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Groundwater management of Skhira aquifer (center east of Tunisia): flow modelıng and planning under climate and anthropogenic constraints

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ABSTRACT

High pumping rates from Skhira aquifer during the previous years led to a significant decline of water levels and degradation of the groundwater quality by seawater intrusion. In order to avoid these major problems affecting groundwater quality and quantity of this aquifer, sustainable water resource management is necessary and a priority to select an appropriate exploitation scheme. For this purpose, geographic information systems and Modflow have been applied to estimate current and future water budgets; hydrodynamic modeling of Skhira groundwater was investigated by using Modflow code to understand the hydrodynamics and the geometry of the aquifer system. The calibration of the mathematical model in steady state (1973) helped to refine the spatial distribution of transmissivity, to restore the groundwater level at each point, and to establish the stock of the groundwater. The assessment of the reliability of the model was conducted by comparing the simulated and observed values of the hydraulic head for the observed wells. It is noticed that there is a satisfactory concordance between these levels, especially in areas, where there is sufficient information about the hydrodynamic properties (transmissivity and piezometry). The results from the steady state were used to calibrate the transient model, to refine the spatial distribution of recharge and storage coefficient, and to determine the drawdowns at all points capturing Skhira aquifer during the period (1973–2014). Using the calibrated model, different scenarios were considered in order to predict the aquifer response under different exploitation conditions and stresses.

Keywords: Water management; Modflow; Modeling; Calibration; Simulations; Skhira aquifer; Tunisia

1. Introduction

Climate constraints, population growth, and economic and social transformations are the reasons for the increasing demand for water in Tunisia [1–3]. This ever-increasing demand has exhausted water resources in Tunisia and many regions in the world [4].

In fact, during the last decades, the usage of groundwater in Tunisia has gradually increased due to, on one hand, the increasing demand for water for several economic sectors and, on the other hand, the shortage of surface water [5,6]. The quantification of reserves and their variations according to natural and anthropogenic activities is necessary in order to establish adequate management plans for the groundwater [7]. Also the modeling aims to take the reality, to understand the evolution of hydrodynamic parameters over time and to predict the state of the system in the future following natural and anthropogenic constraints.

To this end and for optimal and sustainable exploitation of resources, the modeling approach is a useful and powerful

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quantitative tool available to hydrogeologists for evaluating groundwater systems [8].

A groundwater model is a simplified representation of the reality that approximately simulates the input/output stress and response relations of the system [9]. Also, the groundwater model allows, after calibration and verification phases, to simulate under different forcing scenarios, the quantity and quality of water in an aquifer [10].

In Tunisia and for several case studies in the world, several hydrogeological modeling studies were carried out using the Modflow software [1,7,8]. In the present study, groundwater flow modeling is achieved under a steady and transient state condition and predictive simulations using visual MODFLOW software with the finite difference method. The aim of this model is to help identify the Skhira aquifer resources in the study area and to find a solution for the problem of the decline of groundwater in this aquifer.

2. Study area

The present study concerns the coastal aquifer of Skhira, which is located in the central east part of Tunisia. It comprises an area of 514 km^2. It is bounded on the north by the Bir Ali Ouadrane aquifer, on the west by the aquifer of Sebkhat Naoual, on the south by the limit of the aquifer of Gabès, and on the East by the Mediterranean Sea (Fig. 1).

Skhira groundwater is heavily used for agricultural purpose and represents a major source of drinking water and agriculture uses. The study area is characterized by an arid Mediterranean climate with a long dry season [11]. The study area is characterized by an arid Mediterranean climate with a long dry season. Rainfall is irregular with an annual average that varies between 200 and 250 mm year^{-1}. The annual cumulative evaporation in the Tunisian south-east sector is between 1,400 and 2,000 mm year^{-1}, producing

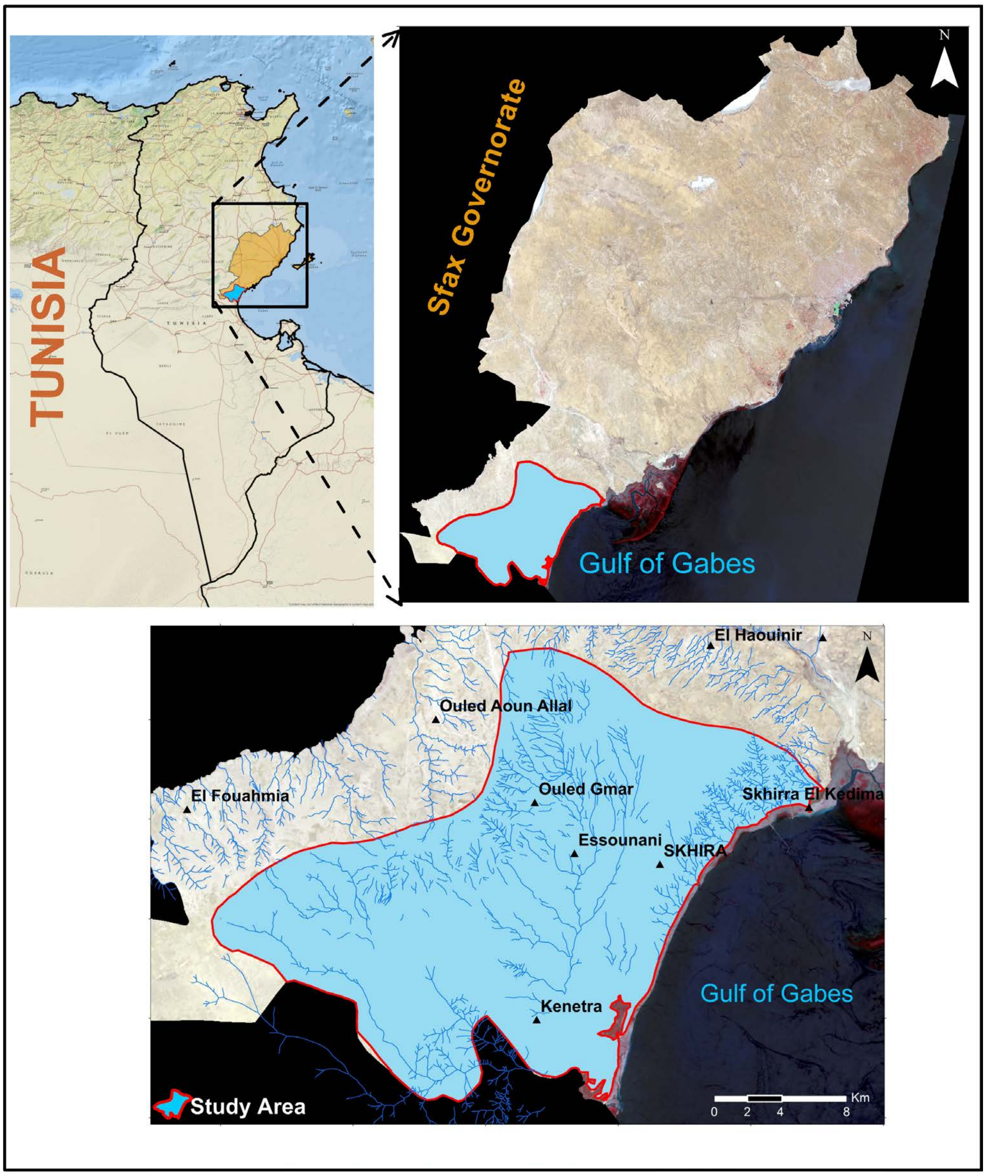

Fig. 1. Location map of the study area.

a negative water balance in this region. This water deficit is estimated between 1,200 and 1,300 mm year^{-1} [12]. Moreover, the annual water balance in the region of Gabes is negative and equal to 1,420 mm.

The geological series across the Skhira region are of Quaternary age. The only Cretaceous age outcrops are located in the western and southwestern limits of the area and constitute the structures of Zemlet el Beida, Zbara el Kbira and Zbara EsSrhira, respectively. Major faults have three main orientations: N-S, NE-SW and NW-SE [13].

The aquifer is formed by four levels consisting of fine sands, separated by semi-permeable clay-sandy levels, allowing communication between the different aquifer levels. The main source of water supply is the infiltration of meteoric water, especially from river infiltration during its NW-SE flow. The subsurface aquifer is formed by four levels consisting of fine sands, separated by semi-permeable clay-sandy levels, allowing communication between different aquifer units. The main discharge for this aquifer is the Mediterranean Sea. Piezometric maps established show a decrease of the piezometric levels, which is due to the over-exploitation of groundwater. In fact, groundwater exploitation was nearly constant from 1970 to 1974 on the order of 5×10^6 m^3 year^{-1} [12].

An overall increase of exploitation to >8.3 mm^3 year^{-1} occurred from 1981 to 2010, following the successive installation of several new wells into the Skhira aquifer, which is the principal source for the water supply of the region (67% for industry, 25% for irrigation and 8% for drinking water) [14].

3. Methodology area

The flow model was realized using the Modflow software developed by the USGS [15]. This code is probably the model of simulation of groundwater most widely used in the world due to its robustness and its reliability [16]. It is a model with physical bases, deterministic, and capable of representing three-dimensional Darcy flows in multi-layer systems [17]. It is an interactive modeling system for flow, mass transport, and heat in two or three dimensions using a finite difference approximation [18].

3.1. Equation

This model makes it possible to calculate the consolidation in the aquifer following the change of the piezometric coasts. It describes and predicts the behavior of aquifer systems by solving groundwater flow equations through porous media.

The MODFLOW model is used to calculate water flows and piezometric heights from Darcy's law and the diffusion equation. According to a study by McDonald and Harbaugh [19], the equation for three-dimensional constant flow in a porous media can be written as follows:

$$\frac{\partial\left(K_{xx}\frac{\partial h}{\partial x}\right)}{\partial x}+\frac{\partial\left(K_{yy}\frac{\partial h}{\partial y}\right)}{\partial y}+\frac{\partial\left(K_{zz}\frac{\partial h}{\partial z}\right)}{\partial z}=S_s\frac{\partial h}{\partial t}+q \qquad (1)$$

K_{xx}, K_{yy} and K_{zz} (LT^{-1}): the values of the hydraulic conductivity along the x, y and z-axis; h (L): the potentiometric head; q (T^{-1}): flow rate per unit volume; S_s (L^{-1}): the specific storage coefficient of the porous medium; t [T]: the time.

Considering the relatively small thickness of the aquifer in relation to its horizontal dimensions, it is assumed that the flow is plane. The steady state is characterized by the constancy of h with respect to the time materialized by $\frac{\partial h}{\partial t}=0$. Therefore this last equation is written in the following form [20]:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \qquad (2)$$

Modflow solves the diffusion equation with finite difference [21]. To do this, the model is discretized according to a rectangular and Cartesian mesh. The process followed has two essential steps: the first stage is based on the establishment of a database integrated into a geographical information system (GIS) [22,23]. The second step is the development of the hydrogeological numerical model of the aquifer system (Fig. 2).

Generally the methodology adopted is the same in all hydrodynamic modeling studies, but the entries differ according to the case study, its geometry, geology, hydrogeology, climate conditions, presence of dam and the quantity and quality of data available [24]

3.2. Hydrodynamic modeling of the Skhira aquifer

3.2.1. Conceptual model

The conceptual model was developed by analyzing the hydrogeological data and previous work. The aquifer is formed by four aquifer levels consisting of fine sands, separated by semi-permeable clay-sandy levels, allowing communication between the different aquifer levels. The main source of water supply is the infiltration of meteoric water, especially at the river basin, and it generally flows from north-west to south-east. The sea is the main discharge for this aquifer. The conceptual scheme of the model in the present work considers the quaternary aquifer as a single hydrogeological entity, forming a single continuous aquifer (Fig. 3).

3.2.2. Construction of the hydrodynamic model of the aquifer system under steady conditions

The aquifer must be discretized in quadrangular meshes, and boundary conditions must be imposed. There are two essential steps involved: The first step is based on the establishment of a database integrated into a GIS. The second step is the development of the numerical model of the hydrogeological system.

3.2.3. Choice of a reference state

Fig. 4 shows the 1973 piezometric map, adopted as a reference state for steady-state modeling.

3.2.4. Grid construction and layer discretization

The groundwater developed for the study area was discretized with a finite-difference grid that was composed

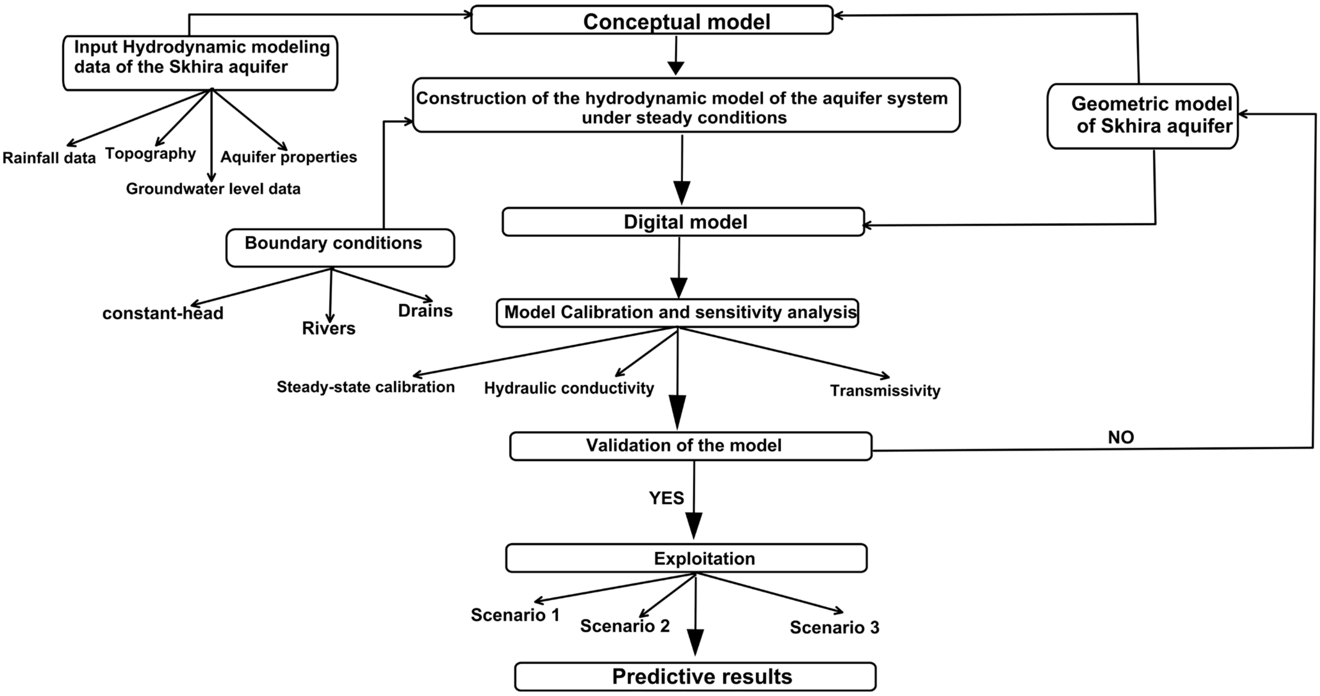

Fig. 2. Diagram of the working method adopted by hydrodynamic modeling.

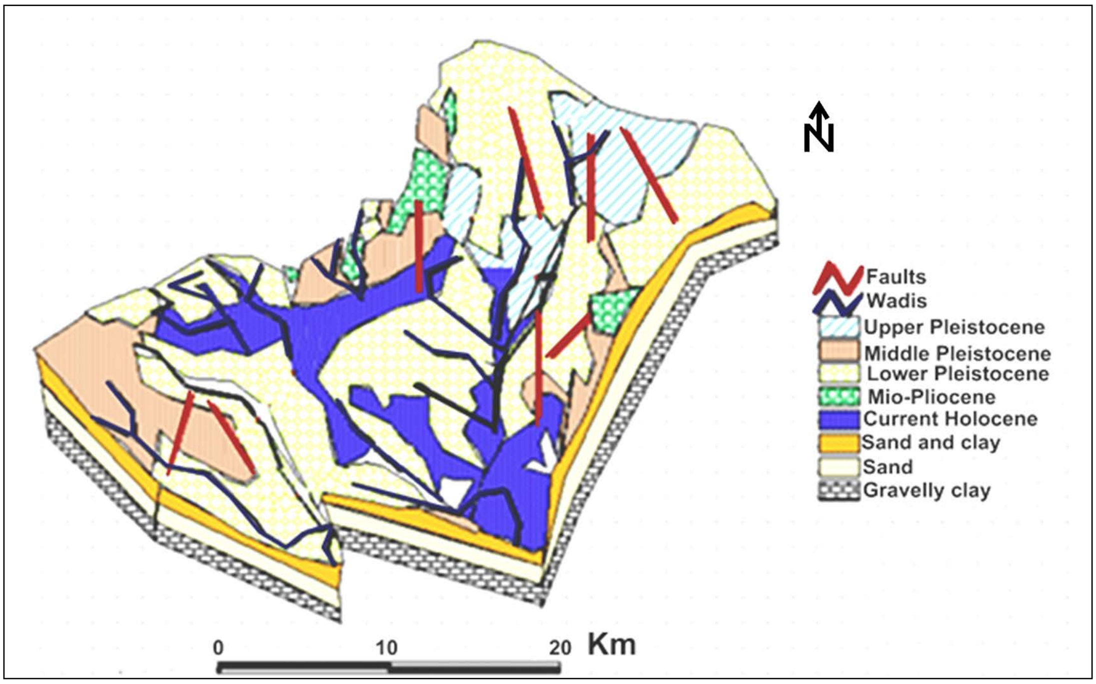

Fig. 3. Conceptual diagram of the study area.

of 55 rows and 78 columns with uniform cell dimensions of 500 by 500 m.

3.2.5. Groundwater recharge

Groundwater recharge can be described as a natural part, among others, of the hydrologic cycle. It is the water penetration to the aquifer usually after precipitation throughout the unsaturated zone and under infiltration and percolation phenomenon [10,25].

For arid zones, groundwater recharge is mainly assured by direct recharge, with a rate generally about 2%–5% of rainfall. But the largest volume of recharge comes from the infiltration of run-off water through the wadi beds and

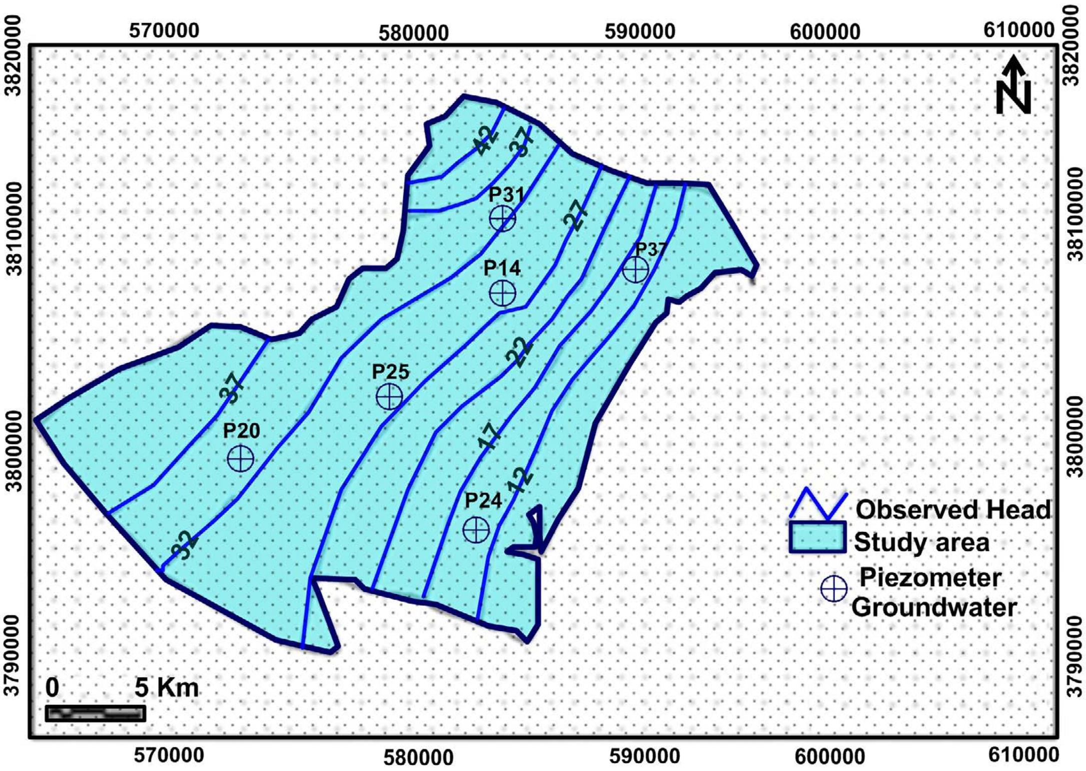

Fig. 4. Piezometric level map of Skhira aquifer and locations of piezometers.

is estimated at 30% of the runoff volume [20]. These reference rates constitute a range of variations that we will refine during model calibration.

3.2.6. Evapotranspiration

The Skhira plateau is characterized by intense evapotranspiration zones that affect the bottom layer and are concentrated in the eastern part of the layer, mainly on the coast where the phreatic level is close to the soil surface. Thus, for the effect of evaporation on the top of the Skhira aquifer, we used the Modflow evapotranspiration module. Evaporation has been estimated by mesh and introduced only in areas where the layer is close to the surface and where the evaporation is intense.

3.3. Parameters of the aquifer

The tests show the variability of the transmissivity passing from 0.00025 to 0.00065 $m^2 s^{-1}$ [12]. These different values of transmissivity were used to construct the initial state of the model to be calibrated. This parameter will then be adjusted along with the calibration in order to obtain a piezometric map simulated by the model, which coincides with the initial piezometric map.

3.4. Steady-state model calibration

The main calibration criterion is the nearest reconstitution of the reference piezometric map and the piezometric values observed punctually. The superposition of the observed and calculated piezometric curves proves that the model faithfully reproduces the distribution of the charges taken as reference. In a steady state, there is a strong coherence between the simulated flow and the natural flow of the aquifer. The comparison between the calculated values and the values measured at the level of 25 surface wells, distributed over the entire Skhira aquifer, confirms the good concordance between them. In effect, the cumulative deviations on all observation points do not exceed 1 m. Fig. 5 shows the strong correlation between the measured and observed head, with a correlation coefficient of 0.95.

According to the calculated budget, shown in Table 1, it is possible to deduce the importance of lateral feeding in the Skhira aquifer system. A large part of this water supply is discharged in the downstream of the aquifer to the Mediterranean Sea.

In addition, the model allows obtaining a better estimate of the evapotranspiration, which represents an important element of the water balance of the Skhira aquifer, as in all phreatic aquifer in arid regions.

Table 1
Water budget calculated by the model for 1973 ($m^3 s^{-1}$)

Parameters	Outputs	Inputs
Boundary conditions	0.53	0.026
Exploitation	–	0.029
Evapotranspiration	–	0.48
Total	0.53	0.53

3.5. Construction and calibration of the hydrodynamic model of the transient aquifer system

For 42 years from 1973 to 2014, the initial conditions correspond with the piezometric state calculated since 1973, representing the steady state. On all supply limits, the imposed potential conditions are transformed into imposed flow conditions. These flows are deduced by the application of the Darcy law on these boundaries with the distribution of the piezometry obtained after the calibration of the model in steady state. This transformation concerns the western limit of the aquifer and means that the external water supply is dictated only by the area outside the aquifer.

3.6. Structural parameters of the calibration initialization

The Skhira aquifer system is an important groundwater resource, which is currently experiencing a significant development of agricultural, industrial and maritime activities, and demographic expansion. A growing demand for water has accompanied this development. From 1981, it is noted an overall increase of operating flow at the level of the aquifer (>11.22 Mm^3 a^{-1}) (Fig. 6), following the successive placement of several new surface wells, which led to an over-exploitation of the coastal aquifer. In transient conditions, three parameters will determine the behavior of the aquifer: exploitation, storage coefficient and recharge. The annual exploitation was provided by the CRDA and DGRE (Fig. 6).and thus constitutes precisely known data [26], which will not be modified during the calibration procedure. This parameter is introduced into the model at the level of each surface well year by year during the period 1973–2014 [27].

The calibration under transient conditions concerned only the storage coefficient and the recharge (Figs. 7 and 8). Time is discretized in annual phases.

After several simulations, consistent reproduction of the historic piezometric in the observation points was obtained. Fig. 9 shows the evolution of the calculated piezometry and that measured at some reference points during

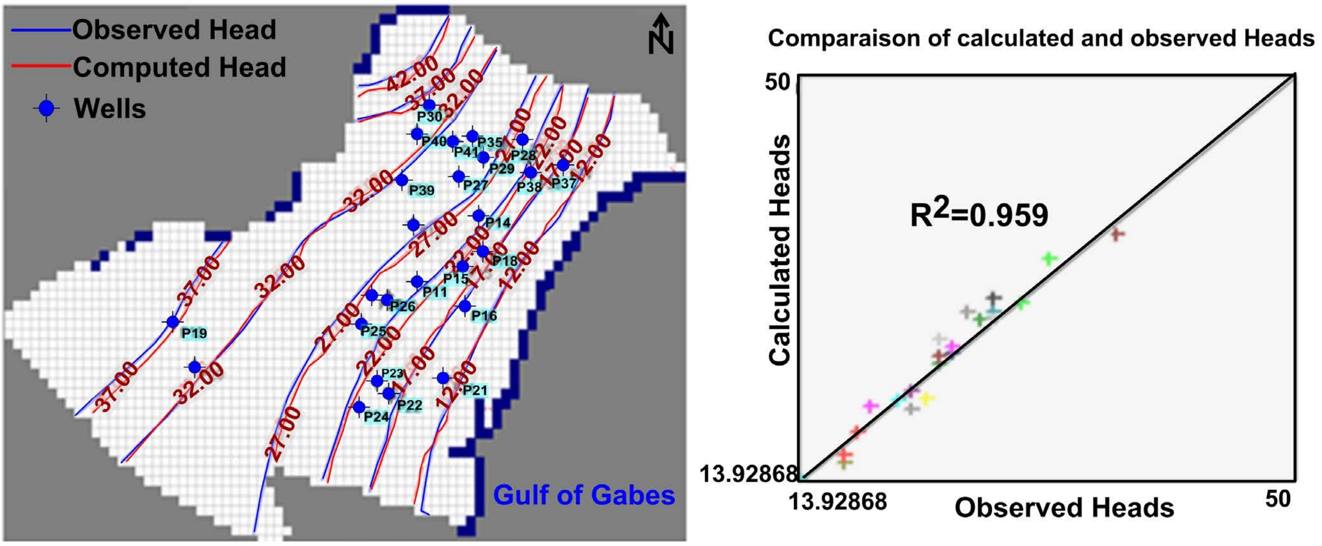

Fig. 5. Piezometric map measured and calculated in steady state; Steady-state correlation line.

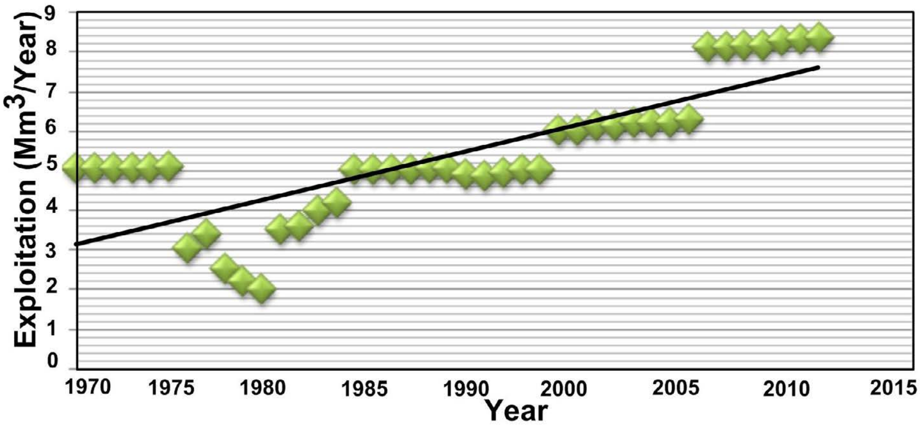

Fig. 6. Evolution of the exploitation of surface wells during the period 1973–2014.

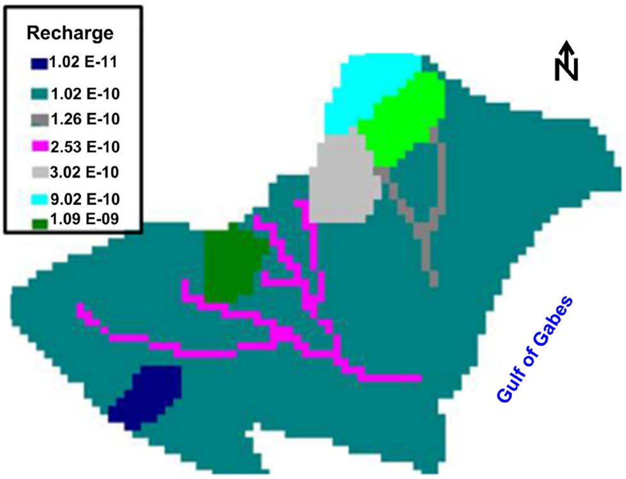

Fig. 7. Recharge after calibration of the transient model.

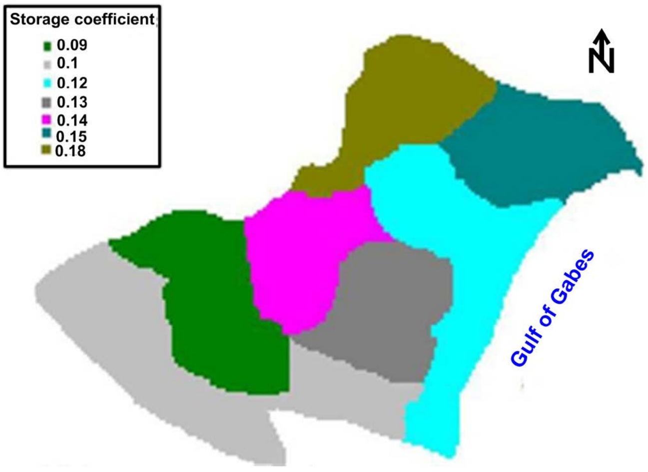

Fig. 8. Storage coefficients after calibration of the transient model.

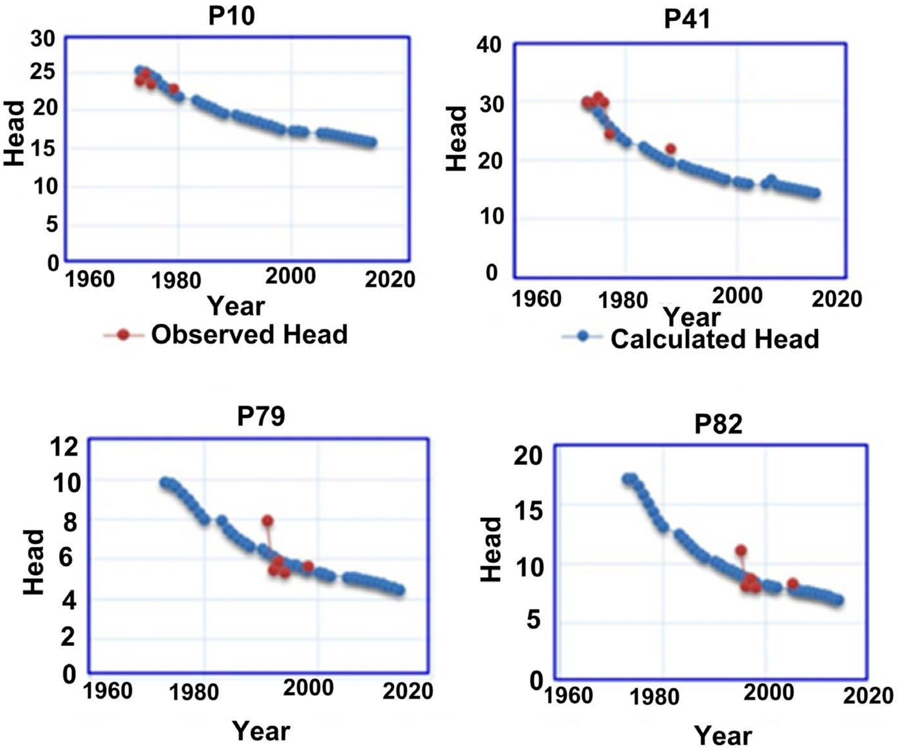

Fig. 9. Comparison of the evolution of calculated piezometry and the one measured in some surface wells during the period 1973–2014.

the simulation period. Overall, the calculated piezometry shows satisfactory and consistent results with those measured. The observation points of the selected piezometric heights are well distributed throughout the field of study (Fig. 9).

The evolution of piezometry over time reflects a confirmed downward trend, which is the sign of constant drain. Since 1973, the piezometric drop has fluctuated between 3 and 21 m. This decrease was more significant in the northwestern part of the Sidi M'hammed area (Fig. 10). This is confirmed by the gradual drying up of the flow of the sources, the weakening of artesianism, and the gradual transition within pumping areas. In this figure, the decrease is confirmed, which brought the level of groundwater to the coastal fringes of the Skhira region below the sea level. This is justified by the penetration of the zero piezometric lines into the continent and certainly resulted in the intrusion of seawater into the aquifer as well as in degradation of water quality. The most significant drawdowns are in the northwest of the aquifer that are about 21 m.

Comparing the balance of flows, calculated for 2014, with that obtained in the steady-state regime, it is noted that

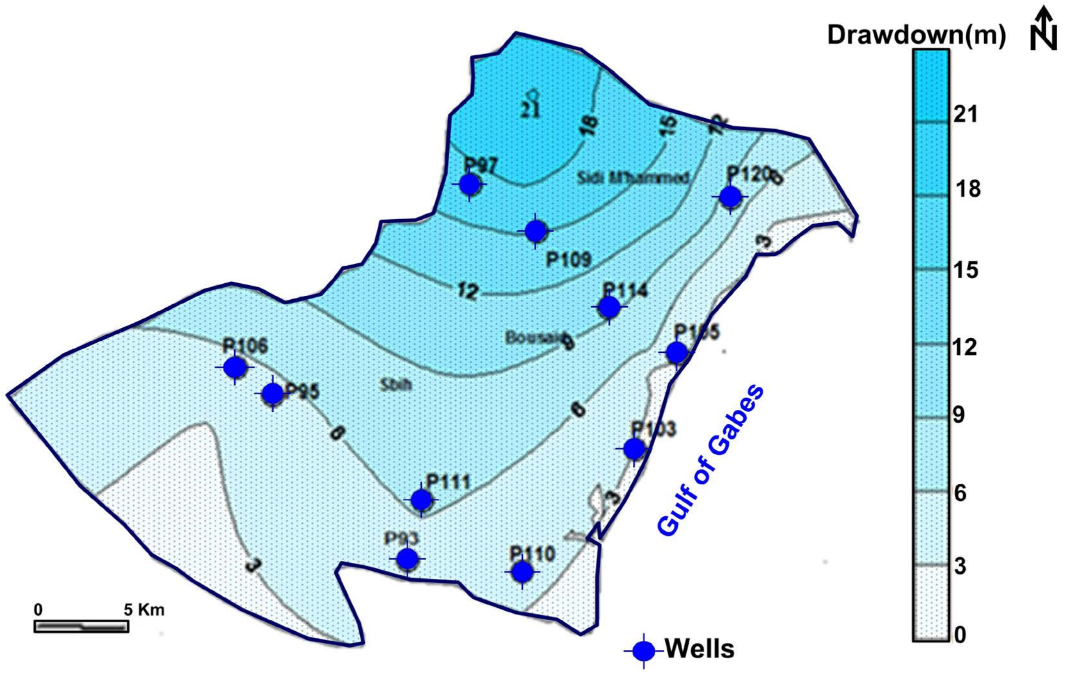

Fig. 10. Map of drawdowns (m) between 1973 and 2014.

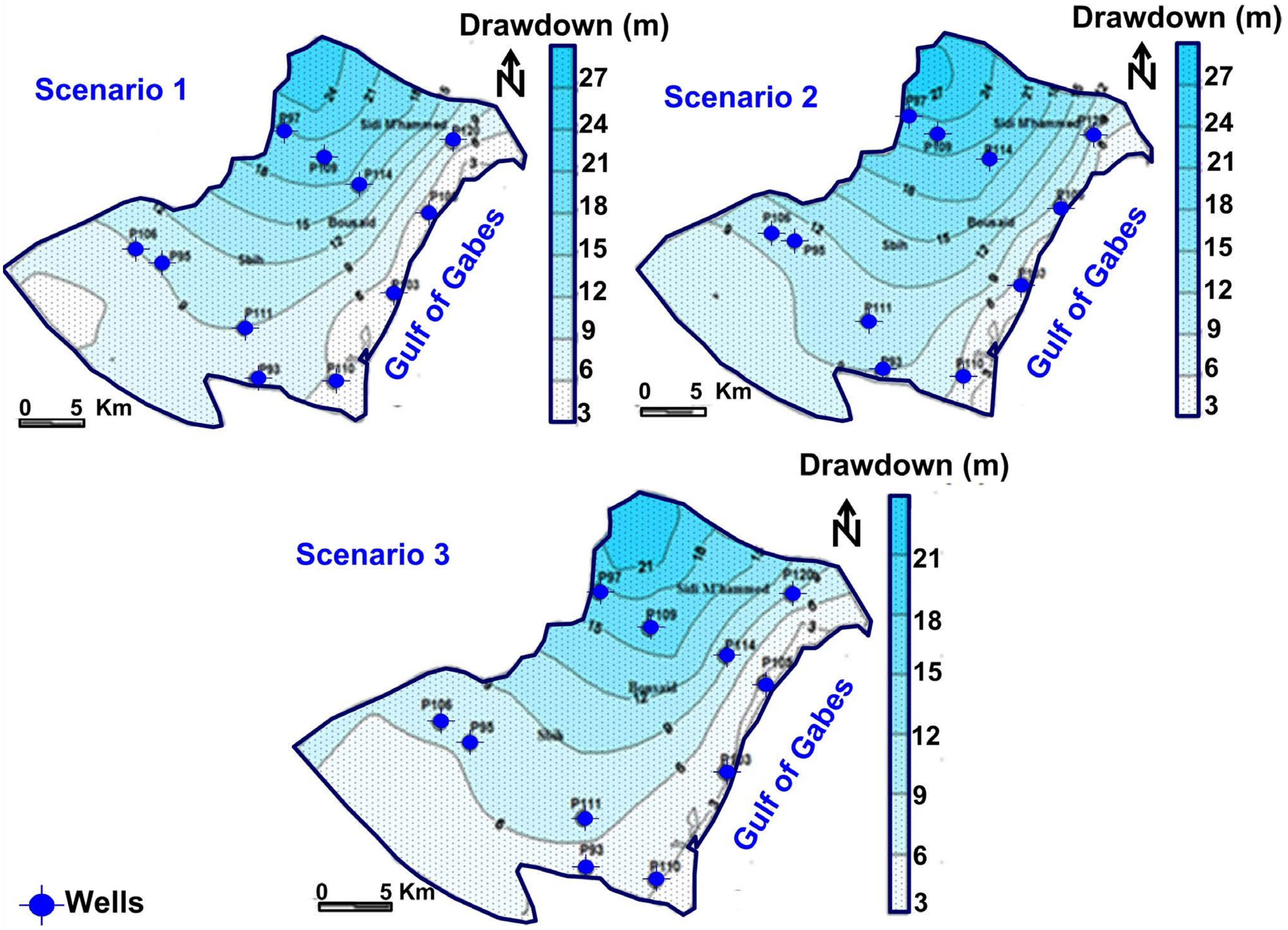

Fig. 11. Drawdowns map (m) of the piezometric levels produced in Scenario 1, Scenario 2 and Scenario 3 of the study area.

the outflow to the sea has decreased as a result of increased exploitation over time and also due to increased water demand in the region especially for irrigation (Table 2).

3.7. Predictive simulations

The constructed model was used for predictive simulations to provide the long-term evolution of the aquifer under the effect of current and future pumping and recharge. Indeed, the elaborated model allows, through temporal extrapolations of the operating parameters, to specify the evolution of the aquifer system under different constraints and at different times. It is precisely these results that can help managers make decisive decisions protect groundwater resources in the region [1]. In order to predict the evolution of the aquifer, three scenarios have been established, depending on the exploitation and recharge at the aquifer level (Fig. 11).

3.7.1. Scenario No. 1

The first scenario consists of maintaining constant exploitation and recharge for 50 years and predicting the effect on the piezometry of the study area. The drawdown map of the piezometric levels, obtained after 50 years by maintaining constant exploitation, shows a significant drop in piezometric levels; 12 m in the central part at the level of the Sbih region to reach 24–27 m to the north-west of the aquifer.

3.7.2. Scenario No. 2

The second simulation attempts to predict the impact of an increase in exploitation compared with the first scenario. The recharge has been maintained constant, and with the continuous growth of water requirements in the area for industrial and agricultural purposes, the sampling rates at the aquifer system have tripled. The results of this simulation predict for 2065 a significant decrease in the piezometric levels, which results in additional drawdowns compared with the first simulation. Indeed, the most substantial drawdowns reach 28 m; they are located to the north-west of the aquifer. By increasing pumping, the drawdown in the center would reach 15 m, the lower piezometric level in the East near the sea would reach 6 m. This confirms the intrusion of salt water and the reversal of flow direction.

Table 2
Water budget of Skhira aquifer for 2014 ($m^3\ s^{-1}$)

Parameters	Outputs	Inputs
Reserve contribution	2.28	–
Recharge (direct infiltration)	8.83×10^{-2}	–
Contribution north-west	0.54	–
Outflow to the sea	–	2.06
Exploitation	–	0.356
Evapotranspiration		0.509
Total	2.9	2.9

3.7.3. Scenario No. 3

The third scenario is to maintain the recharge constantly for 50 years and to cancel the exploitation. The results of this simulation for 2065 show that the piezometric levels generally remain constant over the entire aquifer compared with those of 2014 since one cancels pumping and maintains the recharge constant, but the evapotranspiration represents a significant loss for a coastal aquifer as well.

4. Conclusions

The numerical modeling of Skhira aquifer required an exhaustive definition of the input parameters. Thus, the calibration of the model in steady state on the piezometry of 1973 made it possible to restore the piezometric level at each point and to establish the balance of this aquifer. The good agreement between the calculated and measured levels reflects the reliability of the model, despite the lack of hydrogeological information in certain parts of the aquifer system. The calibration of the model in transient mode allowed refining the spatial distribution of the recharge and the storage coefficient and determining the drawdowns at the points capturing the aquifer system during the period concerned (1973–2014). In fact, during this period, one observes a drop in piezometry in response to growing exploitation. The largest drawdowns are observed in the area of Sidi M'hammed in the northwest. Similarly, one observes that the zero line, representing the level of the sea, has progressed in the continental area of the water table resulting inevitably in the marine intrusion. The predictive simulations adopted for this work show the effect of increasing exploitation rates on the piezometric levels and the drawdowns at the level of the Skhira aquifer.

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