is used to generate 50 realizations each with 8 different abstraction values, randomly selected, for each well field. The range of abstraction was set between a minimum 50% from the 2005 demand and maximum 3 times the maximum anticipated demand in the future after 10 years based on the development history of the area. For each realization the drawdown at the center of each of the 8 well fields is obtained. Also the salt concentrations are monitored at 8 points at a horizontal section parallel to the seashore and at distance 1 Km away from the shoreline.

![Flowchart of the management framework](image)

The drawdowns, salt concentrations, and well fields abstraction were used to train the Artificial Neural Network (ANN), where two networks are used to replace the SEAWAT model. The first network input parameters include 400 values of well fields’ abstractions (e.g., 8 values in 50 realizations) as input to the network and the corresponding water levels at centroid of the well fields were selected as output. The second network input parameters include 400 values of well fields’ abstractions as input to the model and the associated salt concentrations at the 8 observations were selected as output. In the two networks the
inputs and outputs data were normalized. The data is divided into three subsets. The first subset is the training set (70% of the data), which is used for computing the gradient and updating weights and biases. The second subset is the validation set (15% of the data), where the error on the validation set is monitored during the training to avoid overfitting. The last subset is the test set (15% of the data), where the error on the test is not used during training, but it is used to compare different models. Fig 5 presents the performance of the ANN during the training, validation and testing stages. Fig 5 shows a comparison between simulated heads by ANN and the observed heads with the correlation coefficient in each stage. It is evidence from Fig 5 that ANN successfully predict the heads in the aquifer.

The two trained ANN were used to replace SEAWAT simulations and were forwarded to a Genetic Algorithm (GA) model. GA is used to obtain the optimum management scheme. The used genetic algorithmic structure for solving the optimization problem in this study was developed using MATLAB R210B tool box. The GA used to generate up to 2000 management schemes (e.g., population size 20, and 100 generations). Each management scheme has 8 values for well fields’ abstraction. For each management scheme the ANN is used to determine the drawdown and salt concentration as described above. Then a score is assigned for each scheme based on an objective function that accounts for maximizing groundwater abstraction while minimizing the invasion of saltwater front inside the aquifer and minimizing the summation of maximum drawdown at the centroid of the 8 well fields.

Fig. 5. Performance of ANN during training, validation and testing stages

Fig 6(a) presents the performance of GA with the number of generation, where at each generation the box bars present the best and worst score of the objective function, and the solid line shows the variation of the mean value of the population with the generation number. The best management scheme was imported to the SEAWAT model and forward run was carried out to ensure the results of ANN. Fig 6(b) gives the results of head distribution for the best management scheme as depicted from SEAWAT model.
To evaluate the performance of the developed framework, a comparison between the current practices in development with the GA scheme is conducted. Two simulations were used in this comparison. The first simulation presents the use of SEAWAT in simulating the performance of groundwater aquifer for 10 years using the trend of current practices of wells abstraction. The second simulation depicts the implementation of GA abstraction for 10 years. Fig 7 shows the comparison between the two simulations.

Fig 7 (a) shows a comparison between the salt concentrations simulated at the 8 observed points using the trend of the current practices (solid line) versus GA scheme (dotted line), whereas Fig 7 (b) shows the same comparison but for groundwater level. It is evident that GA scheme reduces significantly the salt intrusion. The average salt concentration at a distance 1 Km from the shoreline was reduced from 11,100 mg/L to 6,000 mg/L. In term of groundwater sustainability, the GA scheme provides more sustainable strategy where it reduces the drop in water level and minimizes the well interference effects. The average water level in the 8 well fields using the GA scheme was -1.9 m as opposed to -8.4 m for the current practices. Finally, the groundwater withdrawal and associated benefits in GA scheme is 70% more than the current practices.
5. Summary and Conclusions

Groundwater flow and transport model was developed to simulate the movement and dispersion of the salt water into the Rafah aquifer system through MODFLOW for the groundwater flow pattern and MT3DMS for the transport simulation, which are then coupled with SEAWAT to account for the variable density in the flow simulation. A framework was developed and applied to achieve the best management practices for the coastal aquifers in Rafah. The framework includes the integration of evolutionary algorithms with the traditional simulation models to obtain the optimum management plane. The results showed that using the proposed framework allows increasing the current demand by 304% while keeping the salt concentration within safer limit (e.g., the line of 5000 mg/L moved only 80m in 10 years).

References