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Modeling the Impacts of Climate Change on the Aquifers in Morocco

Abdelkader Larabi, Mohamed Jalal Elhamidi, Mohamed Faouzi and Ilias Bouaamlat

Regional Water Center of Maghreb, LIMEN-EMI, Mohammed V University, Rabat, Morocco

Abstract: Water resources in Morocco are recognized to be upon the most important water resources suffering from scarcity due to arid and semi-arid conditions, aggravated by global climatic changes occurring worldwide. More than 9.5 million people are living in the coastal cities of Morocco and this number is steadily growing. Indeed, in 2015 more than 50% of total population is living in the coastal zone, with an increasing proportion of rural population due to poverty and rural exodus. This situation makes more pressure on many coastal aquifers leading to salinization in the coastal fringe in some catchments in Morocco. These aquifers are located in North-West part of Morocco and are very well known for their role in industrial, economic and social development. Furthermore, in arid areas in the south of the country, groundwater is the only resource that supplies the rural population and the oasis with water for domestic consumption and irrigation. The average of rain decline is due to the impacts of climate change (CC) and causes the recurrent droughts and decreases in recharge, which directly affect the groundwater level. This is coupled with heavy abstraction rates that are used for industrial and drinking water supply for rural and urban areas and irrigation. This situation has led to a major decline in the groundwater levels and may eventually cause a deficit water balance of the aquifer as well as a degradation of the freshwater quality by seawater intrusion on the coastal plains. Hence, effective management of groundwater resources in these aquifer systems is necessary and taking into account the CC. It can be made by developing a regional groundwater flow model that allows us to understand the conditions that govern the behavior of freshwater/saltwater transition zone in the coastal aquifer subject to the various input conditions and to test management scenarios based on various economic assumptions. These tools help the regional water resources authorities for planning economic and water resources development.

Key words: Global climate changes · Recurrent droughts · Groundwater levels · Seawater intrusion · Groundwater flow model · Management scenarios

INTRODUCTION

Morocco is one of the most important physical water resources scarcity due to arid and semi-arid conditions in the world (Fig. 1); it experiences highly variable rainfall and recurrent droughts. The limited water resources are threatened by increasing demands and accelerated quality degradation. In worldwide, the Intergovernmental Panel on Climate Change (IPCC) predicts in its 4th Assessment Report a major contrast between a period when our civilizations have developed, a stable period in terms of climate. Hence, it is described by three parameters that are three greenhouse gases (Fig. 2): CO_2, methane and nitrous oxide. This paper reviews the existing results and literature on the impacts of CC on water resources and also in some other areas in Morocco, followed by two Moroccan case studies.

In 10,000 years, the time when our civilizations have developed, while a very warm period in the history of the planet, these gases have changed little. And at the end of this period, there was then very quick growth of the gas concentration (according to the IPCC report) and these is associated with the beginning industrial era. In fact, it is in a development system which is more recent. As shown by the small grey boxes of Fig. 2 is that the increase in greenhouse gases, it is in fact happened after the Second World War.

The year 2015 was - by far - the hottest in modern history since measurements began in 1880 (and probably the year 2016?). The *National Oceanic and Atmospheric Administration* (NOAA) and the *National Aeronautics and Space Administration* (NASA) which take both the register of global temperatures, have jointly confirmed. The average global temperature across land and ocean

Corresponding Author: Abdelkader Larabi, Regional Water Center of Maghreb, LIMEN-EMI, Mohammed V University, Rabat, Morocco.

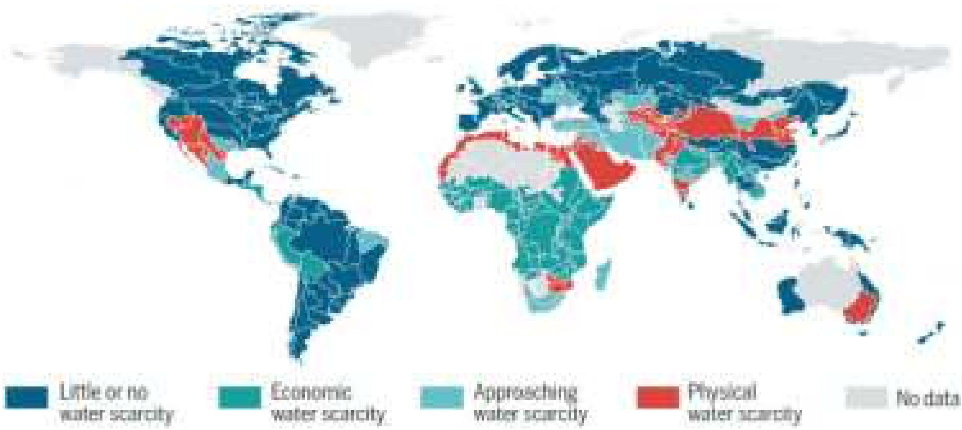

Fig. 1: Areas of physical and economic water scarcity in the world showing Morocco in the north west of Africa [1]

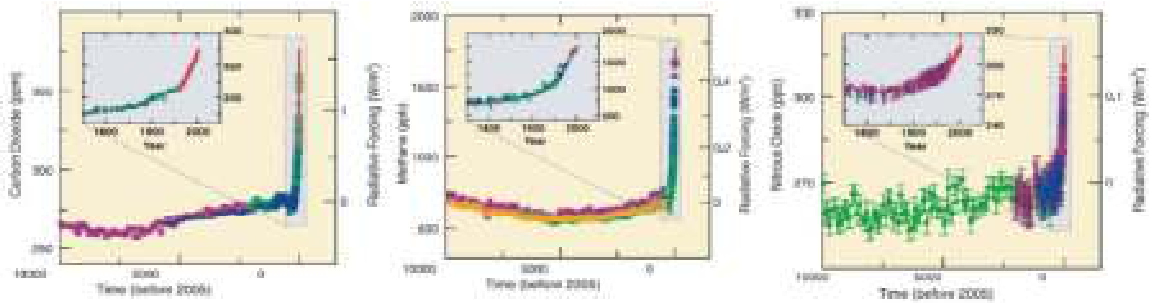

Fig. 2: Atmospheric concentrations of CO_2, CH_4 and N_2Oover the last 10,000 years (large panels) and since 1750 (inset panels) [2]

surface areas for 2015 was 0.90 degree Celsius above the 20th century average, beating the previous record warmth of 2014 by 0.16°C.

Africa is the least responsible continent of the CC, but the most vulnerable to its effects; In addition, the IPCC predicts in its 4th Assessment Report that "*Annual rainfall is likely to decrease in much of Mediterranean Africa and northern Sahara, with the likelihood of a decrease in rainfall increasing as the Mediterranean coast is approached*" [3].

Precipitation of North Africa is characterized by a wet season in winter and dry conditions in summer. The rainy season, which starts in October and lasts until April, has its maximum in the months from December to February [4, 5]. Additionally, the whole region is characterized by high inter-annual precipitation variability. Thus, long-term mean precipitation, especially in the southern region of North Africa, reflects averages over many dry years and some relatively humid years.

Methodology: The methodology is based on analyzing some time series data regarding some areas in Morocco that show the trends of precipitation, temperature and groundwater levels due to CC. The paper also describes the impacts of the CC on water resources in 2 selected case studies based on a 3D groundwater flow models we developed.

Climate Change in Morocco: Statistical downscaling assessments using ECHAM4/OPYC3 predictors of precipitation for a region covering the western parts of Northern Africa shows rainfall increases in December/January of up to about 60 mm in the period 2071–2100 compared to the time period 1990–2019 (Fig. 3a). The results are based on assessments of precipitation changes under the SRES B2 scenario assumptions using a statistical downscaling technique (canonical correlation analysis) [6]. The Souss Massa catchment located in the south of Morocco is a good example to show combined impacts of CC and human activities on groundwater resources [7]. Indeed, Fig. 3b shows a seasonal variability of precipitation with a clear decrease over the last 3 decades, while Fig. 3c illustrates an increase of temperature. As a result, groundwater level in the aquifer is continuing to decrease (Fig. 3d) and making the water availability in this area lower than the national rate (Fig. 3e).

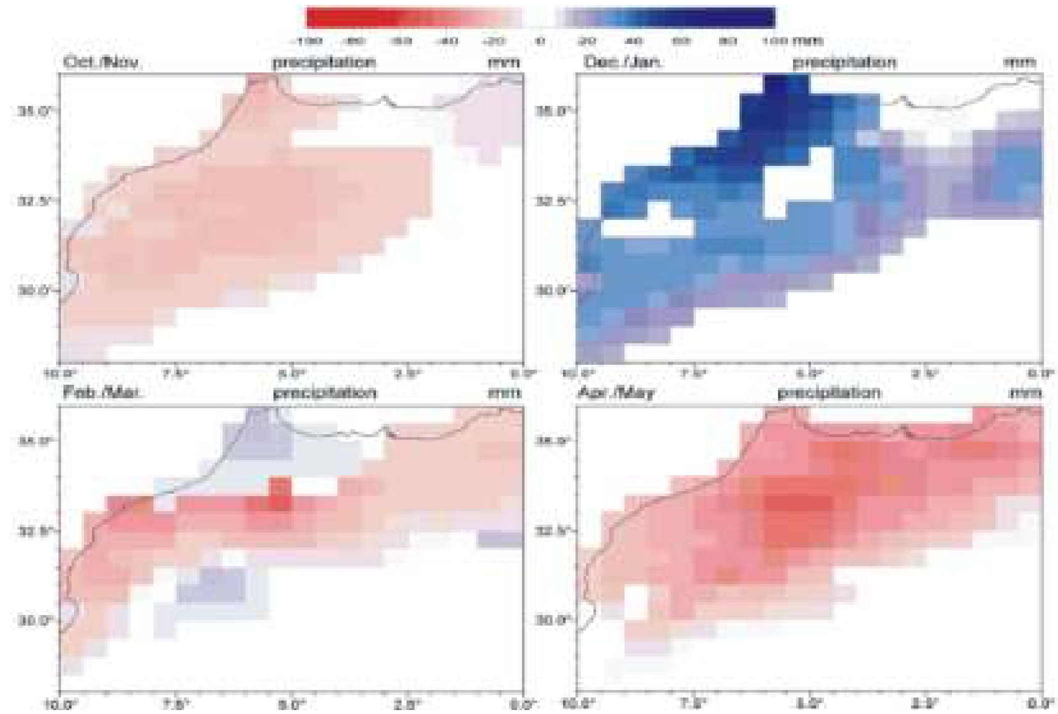

Fig. 3a: Changes of Mediterranean precipitation for the main rainy season from October to May. Differences of the mean 2-month precipitation between the periods 2071–2100 and 1990–2019 in mm. [6]

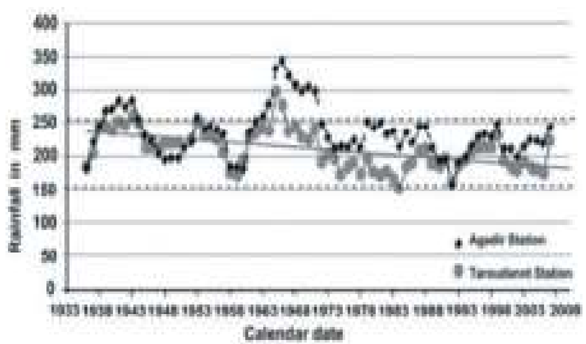

Fig. 3b: Monthly variation of precipitation in two mains stations (Agadir and Taroudant) in Souss-Massa basin.

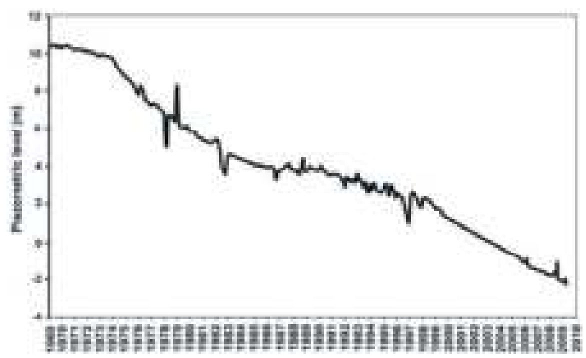

Fig. 3d: Decrease in water table during the last decades obtained from monitoring of a representative well located in the middle of the Souss-aquifer.

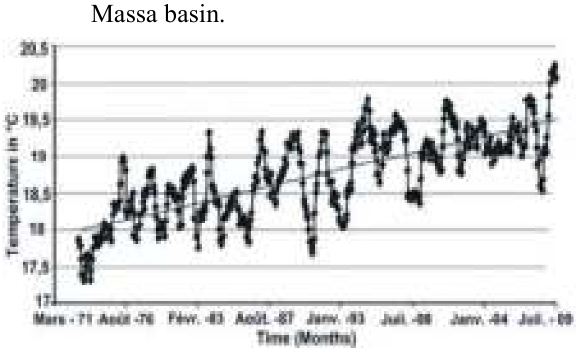

Fig. 3c: Seasonal variation of the monthly temperature in Agadir station: moving average.

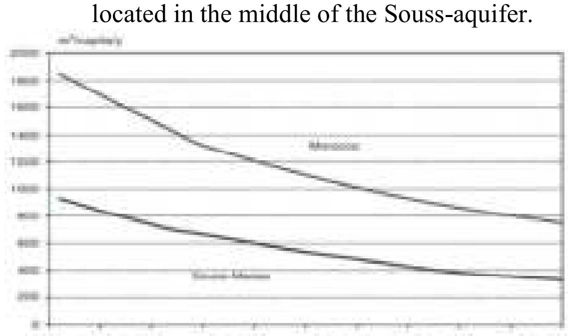

Fig. 3e: scenarios evolution of water availability in Morocco and in Souss-Massa region.

Modeling the Impacts of CC on 2 Local Case Studies: 2 case studies have been selected to assess water resources and to examine: (i) whether any trends can be identified from observed rainfall and temperature data in the region and how can be related to CC. More specifically, what impacts these changes will have on recharge; and (ii) what are the role of human activities on CC and its impacts on groundwater resources in these areas. More specifically, heavy abstraction rates and what impacts these changes will have on groundwater level and water quality. One case study is a coastal aquifer located in the north west of Morocco and the second is an oasis located in the south of the country.

The 2 aquifers have been modelled using a 3D Geoscientific Information Systems (3D SIGS) based on the available data. The conceptual models regarding the 2 aquifers have been also designed and 3D mathematical flow models in steady state and transient flow and transport of pollutants, including seawater intrusion have been developed [8].

RESULTS AND DISCUSSIONS

Case 1 - Rmel-O. Ogbane aquifer: It extends over an area around 303 km^2 and bordures the Atlantic Ocean to the West by the salty bevel, over a 20 Km band. The annual average rainfall in the Loukkos basin reaches more than 1000 mm in the 60th and decline to 500 mm/y in 2014. The seasonal variation using 12-month moving average, the monthly values indicate a decrease over the last five decades after the most important intensity during the 1960's. The variation shows a clear seasonal irregularity (Fig. 4a). The monthly values of the temperature in the Loukkos basin indicate an increase during the last three decades since the 1976's (Fig. 4b). The impact of CC in the Loukkos basin cause the recurrent droughts and decreases in recharge (Fig. 5) directly affect the groundwater level.

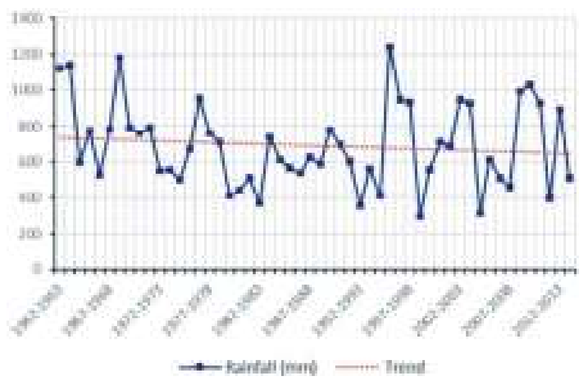

Fig. 4a: Monthly variation of precipitation (1963 – 2014) in Larache station in the Loukkos basin.

Fig. 4b: Monthly variation of temperature (1977 – 2000) in Larache station in the Loukkos basin.

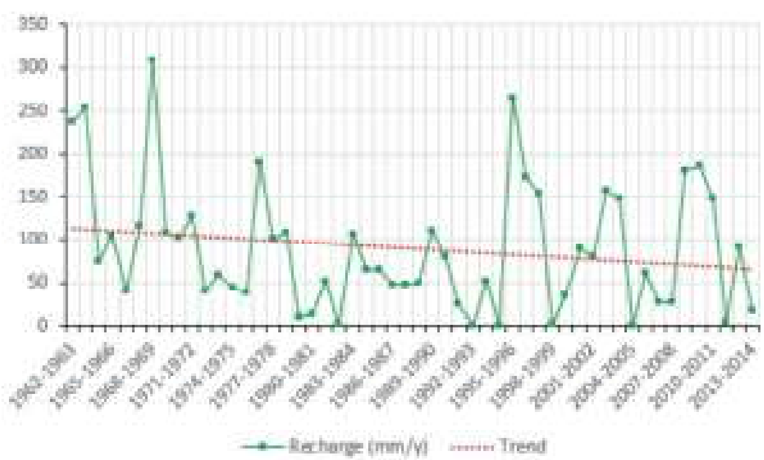

Fig. 5: Monthly variation of natural recharge of Rmel-O. Ogbane aquifer calculated by Thornthwaite method (1948).

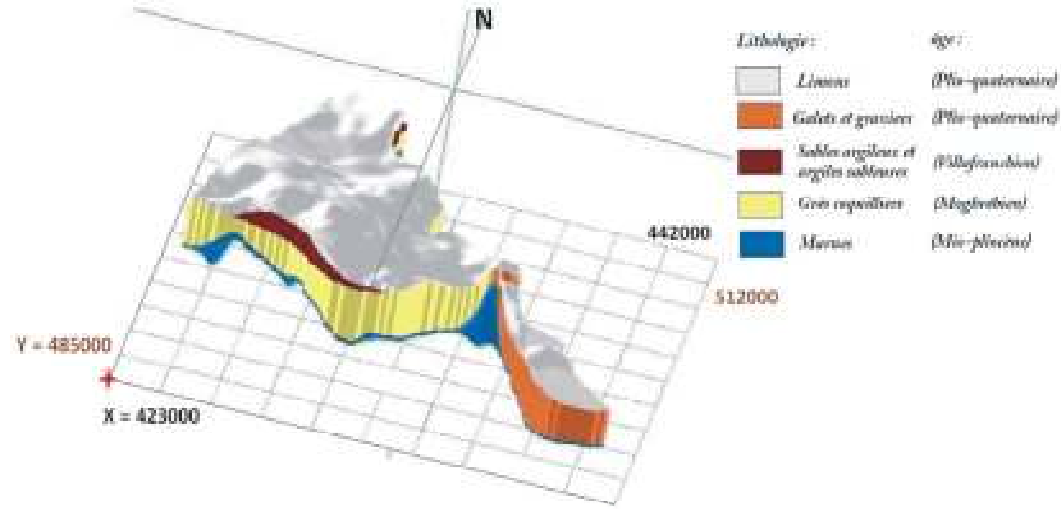

Fig. 6: 3D Modelling of Rmel-O. Ogbane aquifer.

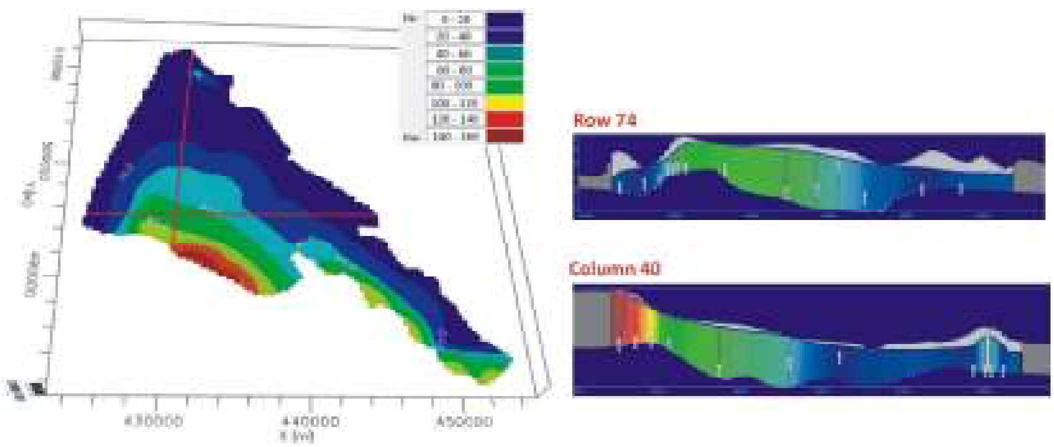

Fig. 7: Calculated Piezometry (m) of the Rmel-O. Ogbane (map and cross-section views) for year 1961/1962.

The hydrogeology of the Rmel coastal aquifer consists of plio–quaternary sands and sandstone, but the bottom is composed of blue marls [9]. To better understand the aquifer reservoir, a 3D Geoscientific Information System (3D GSIS) was elaborated for processing, viewing and analyzing data; showing the hydrogeological structure, the extension and geometry of the reservoir and the conceptual model (Fig. 6).

A three-dimensional numerical groundwater flow model, calibrated under steady state (Fig. 7) and transient conditions resolving Equation (1) [10] for a period from 1963 to 2014, was developed by means of the Visual Modflow [11]. Figure 8 shows the simulation results of the indicated period. The model predicts also the drawdown and the hydraulic head in the aquifer system for the period ranging from 2014 to 2030 under three different groundwater management scenarios and gives the water balance within time.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W = S_s * \frac{\partial h}{\partial t}$$

Equation (1):

where K_{xx}, K_{yy} and K_{zz} are the values of K along the x, y and z coordinate axes (L/T), h is hydraulic head (L), W is the volumetric flux per unit volume and represents sources and (or) sinks of water (T^{-1}), S_s is the specific storage of the porous medium (L^{-1}) and *t* is time.

The coupled flow and transport resolving Equation (2) was used to study seawater intrusion in the Rmel-O. Ogbane coastal aquifer under a distribution of salt concentrations values in the coastal area, ranging from

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(V_i C) - \frac{q_s C_s}{\theta} + \sum_{k=1}^{N} R_k$$

Equation (2):

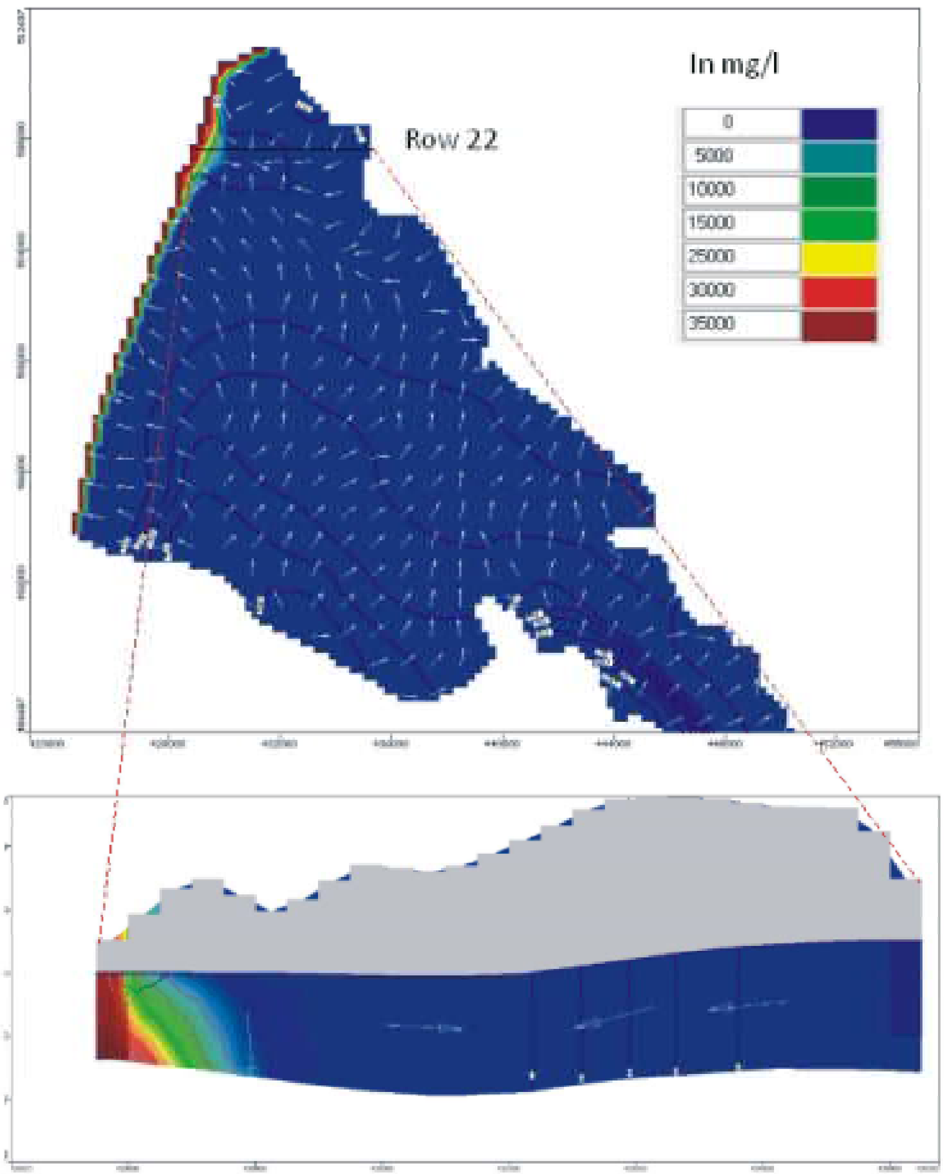

Fig. 8: Piezometry/salinity (for a map and cross-section) calculated in 2000 by the model in layer 3.

where C: concentration of contaminant dissolved in groundwater [ML^{-3}], x_i : distance along the cartesian coordinate axes [L], D_{ij} : hydrodynamic dispersion coefficient [$L^2 T^{-1}$], V_i: fluid velocity [$L T^{-1}$], q_s: flow per unit of volume injected (or pumped) of the aquifer, C_s: concentration of the recharge or discharge flow (q_s) [ML^{-3}], θ: porosity of the porous medium sea salt (35 g/l) in red color and freshwater concentration which is almost 0 g/l in blue color (Fig. 8). The seawater intrusion edge extended 2 Km in the bottom of the aquifer. The results showed also that seawater intrusion increased in 2000 in the northwestern sector, due mainly to (1) *less recharge caused by CC and the recurrent droughts*; (2) *Overexploitation of groundwater by intensive pumping from a well field used for drinking water supply of the Larache city and rural areas exploiting the aquifer system for irrigation.*

Case 2 - Tafilalet Oasis: The Tafilalt Oasis is located in south eastern Morocco in a pre-Saharan area framed on the north and east by the erosional limits of the Hammada and to the west and south by the ancient massifs of the anti-Atlas domain [12]. The plain was formed by erosion during the Quaternary period and is crossed by two major rivers from the mountains of the High Atlas, the Ziz and Rheris.

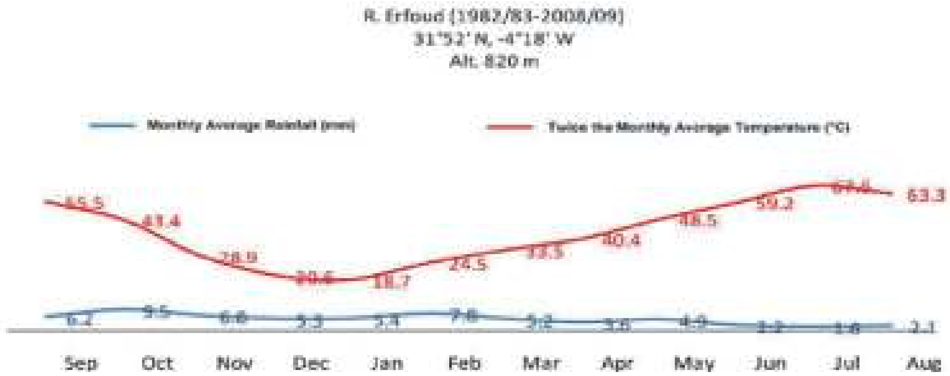

Fig. 9: Ombrothermic diagram for Radier Erfoud weather station. According to [14], the annual dry period is defined as the months when precipitation (in mm) is less than twice the mean temperature.

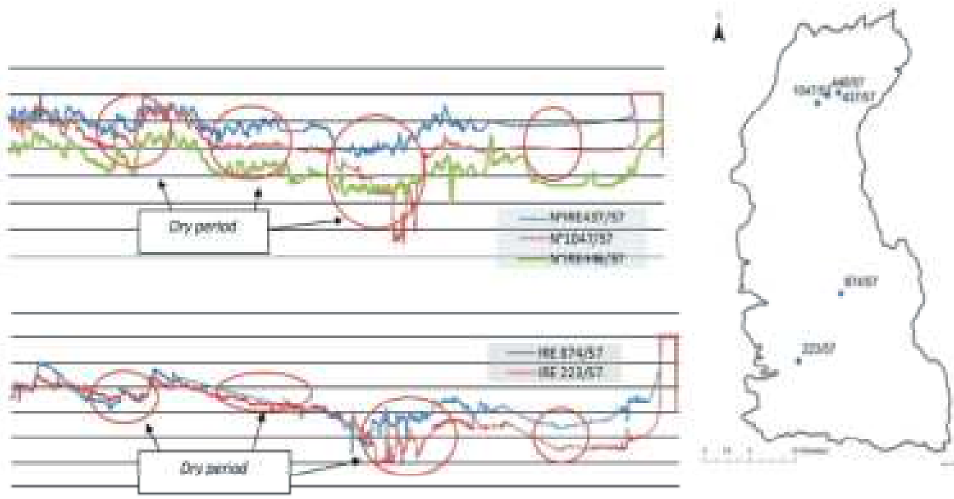

Fig. 10: Succession of dry periods (red circles) which causes decrease of the piezometric level.

The climate of the region is arid-continental. The average annual rainfall recorded from 1982 to 2009 is 54.64 mm. More than 90% of annual rainfall occurs from September to April. The highest average monthly temperature is in July (43.22 °C) and the lowest is in January (-1.11 °C). As shown by the ombrothermic diagram (Fig. 9), there is a year-round water deficit. The maximum dry period is recorded during the months of June to September.

The water table decrease is due to pumping, but mainly by the succession of dry periods which causes the lowering of the piezometric level (Fig. 10).

Hydrogeological properties of Tafilalt Oasis highly depend on several conditions. First, the pre-Saharan climate and local arid conditions make the role of the evaporation very intense on the process of groundwater discharge, while the aquifer is subject to constraints which depend on the weak role of rainfall in the development of groundwater.

On the other hand, the Tafilalt Oasis location ensures abundant and relatively regular surface-water resources (compared to other pre-Saharan rivers), especially after the commissioning of the Hassan Addakhil dam. Finally, the geological structure of the study area, which precludes the existence of deep groundwater reservoir, facilitated the establishment of a large groundwater resource in the Quaternary alluvial cover [12].

A geodatabase was developed and provides several types of information for the 3D representation of the aquifer, it is one of the first steps in the development of the conceptual model [13].

Figure 11 shows the most important available features within the AHGW geodatabase, which represent groundwater objects of the Tafilalt Oasis such as borehole data, wells, GeoRaster, GeoSection and GeoVolume in two and three dimensions.

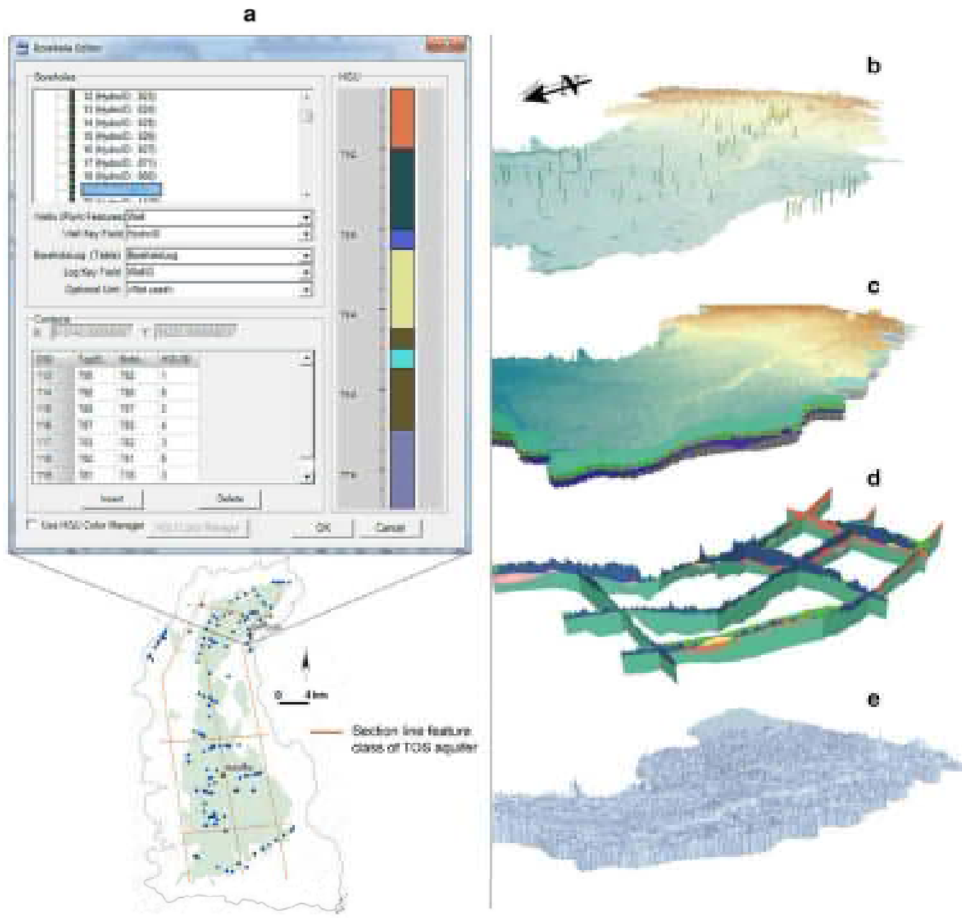

Fig. 11: 3D representation by Arc Hydro Groundwater (AHGW): **a**: Borehole editor tool for visualization of stratigraphic successions,**b**:3D borehole represented with a digital elevation model of Tafilalet oasis,**c** : Interpolated GeoRaster,**d**: GeoSection and **e**: GeoVolume, created from GeoRaster.

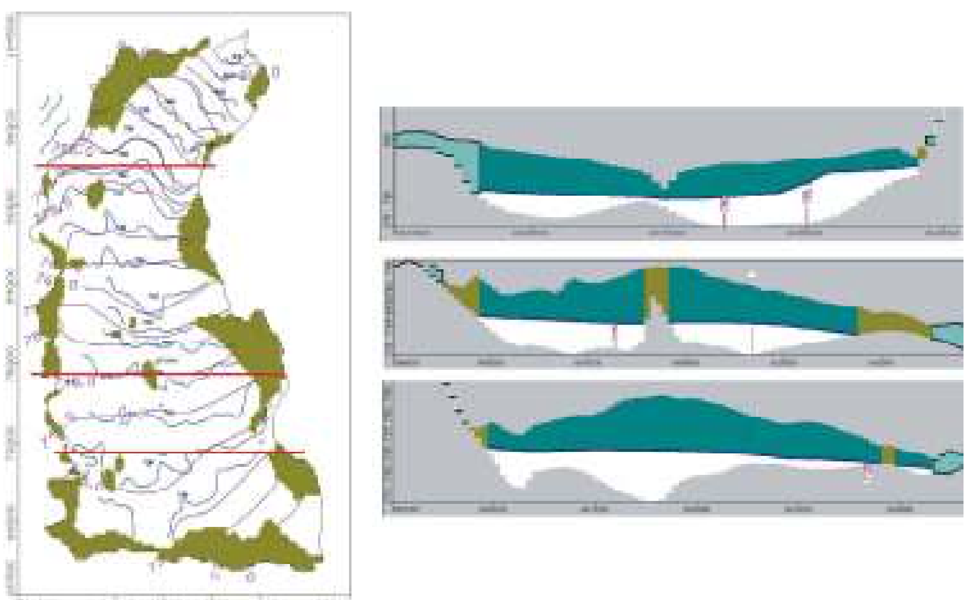

Fig. 12: Observed and calculated hydraulic head in meters in the steady-state calibration (1960).

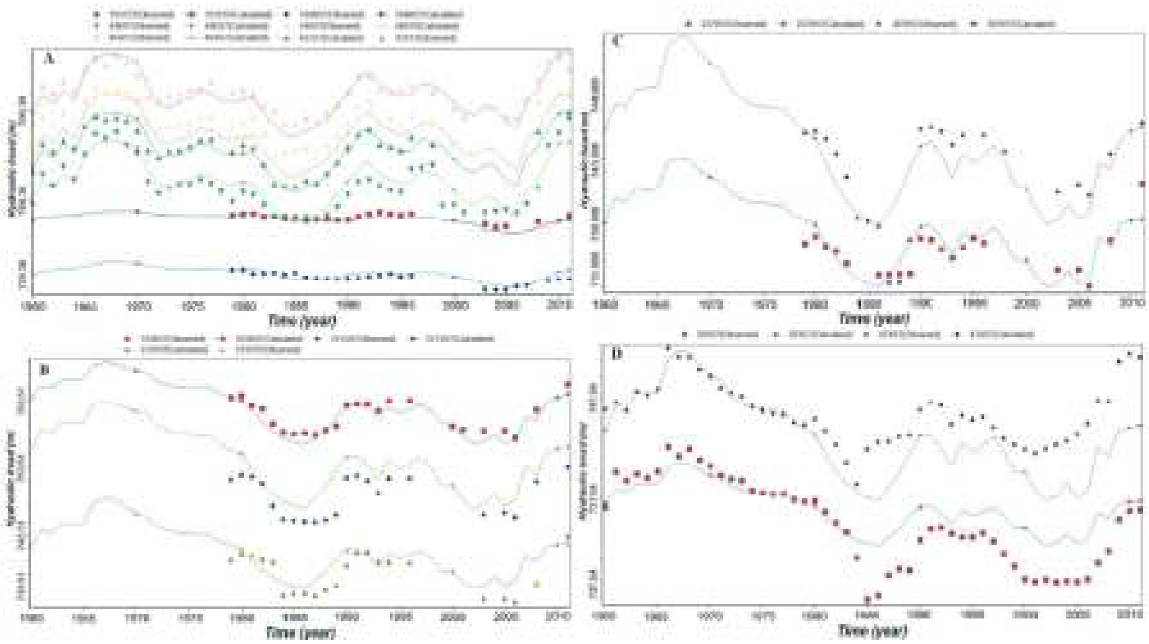

Fig. 13: Measured and calculated heads by transient model calibration and model verification for **a**: six observation wells in Tizimi and **b–d**: seven observation wells in Tafilalet.

Numerical simulations were performed by implementing a spatial database within a geographic information system and using the Arc Hydro Groundwater tool with the code MODFLOW-2000. The results of steady-state (Fig. 12) and transient simulations between 1960 and 2011 (Fig. 13) show that the water table is at equilibrium between recharge, which is mainly by surface-water infiltration and discharge by evapotranspiration.

After the commissioning of the Hassan Addakhil dam in 1971, hydraulic heads became more sensitive to annual variations than to seasonal variations. Heads are also influenced by recurrent droughts and the highest water-level changes are recorded in irrigated areas. The model provides a way of managing groundwater resources in the Tafilalt Oasis. It can be used as a tool to predict the impact of different management plans for the protection of groundwater against overexploitation, CC and deterioration of water quality.

The model reveals the importance of recharge on water-table fluctuations and shows that most exchanges (80%) are vertical, with infiltration beneath riverbeds and irrigation return flow as the primary inputs and ET as the primary output. The Tafilalt Oasis aquifer is thus sensitive to climatic change conditions; increased exploitation by pumping wells accompanied more than it triggers the lowering of the water table. This situation allows the groundwater to play the role of a “buffer” during periods of drought. The model can be used to simulate the reaction of the aquifer, including areas in which groundwater is likely to be stored, under different water resource planning scenarios.

CONCLUSION

The development of a model for the Rmel-O.Ogbane and Tafilalt Oasis aquifers conducted to a better understanding of groundwater flow in this arid and semi-arid region of Morocco under CC and human activities. The Rmel-O. Ogbane coastal aquifer is a good example to aware the water authorities that seawater intrusion phenomenon is dangerous and may lead to reduce water resources development in coastal aquifers, especially with the sea level rise and overexploitation of the aquifer. We conclude that if no measures and actions are taken for this aquifer reservoir, the well field and the coastal agricultural zone will be abandoned, since irrigation and water supply from pumping wells will be more salty and this deteriorates groundwater quality and soil salinization. Improvement of the situation will be reinforced by surface water use for irrigation of the coastal sectors and artificial recharge of the aquifer. This will improve significantly the groundwater quality in the coastal sectors of the aquifer and will protect freshwater from seawater intrusion. For the Tafilalet oasis, adaptation and attenuation are necessary to protect the scarce water in this arid area, which plays a crucial role for the rural population and especially for the production of dates. These results, findings and policy implications of our study may help managers of the Rmel-O. Ogbane aquifer and the Tafilalet oasis to prioritize areas that are most sensitive to coupled human activities and CC and implement best management practices in the context of adaptability and long-term sustainability of groundwater resources.

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