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Impacts of climate change on water resources in arid and semi-arid regions: Chaffar Sector, Eastern Tunisia

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ABSTRACT

Global warming is a worldwide phenomenon causing a temperature increase, which affects water resources. In Tunisia, high temperatures were recorded in the last decades with a warming tendency of about 1.1°C for 2020 and 2.1°C for 2050. The Chaffar region is characterized by an important agricultural activity and a semi-arid climate in which the irregular precipitations reach low values. Its shallow groundwater is overexploited with a disturbed hydraulic balance. A drawdown of its piezometric head has been noticed in the last decade because of high exploitation and rainfall deficit as a consequence of global warming. To highlight the impacts of the climatic changes on water resources in the Chaffar region, a mathematical model was prepared using MODFLOW program. It is of great importance to predict and simulate the effects of global warming on hydraulic head of Chaffar shallow aquifer, which is considered as a forbidden area for creating new wells. Considering a constant consumption, the piezometric maps established for 2020 and 2050 show an important drawdown of the hydraulic heads especially downstream the aquifer. It could be even more alarming by 2050 with a probable seawater intrusion.

Keywords: Global warming; Climate change; Piezometric heads simulation; Chaffar aquifer; Water resources

1. Introduction

Being a problem threatening the planet and its ecosystems, the climate change has been considered for a long time as a disturbing topic. The polemic concerning its origin and effects is still a matter of debate between researchers. The planet is going through global increase in the temperature [1,2] of approximately 0.74°C between 1906 and 2005 with a tendency toward an acceleration during the 50 last years [3]. The global warming is related to an intensification of the hydrologic cycle [4] as a direct effect causing a change in the precipitation volume [5–7] and distribution of groundwater recharge. Therefore, quantifying the impact of climate change on groundwater resources

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requires not only reliable forecasting of changes in the major climatic variables, but also accurate estimation of groundwater recharge [8]. Based on different scenarios, previous studies tried to forecast the hydraulic heads of groundwater. A dry scenario implemented on Grote-Nete catchment, Belgium, predict dry conditions for the whole year. Average annual groundwater levels would drop by 0.5 m, with maximum of 3.1 m on the eastern part of the Campine Plateau [9]. A study on the coastal aquifer of Saïdia, northeast Morocco, was based on Scenario A1FI, which is the worst case scenario. It shows a decrease by 2099 in hydraulic heads due to the reduced unsubstantial recharge, which reaches maximum values around 0.9 m at the southern limit of the aquifer [10].

This study aims to highlight the effect of climate change on water resources in Chaffar region, eastern Tunisia, using a simulation based on a well-determined scenario for 2020 and 2050 and forecasting the contribution of average precipitations for these two years combined with the rates of over-exploitation of the aquifer. In order to design the numerical model of the underground water flow of the Chaffar aquifer, "Processing MODFLOW" software was applied.

2. Study area

Chaffar area is a part of eastern Tunisia, 30 km south Sfax city (Fig. 1). It covers a surface of approximately 433 km^2 with a perimeter of about 129 km [11]. It is dominated by the outcrops of Miocene, Pliocene and Quaternary, recognized as well in the middle of the plain as in the reliefs of edge in the North with a developed hydrographical system among it Chaffar Oued which is the most important temporal hydrographic network. This region has an arid/semi-arid climate, with large temperature and rainfall variations. Averages of annual temperature and rainfall are about 19.4˚C and 221.8 mm, respectively.

The average annual temperature (Fig. 2) varies between a maximum of 20.5˚C in 1999 and a minimum of 18.1˚C in 1980 (during the period of 1980–2010). The tendency curve of the temperature for the period 1980–2010 indicates an increase with a coefficient of determination (R^2) of 0.6 and a general slope of 5%. Besides the warming is more significant in the last decade, since its temperature average is higher than the one measured for the period of three decades (1980–2010).

The study area is limited in Northeast by Medass El Hajeb heights and Mio-Pliocene outcrops of Agareb, in the Northwest by Kodiat Lahfaya, in the Southwest by Oued Chaal catchment and in the eastern part by the Mediterranean Sea with a 14 km long coast. As a part of the coastal shallow groundwater of Sfax, Chaffar aquifer is formed by sandy and sandy-clay levels of the Quaternary, separated by semi-permeable sandy base of an average thickness of 20 m.

According to Hajjem [12], the thickness of Chaffar aquifer is about 25 m, with a good permeability. The recharge the aquifer with fresh water is supplied by Chaffar and Mouridj rivers floods [13]. The aquifer depth is between 10 and 14 m [13], though it gets deeper in the southwest and reaches 10.75, while it is only 3.25 in the northeastern part according to the geological cross-section made by CRDA [14] (Fig. 3).

Evapotranspiration, humidity, and infiltration have a great influence on groundwater quality and quantity besides socioeconomic factor through the exploitation (mainly agricultural) and the supply of the aquifer (irrigated perimeters and urban rejections). To make a good estimation of global warming effect on shallow groundwater system of Chaffar, it would be necessary to have sufficient hydraulic and geochemical data. Based on the lithological map, the established permeability map indicates the presence of three different permeable areas: (1) a sandy area located downstream favorable to the infiltration; (2) an area fairly favorable to the infiltration in the centre and upstream, formed especially by the calcareous villafranchian crust and (3) an unfavorable area to the infiltration, extending on the remaining zones (Fig. 4).

The groundwater flow is generally from Northwest to the Mediterranean Sea considered the principal discharge system. Comparing recent situation of the aquifer to 1983 situation, made by Hajjem [12], a general decrease in the groundwater level is noticed especially downstream where negative values are currently noticed.

3. Materials and methods

Predicting water resources variation, as an impact of the global warming, requires a good knowledge of the behavior of the aquifer in normal conditions, without considering the factor of climatic variability but rather checking its recharge and its exploitation as a reference scenario. Indeed, these projections must be calibrated and validated on well-known situations to be able to simulate aquifer behavior in the future, based on the interactions between the catchment area and precipitations. Nevertheless, uncertainties remain probable and could affect the precision of the model because of the anisotropy and the heterogeneity of the original ground [15].

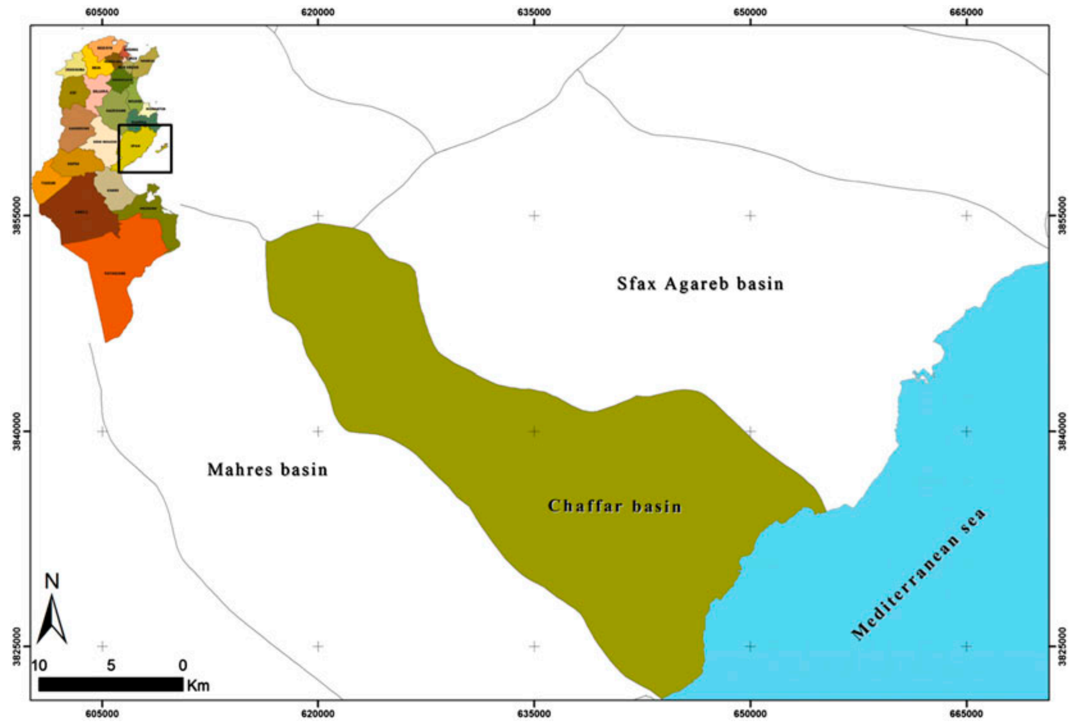

Fig. 1. Location of Chaffar area.

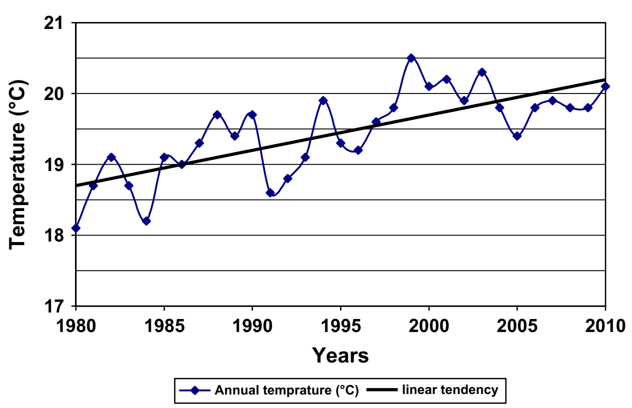

Fig. 2. Variation of annual average temperature in Sfax for 1980–2010.

The present study aims to highlight the effect of global warming on Chaffar shallow unconfined aquifer. The purpose of the numerical model is not to forecast in a precise manner the behavior of the aquifer in such long-term simulations. Instead, it aims to find the main trends in groundwater level and salinity changes [10]. For this reason, it was decided to select a study area with an available data base.

Thematic maps of all factors influencing the groundwater recharge were compiled from the collected data in the initial phase. This step is important, since it gives more hydrogeological details about the geometry, the hydrodynamic characteristics of the aquifer and the groundwater flow direction [16]. Understanding the aquifer behavior is primordial to establish a relevant simulation. For this reason, the thematic maps were established using the Arc view technique and included: (1) the transmissivity (Fig. 5), (2) the aquifer thickness, (3) the topography (Fig. 6), (4) the aquifer bottom, and (5) the exploitation zone (Fig. 7). The database was collected using Arcview as shape files of different components maps. The simulation of the impact of global warming on the aquifer behavior was carried out by MODFLOW software [17] which is a well-known and widely used modular three-dimensional block-centered finite difference code used in layered aquifer systems. MODFLOW is physically based, since it combines Darcy's law and the mass balance for subsurface flow. MODFLOW is able to represent a number of aquifer conditions, including confined, unconfined, leaky, delayed yield, and variably confined/unconfined conditions [18]. It was developed by the US Geologic Survey [19] and first released in 1984, as it is a free software package solving three-dimensional groundwater flow equations [20]. Such models require both geologic and

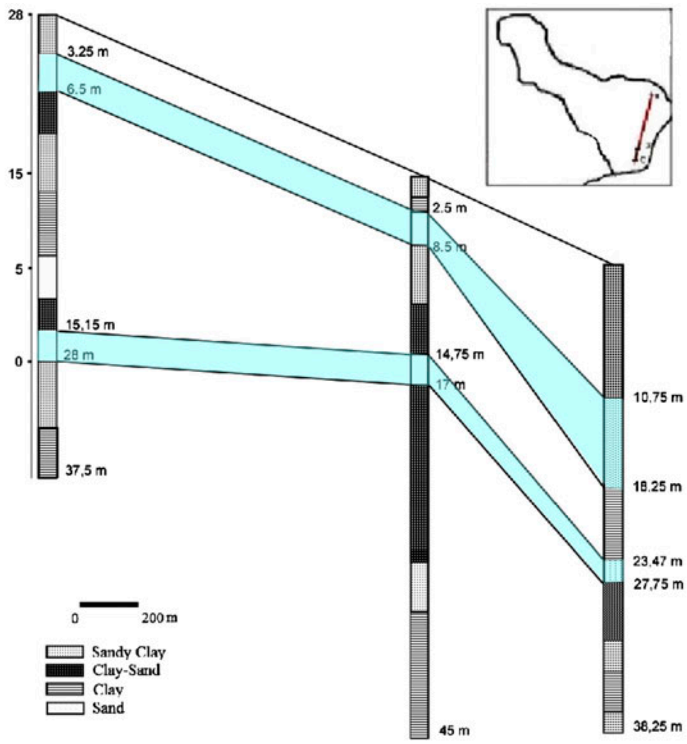

Fig. 3. Correlation cross-section for aquifer water level through Chaffar prospecting drill made by CRDA.

hydrologic data to properly define initial conditions, boundary conditions, hydraulic properties, and possible stresses to the system [21]. This program is (1) applicable to most types of groundwater modeling problems, (2) the original packages in the program are well structured and documented, and (3) the source code is in the public domain and can be checked for errors and modified by anyone with the necessary mathematical and programming skills [22].

The collected data were treated by Arcview software then inserted in Modflow. This step requires a conversion of the map layers shape file extension. shp to .dxf file. These two computer programs suggest to the hydrogeologists a simple and a useful tool in the integration of a great amount of georeferenced data related to groundwater recharge mapping in a hydrogeological model [16].

4. The input scenarios

Due to the global warming, the temperature anomaly in Tunisia has considerably increased with a stronger slope since the 1950s. A National strategy [23] of Tunisian agriculture adaptation and ecosystems to the climate changes developed by the Ministry of Agriculture and the Hydraulic Resources with the support of German Technical collaboration (GTZ). They have modeled Tunisian climate by 2030 and 2050 which required a good choice of projection scenarios to quantify temperature and rainfall variations for each scenario to create a monthly data of regional climate variability and extremes. The choice was based on Tyndall Centre studies which compared several models (CGCM2, CSIROmk2, DOEPCM, and HadCM3) using IPCC scenarios (A1, A1F1, A2, and B2) to select HadCM3 as the most suitable model and A2 and B2 as the most fitting scenarios to Tunisian climate tendency through 1950–2004 period. A2 scenario is one of the most used SRES emissions scenarios [24–28]; it was selected as a reference scenario to study water agro-systems and ecosystems. According to this study, the expected increase in the average temperature in Tunisia is of 1.1˚C in 2020. It is supposed to reach 2.1˚C by 2050. A general drawdown trend in average rainfall will be moderate in 2020 with a 7.5% decrease but expected to witness a decrease of 20% by 2050 [23]. According to the scenario of this strategy related to the study area, a decrease in 6% in annual rainfall is expected by 2020. Whereas the temperature decrease would be about 15% in 2050. This scenario is implemented to the numerical model.

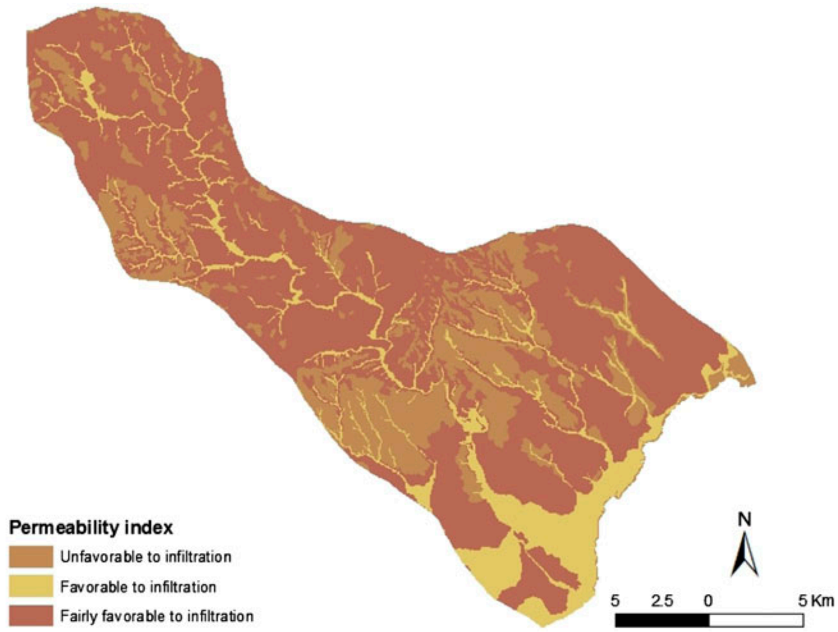

Fig. 4. Permeability index of Chaffar basin [14].

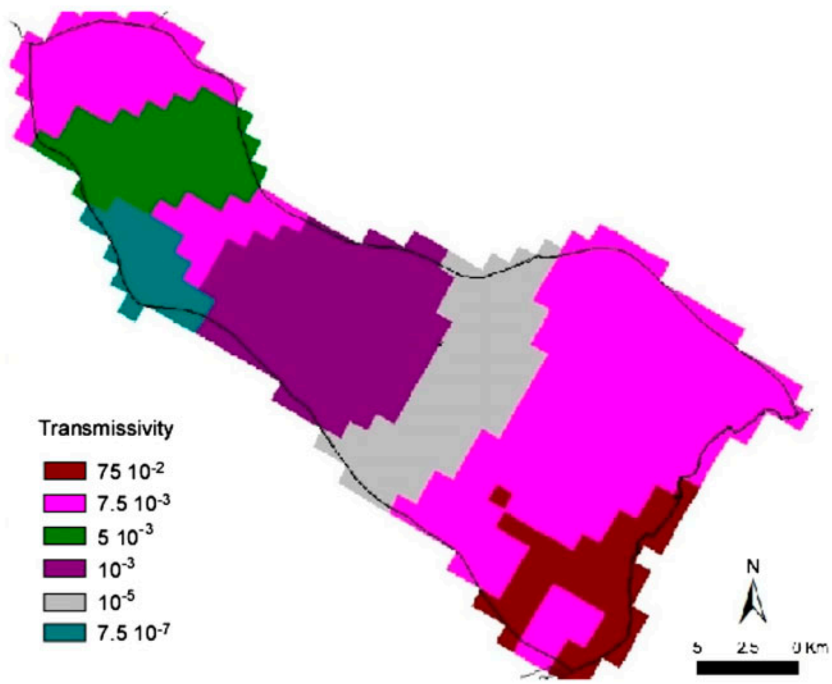

Fig. 5. Chaffar aquifer transmissivity map.

5. Numerical model

Certain conditions called "boundary conditions" should be imposed by the limits of the field in order to provide a possible solution of a physical problem, such as liquid flow [29]. Thus, for the studied aquifer, imposed potentials corresponding to the limits of the catchment upstream and coastal limits are assigned to peripheral cells. Imposed flow rates are attributed to all the internal cells, including recharge areas where infiltration of rain water is important as well as

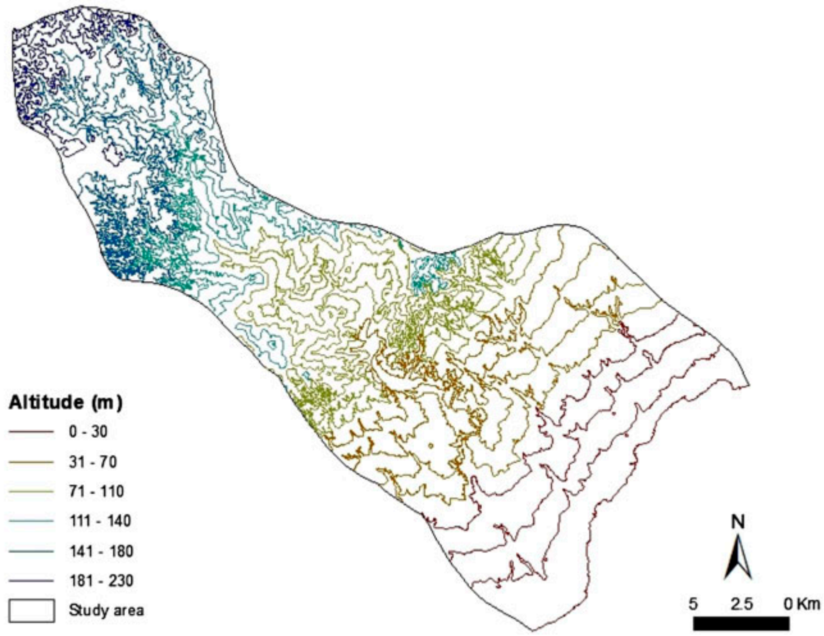

Fig. 6. Chaffar aquifer topography map [14].

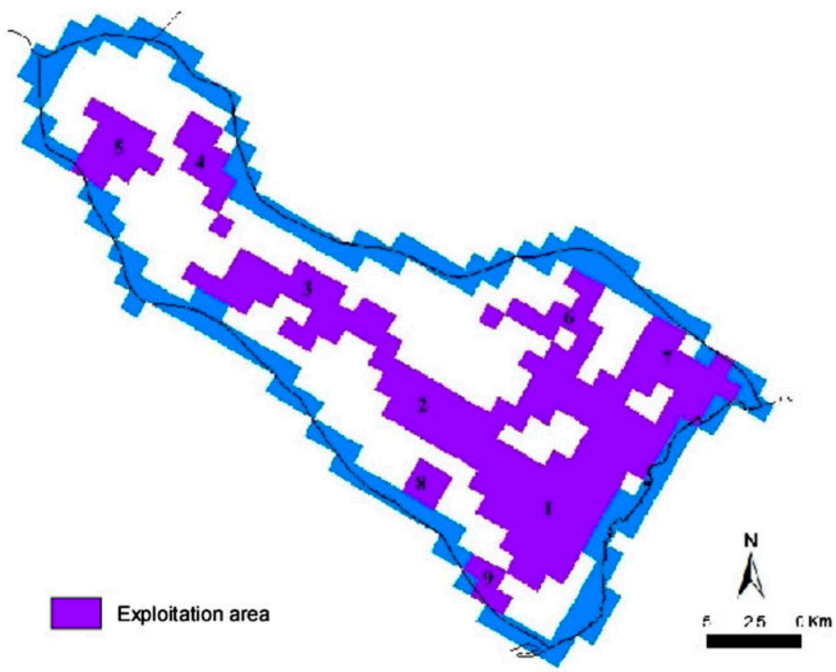

Fig. 7. Chaffar aquifer exploitation zone.

sampling areas defined by the exploitation of shallow wells exploiting the ground water.

Since the year 1983 was marked by a balanced water budget and lower exploitation, the aquifer level during this year was chosen as a steady state. Hydraulic and geometric properties are the principal inputs in the model after the boundary conditions. Transmissivity, which depends on permeability [14] and aquifer thickness, is also taken into consideration. Thus, eight areas are noticed in the Transmissivity map, each one of them is characterized by an average value related to the ground lithology as well as the aquifer geometry.

Recharge areas are defined considering the effective infiltration characteristics measured using Fersi formula:

$$I_1 = \frac{5 \times P}{100} - 3.4 \quad (1)$$

$$I_2 = \frac{2.5 \times P}{100} - 4.6 \quad (2)$$

where I_1: effective infiltration for favorable to the infiltration area (mm); I_2: effective infiltration for fairly favorable to the infiltration area (mm); P: average annual rainfall (mm).

In 1983, exploitation was $1.45 \times 10^6\,m^3$ equivalent to $0.046\,m^3/s$ [12], outflow rate is not attributed to the whole aquifer. It should be distributed according to the number of shallow wells. Therefore, this rate was subdivided in eight exploitation areas depending on the percentage of shallow wells.

For calibration, the behavior of the numerical model should converge to the behavior of the mathematical model to ensure that the discrete equation is representative of the original equation. The first test of calibration showed a large discrepancy downstream requiring an adjustment of transmissivity values (Fig. 8). The second test had an acceptable variance of 5.76%. As shown in the scatter diagram, since simulated piezometric heads were similar to measured ones (Figs. 9 and 10). However, a slight shift remained downstream the aquifer. This shift is especially noticed at the southwestern part of the 50 m curve. In spite of the corrections, this part continues to be an anomaly area. This is probably due to the lenticular nature of the aquifer, which has necessarily, an influence on the hydraulic parameters.

The transient state is a major step to set the model. It is used essentially to validate the steady state and to follow the evolution of the groundwater. The morphological and lithological inputs are maintained constant. Therefore, the validation is made for 2006. Two factors are included to these inputs: the specific storage and the artificial recharge through irrigation zones (Fig. 11) besides the exploitation and natural recharge during 2006.

Though the anomaly reported for the 0 m curve, which is probably related to the intense exploitation downstream, the simulation for the transient state closely fits the real situation with a good variance of 9.23% in Scatter diagram (Fig. 12).

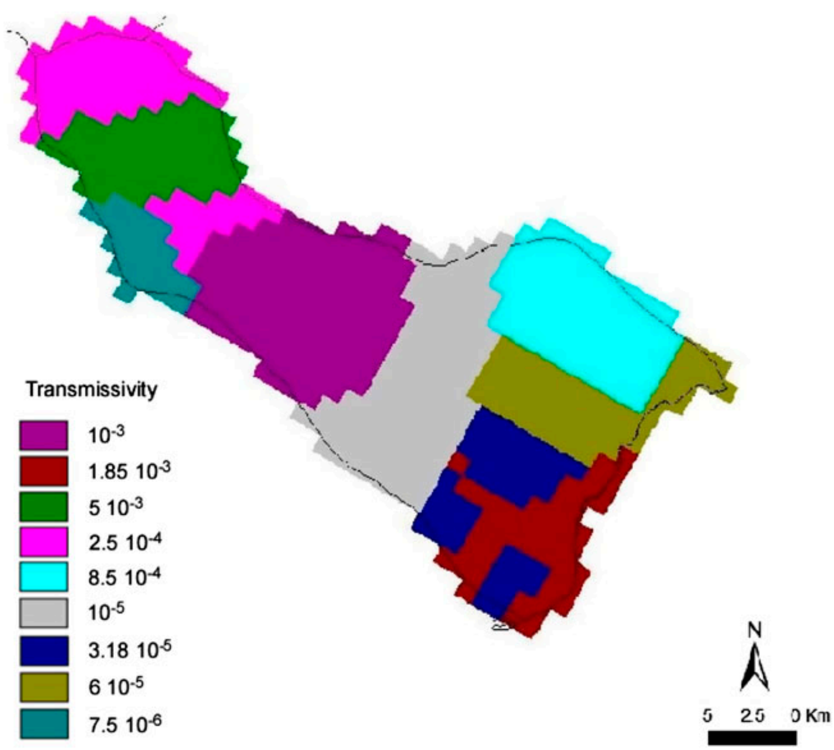

Fig. 8. Chaffar aquifer calibration transmissivity.

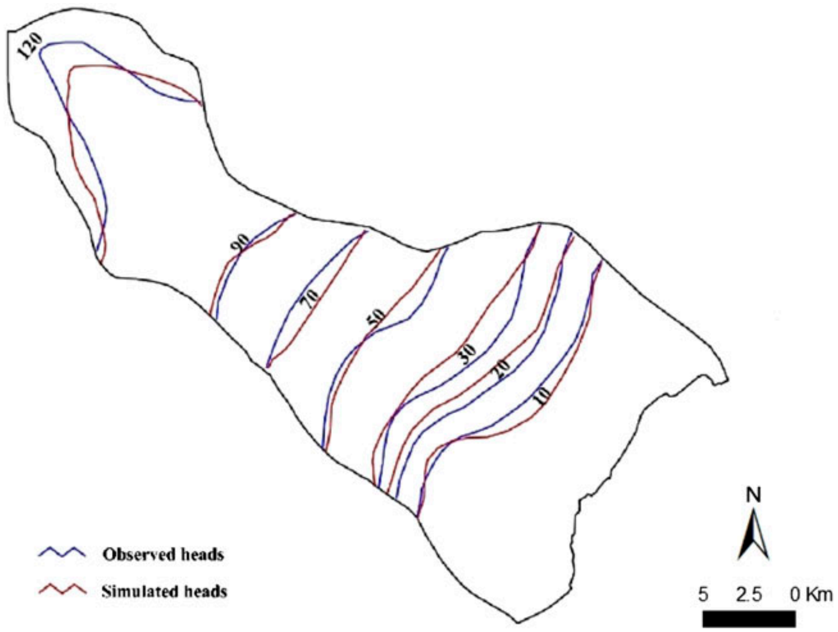

Fig. 9. Observed and simulated heads: steady state (1983).

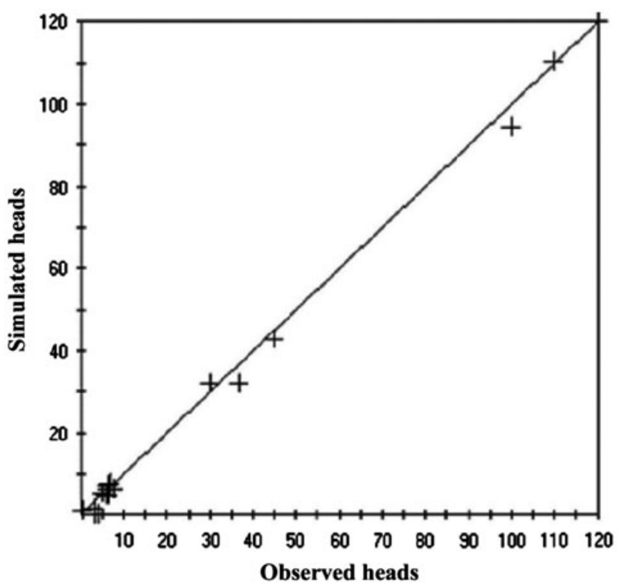

Fig. 10. Scatter diagram for observed and simulated heads: steady state (1983).

6. Results and discussion

The first scenario is for 2020 where the precipitation will discreet by almost 6%. This variation is assigned to the value of the average annual precipitation. Thus, a rainfall average of 208.5 mm is expected in 2020.

The Chaffar aquifer is a protected water table, since the total number of shallow wells is 1,435, and it is invariant from 2007 until 2010 [14]. Hence, in this case, exploitation will be maintained constant. Subsequently, the recharge would be the only variable among the transient state and the simulation.

The hydraulic heads simulated by MODFLOW for 2020 (Fig. 13) show a similarity with the aquifer level in 2010 in the upstream. Reversely, the downstream zone would be prone to a decrease in piezometric heads illustrated by a shift upstream with a drawdown of 10 m. Compared to the shift of the southwestern part, this shift is considered small in El Hajeb area, where we find the irrigated areas.

The second scenario is established for 2050 where the average annual precipitations would decrease by almost 15% with an expected rainfall about 188.57 mm. The consumption is kept constant associated with a recharge variation.

The hydraulic heads simulated for 2050 (Fig. 14) show an overall decrease across the aquifer. It is slight in the upstream, medium in the center and severe downstream. The curve of 0 m, expected in 2050, is slightly close to the current curve of 30 m. The drawdown would be about 30 m. Even the recharge areas are likely to lower their hydraulic heads, although it would be less obvious comparing to the central and Southwestern areas. The flow direction of the shallow groundwater would present a remarkable convergence towards the exploitation areas.

The numerical model applied to the shallow groundwater was used to simulate the behavior of its piezometric heads for 2020 and 2050. In both scenarios, and in order to determine the effect of climate

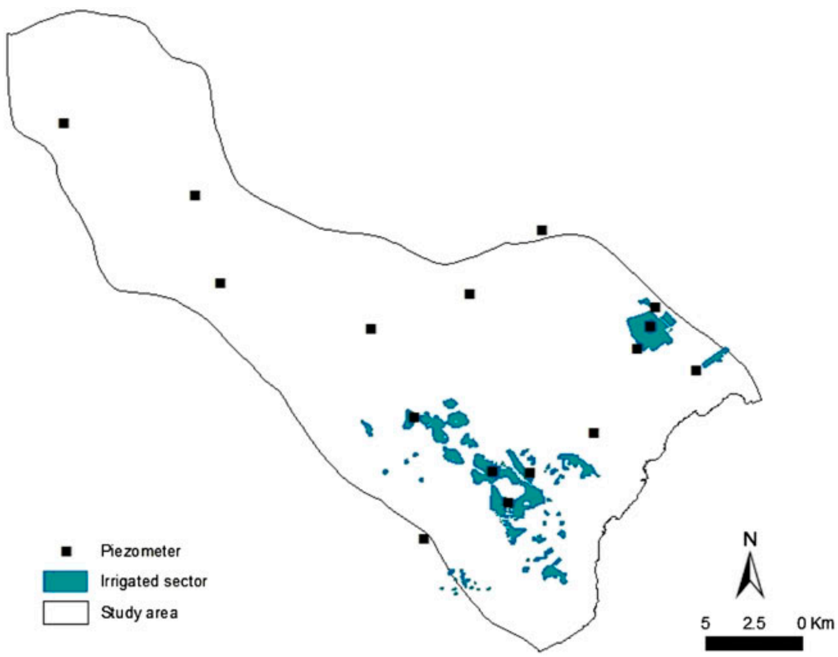

Fig. 11. Localization of irrigation zones [14].

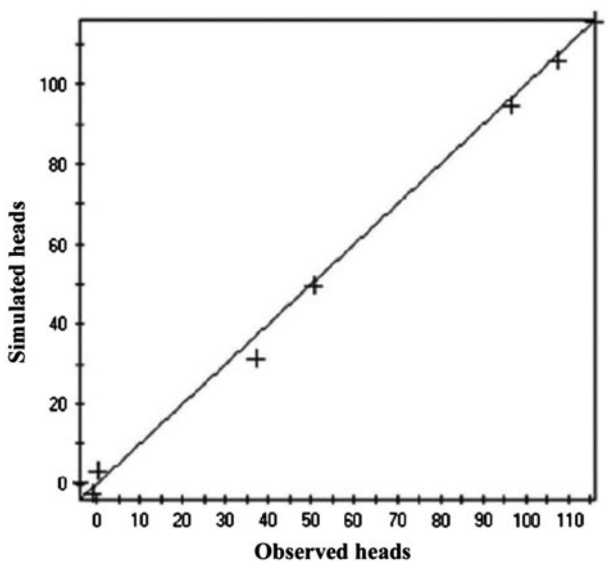

Fig. 12. Scatter diagram for observed and simulated heads: transient state (2006).

change through an increase in temperature and a decrease in rainfall, it was considered that the natural and artificial recharge areas are the only variable. Accordingly, only one case was produced with a constant exploitation, since Chaffar groundwater is protected as it is forbidden to drill new shallow wells.

The decrease in precipitation expected for the year 2020 and 2050 would affect the groundwater by a general drawdown that would be about 30 m downstream by 2050. Taking into consideration the growing demand of the agricultural sector, a scenario recombining impact of overexploitation and climate change, the drawdown would greatly exceed the 30 m in 2050. Therefore, several cases could be established according to these two scenarios with a variation of exploitation and artificial recharge, which could partially compensate the effect of intense exploitation and reduction of rainfall contributions.

However, considering the increase in exploitation by 2020 and 2050, the situation may further deteriorate and groundwater drawdown of the level would be even more obvious. Therefore, it is recommended to add more hydraulic structures of artificial supplying and to arrange Chaffar catchment, by water and soil conservation structures, to increase groundwater recharge and compensate for the uncontrolled exploitation.

The hydraulic heads variation is minor upstream the aquifer. This may be explained by the input distribution in this zone, such as the reduced number of piezometer. In addition, due to the absence of accurate data and sufficient values of transmissivity which is the main parameter during all phases of this numerical model, the simulated maps need to be improved by additional data. Thus, it is recommended to make new boreholes or piezometers especially in the upstream part of the aquifer. And, even if a model is considered acceptable, predictions based on that

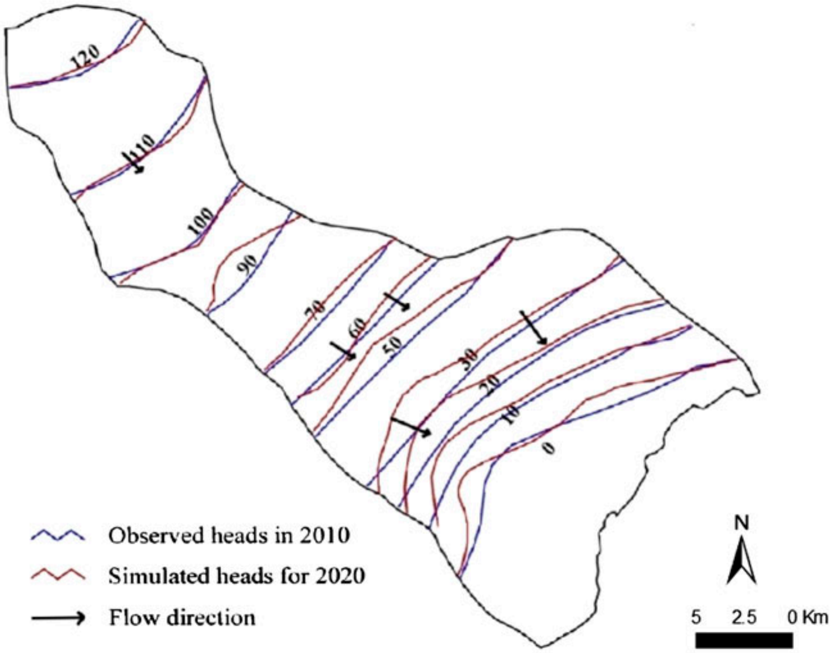

Fig. 13. Simulation of hydraulic heads in Chaffar aquifer for 2020.

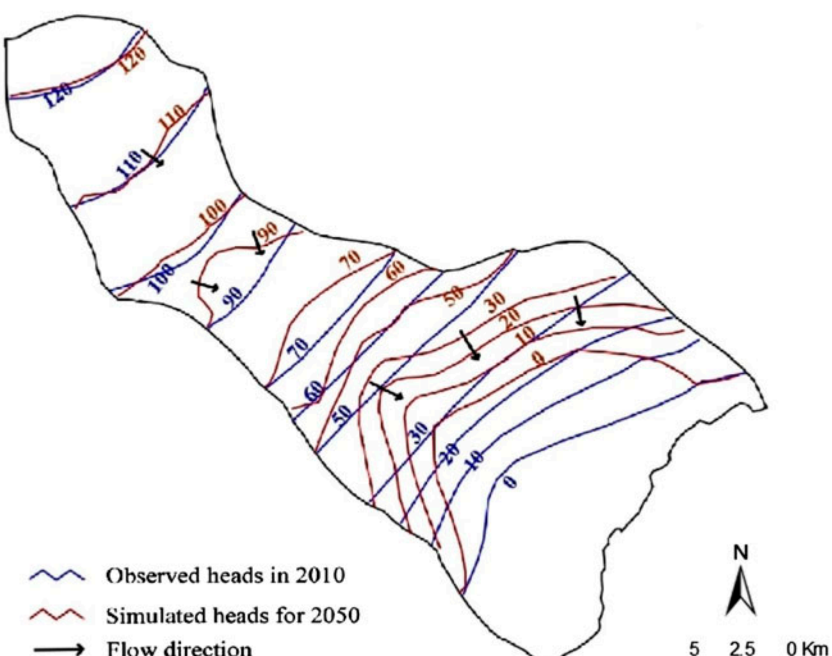

Fig. 14. Simulation of hydraulic heads in Chaffar aquifer for 2050.

model are subject to uncertainty because rarely, if ever, can all model parameters be determined with sufficient degree of accuracy as to eliminate any uncertainty in model predictions [30].

7. Conclusions

The last decade was the hottest, since the first thermal recordings in the history of Tunisia with a warming tendency of 1.1°C at the horizon of 2020 and

2.1°C in 2050. The established piezometric maps, using MODFLOW program, show a general drawdown of the aquifer level especially downstream where the shortage would be noticeable. This drawdown would be more alarming in 2050: the sea would gain on the continent. Since the study area is an area of prohibition for new wells creation, these simulated results are obtained considering a constant consumption.

However, if we consider an increasing consumption in 2020 and 2050, the situation would be darker and the drawdown of the hydraulic heads of the aquifer would be even more obvious. For that, we recommend to add more artificial recharge structures to increase the recharge of the groundwater and to compensate for the anarchistic exploitation as well as to reduce the rainfall deficit in the area.

The simulated piezometric heads show that the variations are especially observed in the downstream. However, the upstream shows a light piezometric amendment. This could be explained by the lack of inputs in this part compared with the downstream part due to the lack of piezometers upstream and this generates a bad distribution of the data. In addition, due to the lack of precise and sufficient data of the transmissivity, the main parameter during all the stages of this model, and the negligence of the communications with other aquifers (boundary conditions), the simulated cards deserve to be improved by complementary data. Thus, the realization of new drillings or piezometers especially in the upstream is recommended.

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