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Groundwater flow simulation at the Grombalia phreatic aquifer (Cap Bon, Northeastern Tunisia)

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ABSTRACT

During the last few decades, the Grombalia shallow, an unconfined aquifer, had been under stress by groundwater pumping due to the increasing population and development of agricultural activity. Recently, the aquifer has displayed an important decline in the water level of boreholes and wells, and considerable deterioration of groundwater quality due to saltwater intrusion. A groundwater numerical model for the Grombalia aquifer has been developed based on the Visual Modflow 3.1 code to simulate the groundwater changes under steady state regime and transient conditions. The results of the model show reasonable agreement between observed and estimated groundwater levels in the observation wells. Sebkaht Soliman wetland aquifer connection has been identified. This paper presents the effect of different groundwater management scenarios and pumping discharge on groundwater resources in the Grombalia aquifer (Cap-Bon peninsula, Tunisia).

Keywords: Numerical model; Groundwater; Seawater intrusion; Grombalia; Tunisia

1. Introduction

Any development in the coastal region may result in changes in the hydrologic conditions, including the freshwater/saltwater balance. During the past decades, groundwater salinity changes have been intensively studied, particularly in coastal aquifers, triggered by scientific interest as well as by social relevance [1–8]. However, main processes controlling the changes of salinity along time and space have to be defined in order to identify salinization sources. Present-day distribution of fresh and saline groundwater still may reflect previous hydrological conditions; so long-term geological processes and recent anthropogenic changes are combined, making it difficult to distinguish one effect from another [7–10].

The use of groundwater models as hydrologic tools is prevalent in the field of environmental science. By mathematically representing a simplified version

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of a hydrogeological system, reasonable alternative scenarios can be predicted, tested, and compared. The applicability or usefulness of a model depends on how closely the mathematical equations approximate the physical system being modeled. Nevertheless, in order to evaluate the applicability or usefulness of a model, it is necessary to have a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations.

The modeling studies in Tunisia have so far been limited to academic and research purposes. The objectives of modeling studies in Tunisia have been mainly addressed with respect to: (i) groundwater recharge, (ii) water table dynamic, (iii) stream-aquifer interaction, and (iv) sea water intrusion [10]. The practitioners and professionals of groundwater hydrology, generally, still prefer to apply lumped models for groundwater development and recharge planning. Such models completely ignore the distributed character of the groundwater regime. Thus, they are based upon rather conservative concepts like safe yields, and are incapable of accounting for the stream–aquifer interaction and the dependence of lateral recharge on the water table pattern.

In the Grombalia region in the northeastern Tunisia, groundwater is the only reliable source for urban and agricultural water supply. In recent years, groundwater pumping increased along with increased population, and water level in the unconfined aquifer has largely declined. Also, groundwater quality has progressively deteriorated in the region. The purpose of this research is to simulate the flow behavior at the Grombalia aquifer under current conditions. A second objective is to assess possible aquifer impacts under three different management scenarios.

2. Study area

2.1. The Grombalia region

The plains of the eastern coast of Cap-Bon, extending over a surface of 430 km^2 (Fig. 1), is a coastal band opening along 50 km of the seashore . The study area is boarded to the north by the Gulf of Tunis and the Tekelsa Hills, to the east by the Abderrahman Mountain and the oriental coastal highlands, to the south by the Hammamet Hills, and to the west by the Bou Choucha and the Halloufa mountains. The study area, which is located about 40 km south of Tunis, is a bay widely opened onto the northwest and communicating with the Bay of Tunis (Fig. 1).

The climate is of Mediterranean type. The long-term mean annual rainfall ranges between 400 and 500 mm (1990–2010 period, Grombalia station). About 80% of this precipitation occurs between September and March, followed by dry spring and summer months. The annual temperature is 19˚C with maximum in August up to 28˚C and minimum in January up to 12˚C. Evapotranspiration, calculated according to the Blaney Cridle method, is about 1,500 mm, resulting in an average water annual deficit of 1,000 mm [11].

Regionally, the surface flow (Fig. 1) is toward the north, reflecting regional topographic gradients. It is constituted by several ephemeral Wadis (El Bey and Bzikh), which collect surface runoff from the surrounding highlands toward the Mediterranean Sea. This network plays a principal role for the Grombalia aquifer upstream recharge (Wadis Bey), and downstream discharge (Wadis Bey). Main water resources depend on groundwater.

Soils in the study area are described as being composed of alluvial coarse materials belonging to the Quaternary formation. Soils are reddish to brown color with low sand-silty material, and organic matter-rich, generally suitable for horticultural and orchard cultivation. The dominant vegetation cover changes from a mix of fruit-bearing trees like citrus [11] to vegetables and legumes.

From the geologic point of view, the Grombalia Basin (Fig. 2) system [12,13] is described as a small basin, NW–SE oriented, and filled with Quaternary sediments, the edges of which were related to two normal faults that appeared during the Middle Miocene [14–18]. The geology within the basin comprised recent Quaternary sediments and terraces that partially cover the Eocene, Oligocene, and Miocene Formations. The Eocene deposits are mainly constituted of Glauconeous sands of the Souar Formation, which locally outcrops in the north of the Halloufa Mountain. The Oligocene unit is principally made up of coarse to medium-grained sandstone belonging to the Fortuna Formation [19,20]. The Miocene sandstone and clay series are found essentially in the Oriental coastal hills and in some restricted areas along the foot of the Halloufa and Bouchouch mountains. The Quaternary detrital sedimentations of the Rejich Formation mainly consist of fine to coarse-grained sands, clayey sands, sandstone, silt, and abundant evaporated deposits [20–22].

2.2. The Grombalia aquifer

The Grombalia aquifer is bounded northward by the Mediterranean Sea and westward by the Gulf of Tunis.

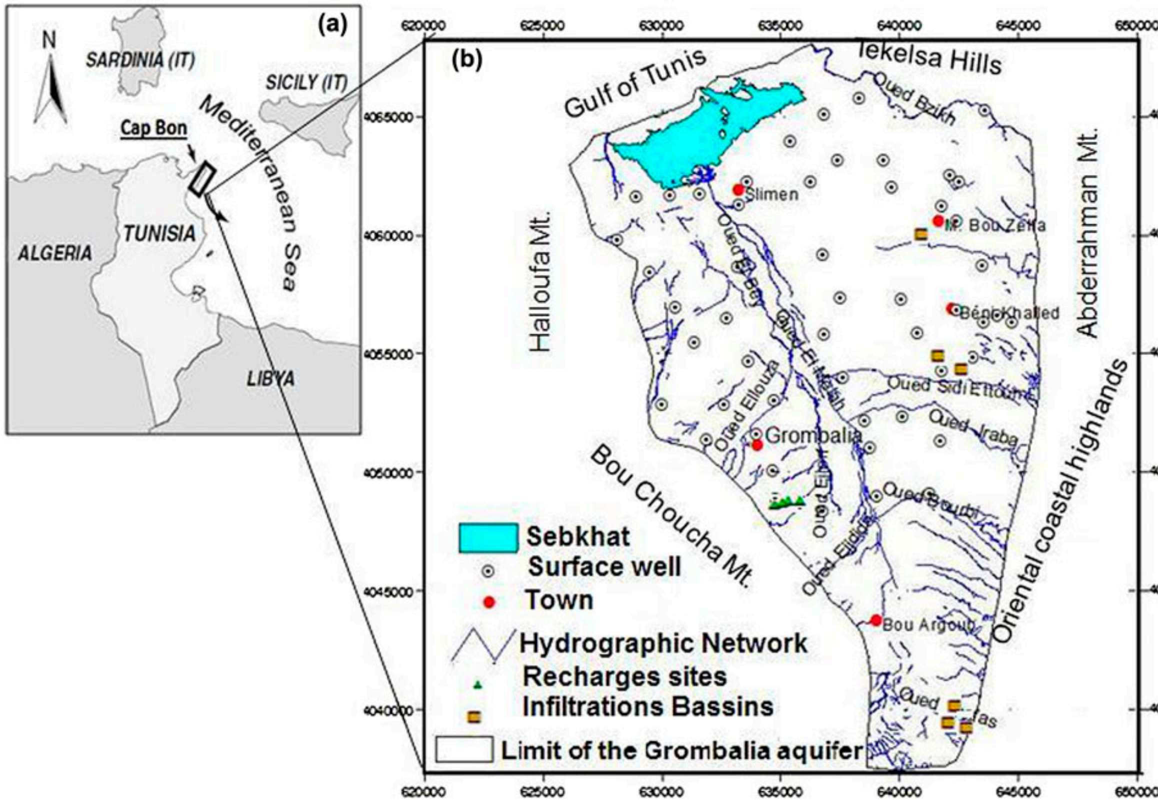

Fig. 1. (a) Map of Tunisia and (b) surface extent of the Grombalia aquifer.

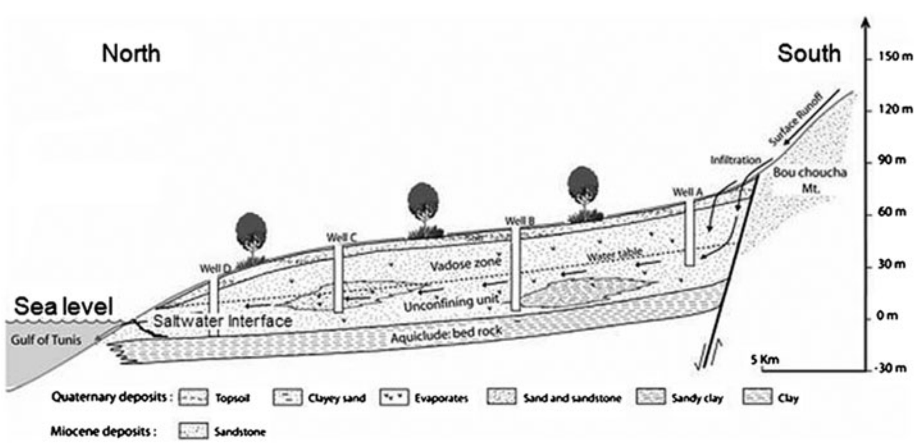

Fig. 2. The Grombalia upper unconfined aquifer hydrogeologic schematic cross-section [23].

The Grombalia system aquifer is composed of alternate permeable layers of sandblasters and impervious silty layers. It constitutes a complex aquifer system formed by shallow unconfined, semi deep, and deep aquifers with different exploitation levels [14]. The interest of the study relies on the upper aquifer.

The unconfined aquifer, with an average thickness of 50 m, is hosted in the Quaternary continental sand, clayey sand, and sandstones deposits overlying a 15 m-thick clayey bedrock. Top elevation, bottom, and thickness spatial distribution of the upper aquifer has been plotted in Fig. 3. The top elevation of the

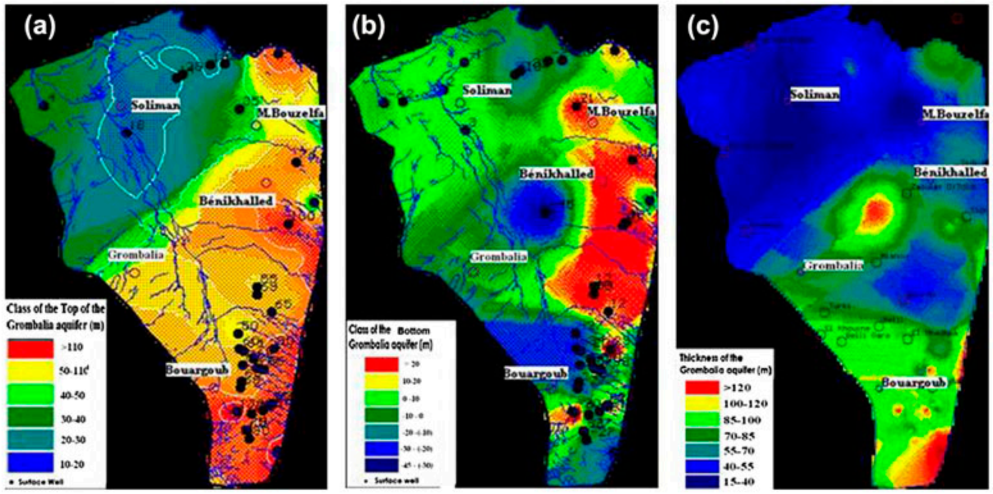

Fig. 3. (a) Top elevation (m) of the Grombalia unconfined aquifer. (b) Bottom elevation (m) of the Grombalia unconfined aquifer. (c) Thickness (m) of the Grombalia unconfined aquifer.

Grombalia aquifer increases towards the south and southeast, reaching a maximum of 110 m in the area of Bou Argoub. The aquifer wall varies between 45 and 20 m, and the depth from 0 to 46 m, reaching 46 m in the eastern part of the aquifer.

The aquifer's hydraulic properties are characterized by significant lateral changes due to the heterogeneity of the lithological facies. The hydraulic conductivity and the transmissivity values range from 5.4×10^{-6} to $6.5 \times 10^{-3}\,m\,s^{-1}$ and from 9.4×10^{-5} to $11.3 \times 10^{-2}\,m^2\,s^{-1}$, respectively [11]. The estimated specific yield ranges from 0.01 to 0.46.

At present (2010), the piezometric level of the aquifer ranges between 0 and 70 masl, being below zero in the estuary area. Flow direction is toward the north.

Over the years, groundwater level has shown a lowering trend, being about 10 m in the region of Belli for the last 50 years, (Fig. 4(a,b)) producing a rise in the fresh water/saltwater interface. A comparison of the 1972 [13] and 1992 [11] piezometric maps (Fig. 4(b, d)) reveals that the zero contour has shifted inland about 2.7 km from the seashore after 20 years. Changes of piezometric maps from 1992 to 2010 (Fig. 4(c,d)) reveal that zero contour (masl) is around 4.2 km inland, being the area extending between the coastal line and the Sebkhat Soliman (costal wetland) delimited by zero contours of $10\,km^2$. The zero contour displacement towards the continent indicates possible changes of the seawater pressure interface.

The Grombalia aquifer is currently exploited by 8,430 shallow wells having depths lower than 40 m; 6,667 surface wells are equipped with submerged pumps and with a water abstraction of $93\,Mm^3$ in 2010 (Fig. 5). The increased exploitation of the aquifer has led to a more or less generalized decrease in the piezometric level, and a progressive and continuous degradation of the chemical quality of groundwater. Groundwater depression cones show negative values (−5 to −10 masl) resulting from local abstraction, and leading local flux towards inland.

The area is under artificial recharge from 33 infiltration basins in three places located between Menzel Bou Zelfa and Béni Khalled (Fig. 1). Recharge water is provided by the local dams (Table 1).

Hydrologic components of the Grombalia water balance are: Wadi's recharge, direct and indirect recharge by dam and stream flow, artificial recharge, evapotranspiration, wells pumping, vertical leakage, and discharge to the sea.

3. Methodology

3.1. Data collection

In order to characterize the subsurface hydrology of the study area, data were obtained from existing field campaigns conducted from 1950 to 2010. Data were provided by the Water Resources Services in Regional Commissariat of Agricultural Development in Nabeul and the National Institute of Research in Rural Engineering of Water and Forestry (INRGREF-Tunisia),

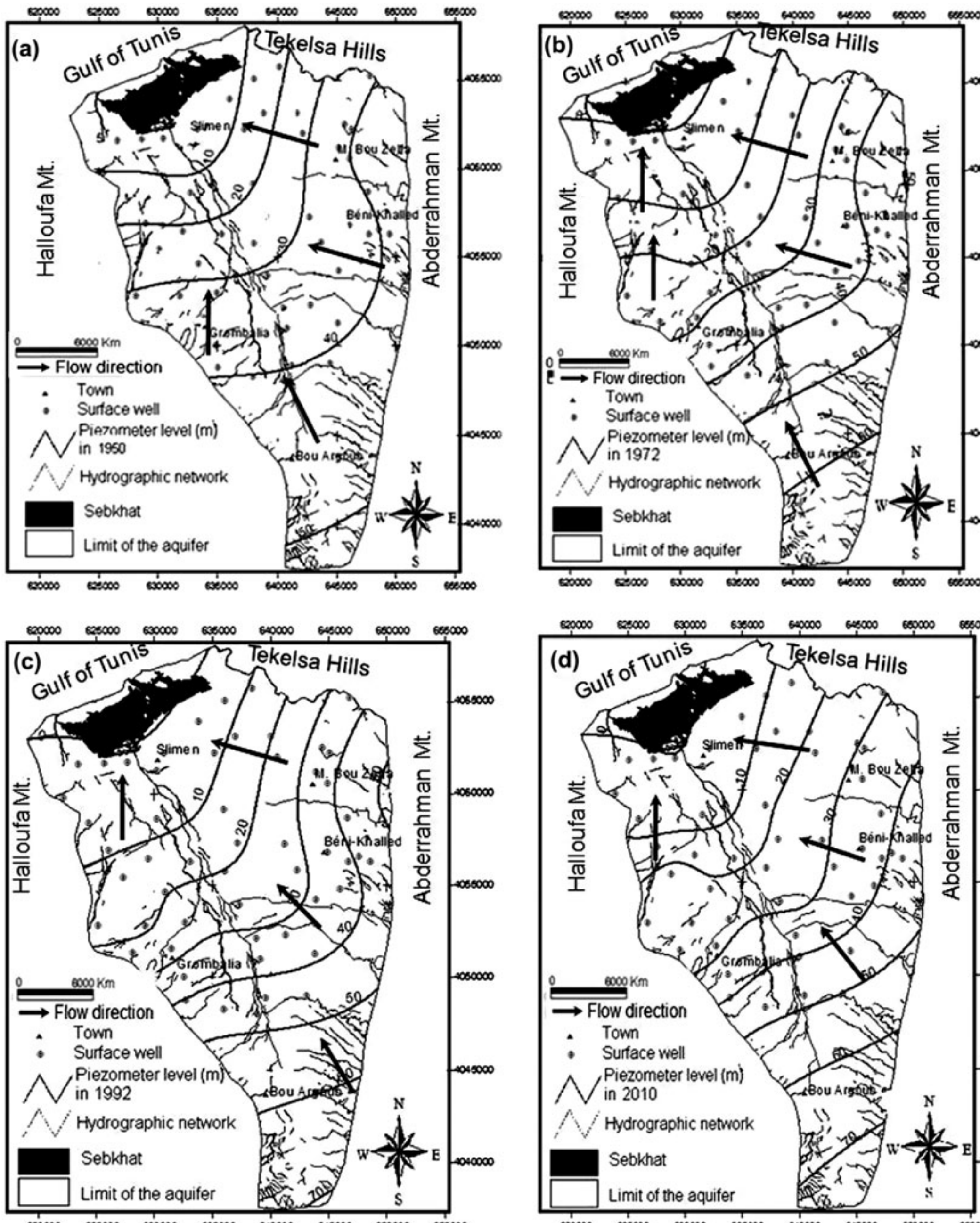

Fig. 4. The Grombalia unconfined aquifer (a) 1950 piezometric map, (b) 1972 piezometric map, (c) 1992 piezometric map, and (d) 2010 piezometric map.

During the 2010 field campaign, groundwater level, water temperature, pH, and electric conductivity was obtained *in situ*.

Aquifer top elevation map was estimated through interpolation of 38 data with geological information based on the inverse Distance Squared method [24]. The aquifer bottom was also obtained by interpolating 47 data points. The aquifer thickness was obtained by the difference between the top and bottom values.

3.2. Modeling approach

The VISUAL MODFLOW 2009.1, based on VISUAL MODFLOW 280 3.0 code, was selected for the numerical simulation. Governing equations for the

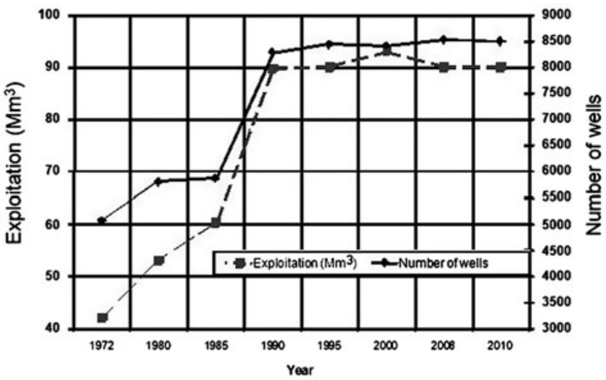

Fig. 5. The Groundwater exploitation and number of wells (1972–2010) in the Grombalia aquifer.

flow problem under saturated conditions can be found in [26]. Visual MODFLOW which includes MODFLOW- 2000 pre/post processor is a commonly used code [28]; version 4.2 was applied in this study.

MODFLOW is a known finite differences numerical code [25] being used for groundwater numerical simulation. MODFLOW has been widely used to simulate groundwater flow system for water supply, containment remediation, mine dewatering, and climate change [26] among others. The MODFLOW consists of a groundwater flow code [27,28], where processes are divided into independent subroutines or modules. These modules are grouped into packages which deal with specific aspects of the simulation [29–32]. The modular structure of the MODFLOW facilitates the development of different packages to freely handle the impacts of boundary conditions, sinks, and sources [33–36].

Over the Grombalia aquifer area, a grid of 154 rows and 104 columns was over imposed with a spacing of 200 m × 200 m, accounting for a total of 9,000 cells (Fig. 6). The upper aquifer was simulated by one layer and run to simulate the piezometric level. One month was chosen as the period within which all hydrological stresses are assumed to be constant. Each stress period included two time steps in order to compare the calculated with the measured groundwater levels.

The top upper limit of the layer corresponds to the top aquifer surface and the lower limit of the layer to the depth thickness. Boundary conditions were based on the 1972 piezometric level observations and aquifer natural boundaries (Fig. 6). Constant head conditions (blue) for layer 1 were defined and based on wall topographic surface; on the lower boundary, no flux-boundary condition was defined. The Mediterranean Sea boundary (brown) was considering constant head condition. No flow condition was considered for the rest of the aquifer boundary (green). The sebkhat is not connected to the regional aquifer (Fig. 6).

Estimates of the natural distributed recharge and irrigation returns assigned to the uppermost active cells were obtained through a soil–water balance.

Hydraulic conductivity obtained from several pumping tests ranges from 4 to 40 m d^{-1}. Final estimates of the hydraulic parameter values were obtained through model calibration based on observed values. For the simulation, the hydraulic conductivity values and the groundwater recharge were imported to the model grid from the corresponding GIS-maps.

Initial condition for simulation was the 1972 piezometric data (Fig. 4(b)). The model was performed in a transient state regime for the 1972–2005 period and the parameters were calibrated using the data from spatially distributed piezometers in the study area. The model validation period was 2005–2010.

The steady state calibration was carried out using the 1972 piezometric values as initial state of the Grombalia aquifer system. For calibration, the hydraulic parameters, mainly transmissivity, were thus decreased at some locations. In addition, hydrological stresses such as the infiltration recharge coefficient were also changed; the coefficient was initially suppressed to assess the effect on computed potential heads. During the calibration process, the storage parameters were automatically estimated using PEST. Modeling with the loosely coupled approach included multiple simulation runs using variable recharge and hydraulic conductivity values.

The transient-state model was validated using the available water level data from the 2005–2010 periods;

Table 1
Evolution of the artificial and natural recharge from 1972 to 2010

Year	1972	1973	1982	1987	1992	1997	2002	2010
Precipitation (mm)	724	408.2	818.9	282.3	425	595.2	355.3	202.9
Natural recharge (mm)	16.9	9.5	19.1	6.6	9.9	13.9	8.3	4.7
Artificial recharge (mm)	50.7	28.6	57.3	19.8	29.8	41.7	24.9	14.2

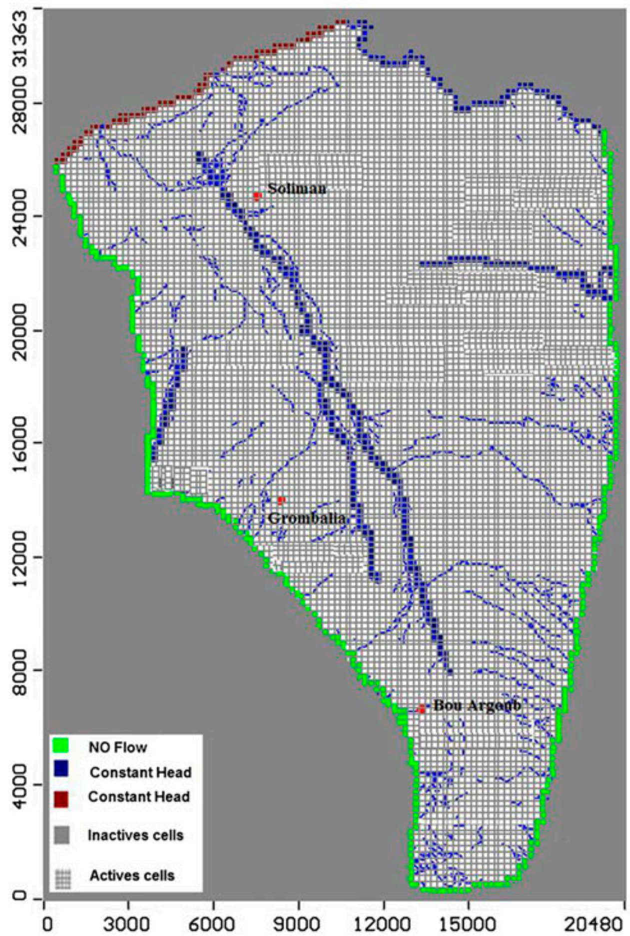

Fig. 6. Finite difference grid indicating boundary conditions of the Grombalia aquifer.

during this period, large seasonal fluctuations in water level occur. In the initial run, the calibration process was mainly focusing on hydrogeological parameters; lateral recharge from upstream at the foothills in the eastern part of the region was not taken into consideration.

3.3. Scenarios definition

Estimated simulations aim to predict the impacts of the current and future exploitation on the hydrodynamic conditions of the aquifer system. Three scenarios for aquifer simulation were proposed based on different exploitation management.

The first scenario considers that the 2010 groundwater abstraction remains constant during the 20 years of simulations up to 2030. We also assumed that artificial recharge volume remains constant.

The second scenario, more realistic, assumes a growing trend of groundwater abstraction around 0.6 Mm^3/year. This estimation was based on the average calculated increase from wells exploitation from 1995 until 2000.

In the third scenario, similar conditions prevailing in the second scenario were considered plus the artificial recharge at the Wadi Sidi Said river bed infiltration ponds, about 10 Mm^3/year.

4. Results and discussion

4.1. Model results

Visual inspection of simulated water level contours at the Grombalia aquifer shows that the model performs rather well and reproduces overall levels to a satisfying degree (Fig. 7). Poor simulated results have been obtained at the southwestern part of the Bou Argoub plain (South of the study area); the lack of data does not allow judging the quality of the calibration. Residuals of simulated observed values vary between 0.64 and 0.76 m. The highest variations are observed in the area of North Soliman (North). The

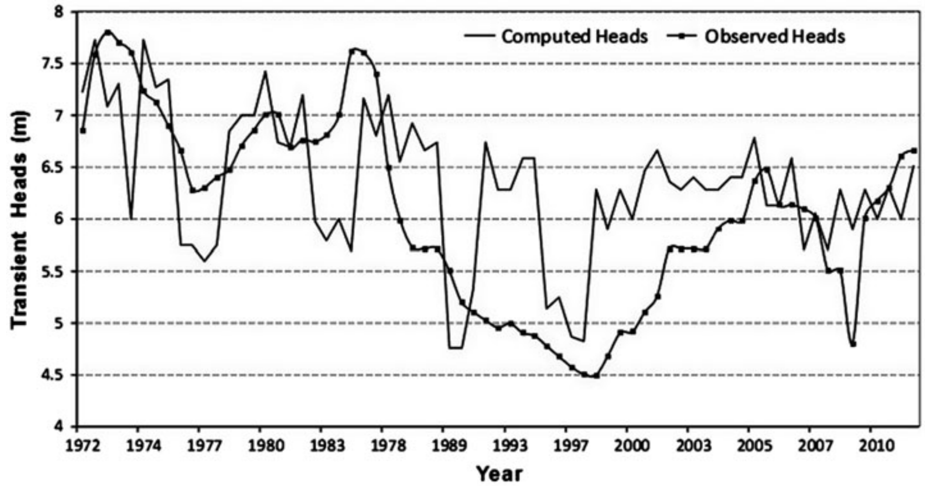

Fig. 7. Transient head levels of the Grombalia aquifer (1972–2010).

Table 2
Water budget of the Grombalia aquifer (1972)

Input (Mm^3/year)		0utput (Mm^3/year)	
Wadi's recharge	7.085	Pumping	41.902
Artificial and natutral recharge[a]	44.324	Drainage by Wadi's	3.645
		Discharge to the Miocene aquifer	6.715
	51.409		52.262

[a]From dam and stream flow.

natural recharge of water by direct rainfall and irrigation was estimated at 50.6 mm/year for 1972 which is 7% of the rainfall. By integrating this quantity over all the water, the flow is 5.9 10^{-5} m^3/s per cell for a total of 16.9 Mm^3/year;

Table 2 shows the steady state water budget at the Grombalia aquifer. Fig. 8 presents the water balance for 2010 (transient simulation) and Fig. 9 changes in water budget for the 1972–2010 period.

4.2. Scenarios' results

Results of the model simulation for the three scenarios are shown in Table 3.

For the first scenario, assuming constant groundwater exploitation of the aquifer, drawdown maps (Fig. 10) shows a clear piezometric level decrease from 0 to 8 m, being the most significant values in northern part of the aquifer. The piezometric maps for the 2015,

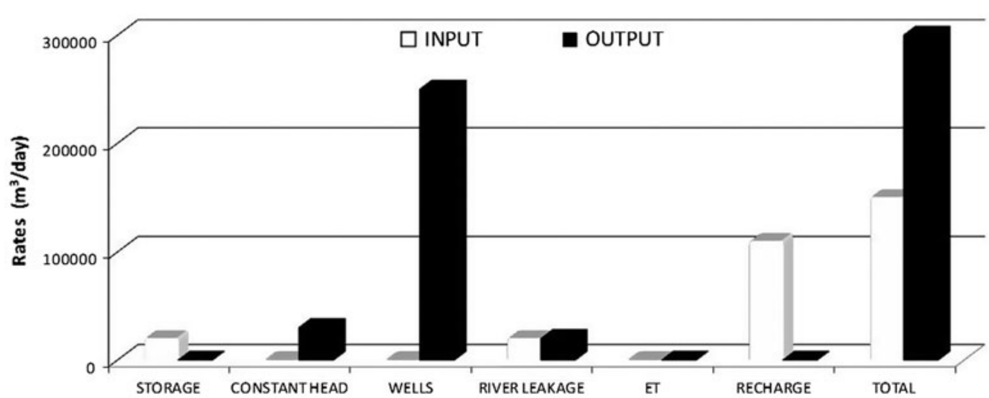

Fig. 8. Water budget of the Grombalia aquifer as computed by the model in 2010.

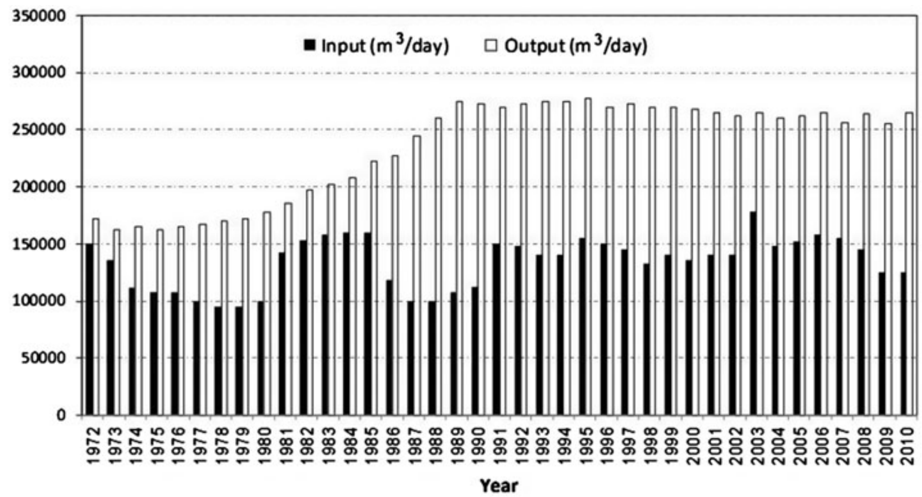

Fig. 9. Time evolution of water budget in the Grombalia aquifer (1972–2010).

Table 3
Result of three simulations

	Scenario 1		Scenario 2		Scenario 3	
	Average drawdown (m)	Output (Mm^3)	Average drawdown (m)	Output (Mm^3)	Average drawdown (m)	Output (Mm^3)
2010	6	8.5	6	8.5	6	9.6
2015	8	8	12	7.3	12	9.5
2020	12	6.5	14	6.8	15	7.6
2030	14	5	16	2.8	17	5.4

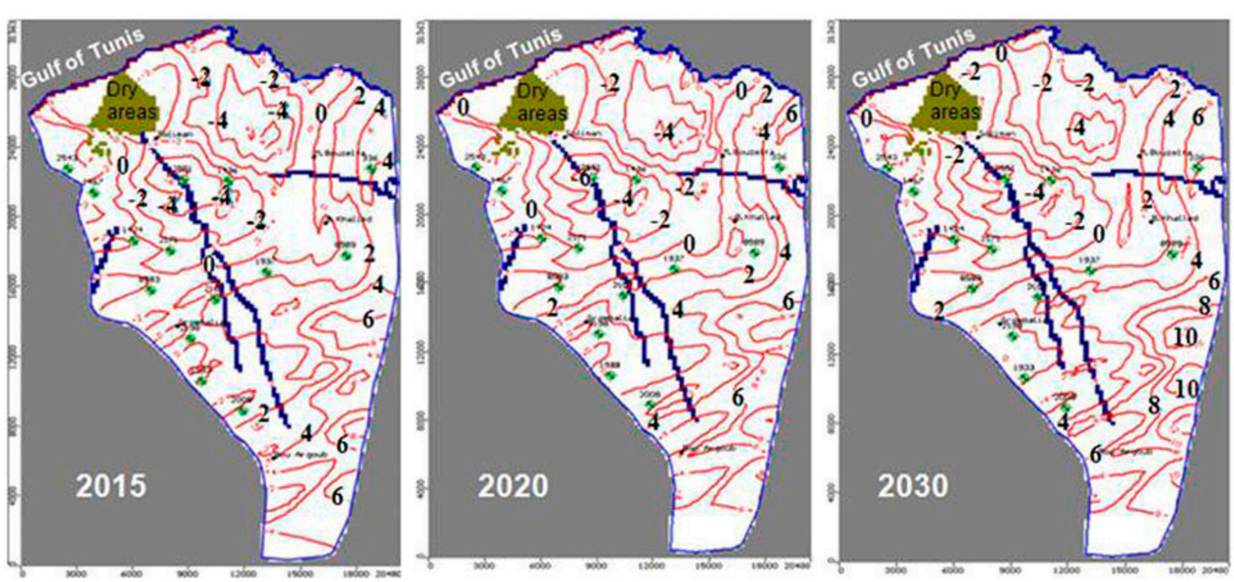

Fig. 10. Simulated hydraulic drawdown (m) for the Scenario 1(a) 2015, (b) 2020, and (c) 2030.

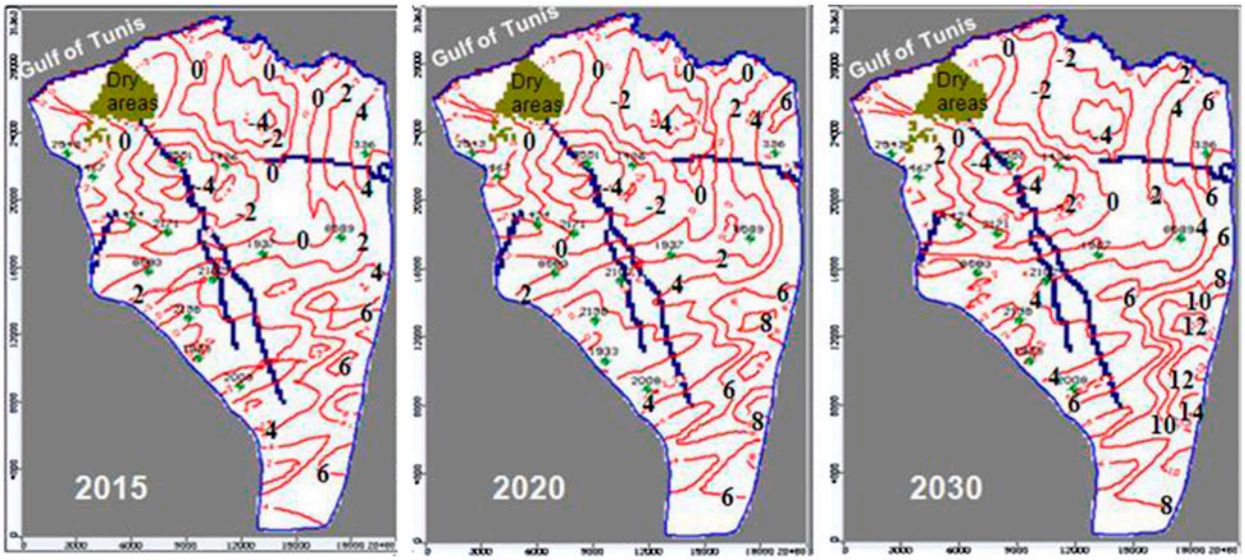

Fig. 11. Simulated hydraulic drawdown (m) for the Scenario 2 (a) 2015, (b) 2020, and (c) 2030.

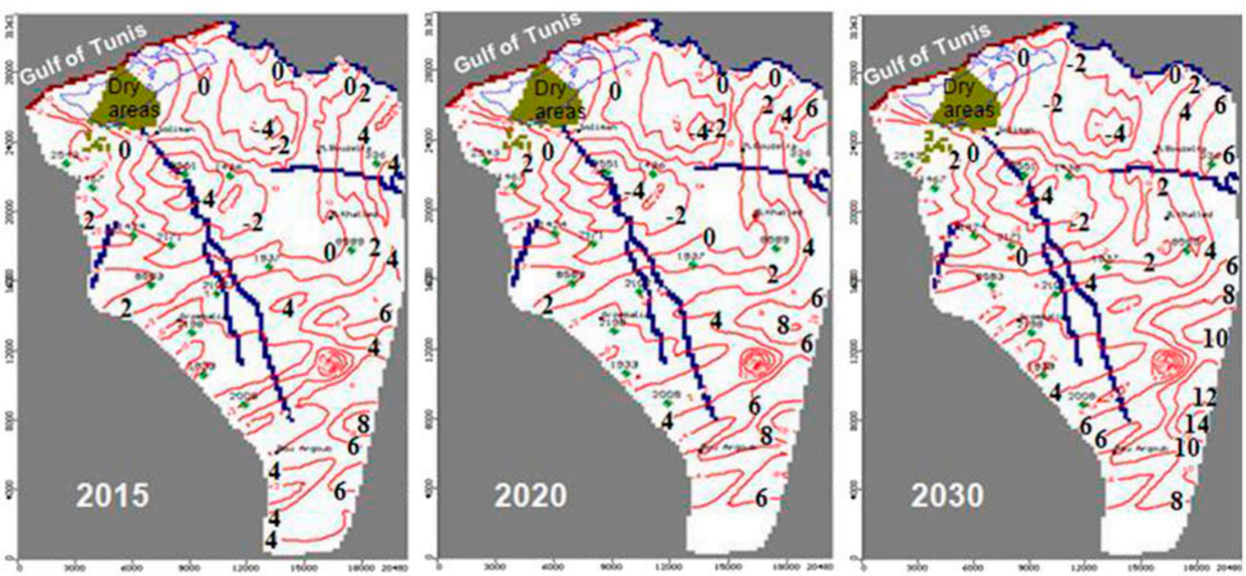

Fig. 12. Simulated hydraulic drawdown (m) for the Scenario 2 (a) 2015, (b) 2020, and (c) 2030.

2020, and 2030 horizons show a downward piezometric trend. As well, from 2010 to 2030, dry cells have been formed at the coastal area. As can be observed in Fig. 1, this area corresponds to the surface extension of the Soliman Sebkhat, which according to model result is directly connected to the aquifer (Table 3). This constitutes one of the findings of the modeling. This situation could also lead to seawater intrusion.

This evolution of hydraulic head translates an overexploitation state and shows the beginning of sea water intrusion to the aquifer.

For the second scenario, simulated drawdown (Fig. 11) values may reach up to 10 m in the central part of the plain, and a reverse of groundwater natural flow. The piezometric maps for 2015, 2020, and 2030 show the effect of the exploitation increase. (Table 3). However, the most significant decrease between 2 and 14 m, being for shallow wells up to 8 m north of Bou Argoub was observed for 2030. The water budget calculated for the aquifer system shows that the recharge remains constant as no changes in precipitation are foreseen; nevertheless, sea water input in the aquifer balance accounts for 3.1 Mm^3/year.

In the third scenario, the results show (Fig. 12) a significant drawdown in the coastal areas and sea water input is particularly observed in the Soliman region.

5. Summary and conclusions

The hydrodynamic conditions for the Grombalia Cap-Bon aquifer flow steady and transient conditions, three temporal horizons, and water resources management were simulated under the VISUAL MODFLOW and three temporal scenarios. Simulated results under steady state and transient conditions show a good agreement between observed and estimated piezometric levels.

Soliman Sebkhat aquifer connection has been currently considered inexistent; however, our modeling result has shown the existing hydrodynamic connection. For all simulated scenarios, the sebkhat will dry in greater or lower extension. Even the obtained good results and model outputs should be improved by new data regarding spatial distribution of exploitation rate and their temporal evolution.

The model was run under the current and future exploitation to predict the impact of groundwater exploitation for 2015, 2020, and 2030. Obtained results highlighted the aquifer vulnerability at the coastal zone and the possible advance of seawater intrusion. This fact needs to be assessed through field campaigns to monitor hydro-chemical parameters, sea aquifer interface, and appropriate numerical modeling and code.

In order to preserve and to ensure a sustainable management of the groundwater resources in the Cap Bon north-eastern Tunisia, it is necessary to set pumping limitations in the coastal areas to delineate suitable plan for future groundwater management and to examine the possibilities of artificial recharge in the most vulnerable area to the marine intrusion.

Acknowledgments

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