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Research Paper

Assessing the impact of artificial recharge on groundwater in an over-exploited aquifer: A case study in the Cheria Basin, North-East of Algeria

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Abstract: The Cheria region in Northeastern Algeria has been facing aquifer overexploitation by the agricultural sector and prolonged droughts, resulting in a considerable decline in groundwater levels. This study investigates the feasibility of implementing artificial recharge techniques to replenish the Eocene aquifer which serves as the primary water source in the Cheria region. A 3D transient numerical model, based on the finite difference method, was used to simulate groundwater flow from 2021 to 2031 using Visual MODFLOW Flex. During the modelling process, three scenarios were considered: (1) including pumping without a recharge, (2) recharge of the entire area through efficient infiltration without pumping, and (3) artificial recharge using river water infiltration basins at two sites, Draa Douamis sinkholes and Eocene limestone outcrops. The simulation results showed that aquifer exploitation without recharge caused significant drawdowns, which were 3 m to 7 m in the north-eastern part and 8 m to 12 m in the central and southern parts. In contrast, the second scenario, involving recharge without pumping, showed a rise in groundwater levels of 2 m to 2.7 m in the north-eastern part and 3 m to 3.62 m in the central and southern parts. The third scenario, employing artificial recharge, indicated a positive response to artificial recharge, with increased piezometric levels at the proposed sites, signifying a beneficial impact on the aquifer. These findings underline the potential of artificial recharge as a promising approach to address the groundwater depletion and environmental issues in the Cheria Basin.

Keywords: Eocene limestone; Piezometric level; Numerical simulation; Visual MODFLOW Flex; Artificial recharge

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Introduction

Groundwater constitutes a significant proportion of the world's potable water resources (Sawyer et al. 2016, Silva et al. 2021). In response to dwindling surface water resources, groundwater has been subject to intensive extraction over the years (Cheng et al. 2021, Bai et al. 2022). Factors such as population growth, industrial development, and increase in irrigation areas have exacerbated the water scarcity, particularly in arid and semi-arid areas (Barceló and Sabater, 2010; Britto et al. 2019). To address declining piezometric levels and excessive groundwater exploitation, the restoration of the groundwater system has gained attention, especially during the last decade (Saghi-Jadid and Ketabchi, 2021). Artificial recharge, an efficient solution for managing groundwater resources in a stable and continuous manner, involves replenishing underground water during surplus periods and using it during water deficit. (Xanke et al. 2016; Iftekhar and Fogarty, 2017). The primary sources that contribute to Precipitation and streams water are primary contributors to underground

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storage (Batlle-Aguilar et al. 2015). Artificial recharge offers several advantages, including storing surface water during periods of flooding, reusing wastewater, improving water quality, and protecting against saline intrusions (Abdoulhalik et al. 2017; Müller et al. 2020; Alam et al. 2021). Universal techniques, such as aquifer storage, transfer, and recovery (ASTR), infiltration basins, soil aquifer treatment (SAT), percolation tank, banking infiltration, stream modification, well injection technique, and storage dams, etc. have been employed for sustainable management of groundwater resources (Dillon et al. 2018; Sasidharan et al. 2019). However, the application of Managed Aquifer Recharge in karstic environments is limited (Daher et al. 2011) due to the complexity of underground karst structures, including variable porosity, fractures, conduits, and changing recharge conditions over time (Bakalowicz, 2005; Einsiedl, 2005; Maurice et al. 2012; Filippini et al. 2018). Effective decision-making groundwater management can be facilitated through groundwater modelling (Glass et al. 2018; Qin, 2021). In this context, a conceptual groundwater flow model was developed to assess the feasibility of implementing managed aquifer recharge, and numerical transient flow model was built using Visual MODFLOW Flex (Samanta et al. 2020; Mushtaq et al. 2023; Eltarabily et al. 2023).

Over the past few decades, the town of Cheria has been suffering from severe water scarcity due to drought, limited rainfall, and overuse of the resources, given its heavy reliance on groundwater. The adverse effects of over-exploitation, such as the land subsidence characteristic of karst areas (Fehdi et al. 2011; Nouioua et al. 2013; Baali et al. 2015; Chamekh et al. 2018), underscore the urgent need for sustainable management and use of groundwater in the region. Artificial recharge of groundwater emerges as a crucial approach to augment groundwater resources.

To better manage the karst aquifers, it is essential to understand and control the changes in piezometric levels and the distribution of seepage (Chamekh et al. 2018). Therefore, a three-dimensional numerical model of the main aquifer in the Cheria area, the Eocene aquifer was established and calibrated in both steady state (1999) and transient (1999–2021) conditions using Visual MODFLOW Flex version 6.1. Subsequently, three scenarios were simulated for the period 2021–2030 to examine the long term effects of pumping without recharge, the influence of natural recharge, and the positive effect of artificial recharge. In particular, the infiltration through basins holds great promise in the northern and southern areas, where the groundwater levels have experienced the most significant decline.

1 General setting

The Cheria basin, situated approximately forty kilometers southwest of Tebessa city in north-east of Algeria, occupies the center part of the study area and is surrounded by mountains ranges, including Djebel Dokkane (1 551 m) and Djebel Metaguinaro (1 713 m) (Fig. 1). The region experiences a semi-arid, characterized by low to average rainfall, typically less than 300 mm/a, and an average annual temperature of 15°C. Snow cover occurs

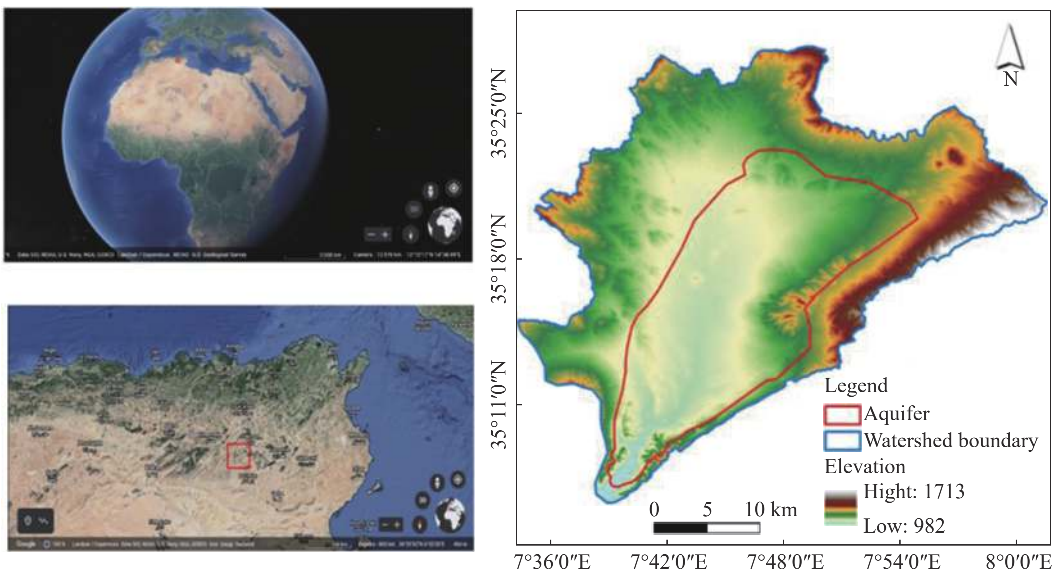


Fig. 1 Location of watershed and aquifer of study area

for 10–15 days annually, while thunderstorms contributes appreciable amount of water during June, September, and October. The combination of existing fractures, fissures, distinct climate creates favorable conditions for the formation of karst landscapes (Baali et al. 2007).

The Cheria plain, which formed during the Miocene, is a subsiding basin within the great Mio-Plio-Quaternary tectonic depression (Vila, 1980). Its bedrock comprises the Danian Tertiary marl and the Cretaceous limestone and marl, with the Upper Cretaceous marine-origin filling sediments. (Gaud, 1977) (Fig. 2). The Eocene formations, primarily composed of limestone, are highly fractured and overlaid by Quaternary alluvial deposits consisting of gravel, sand, silt, and clay. The Eocene limestone formation serves as the most extensive aquifer in the Cheria basin and is delimited by the marl-limestone bedrock. The thickness of the aquifer increases toward the center of the basin, while the alluvial aquifer's limited thickness and its poor water quality reduce its importance in water supply (Baali et al. 2007; Fehdi et al. 2011; Chamekh et al. 2018).

Recharge to the Eocene aquifer primarily occurs through precipitation. with weak supply from the upper boundaries and no supply from the lower boundaries (Danian marl). The main recharge sources from thelateralinflows at the eastern, north-eastern, western and northwestern borders of the basin. Groundwater abstraction is the main discharge from the aquifers. The hydrographic regime of the Chéria plateau is characterized by streams that converge from the edges toward the northern part of basin. Seasonal streamslike El Blilia, El Goussa, and Douamis collect water from storm that drains towards the center of this part of the plateau, contributing an average annual inflow of 2.02 Mm^3, which can reach the town of Chéria during high floods. In the southern part, the the Chéria provides an average annual inflow of 1.15 Mm^3. Despite the dense hydrographic network, the river water supply is limited to periods of high flooding, the efficiency of this supply depends on the permeability of the riverbed formations where water can infiltrate quickly and escape from evaporation.

Over the past few decades, intensive groundwater extraction, primarily for agricultural purposes, has caused a significant decline in the aquifer's water level in Cheria. The number of wells and boreholes for groundwater extraction has steadily increased from 192 in the early 1990s to 414 in 2021 producing 14.95 Mm^3 against 0.93 Mm^3 for 61wells in 1981 to meet various demands, including drinking water supply and agricultural use (Fig. 3).

In 2019, the daily demand for drinking water supply in the Cheria region reached 13 252 m^3, while the production capacity was 7 344 m^3 per day, leading to a deficit of 7 798 m^3/d for a population of 88 346. In addition, intermittent piezometric measurements (Fig. 4) indicate irre-

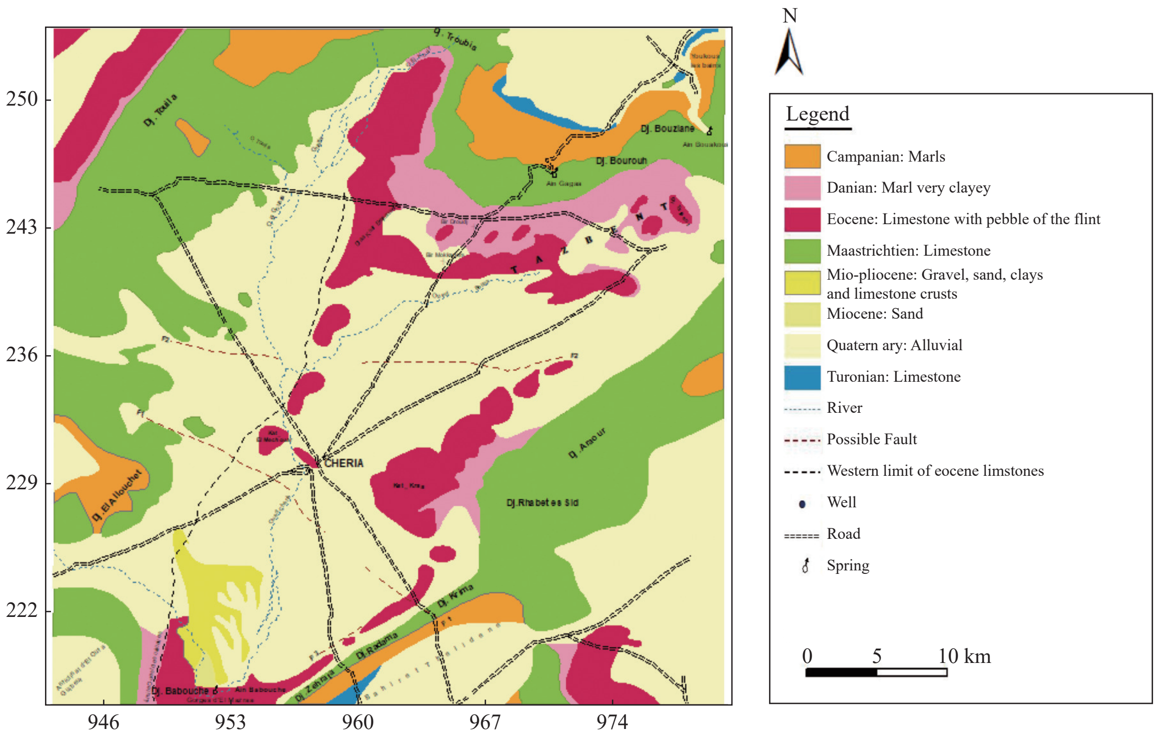


Fig. 2 Geological map of the study area

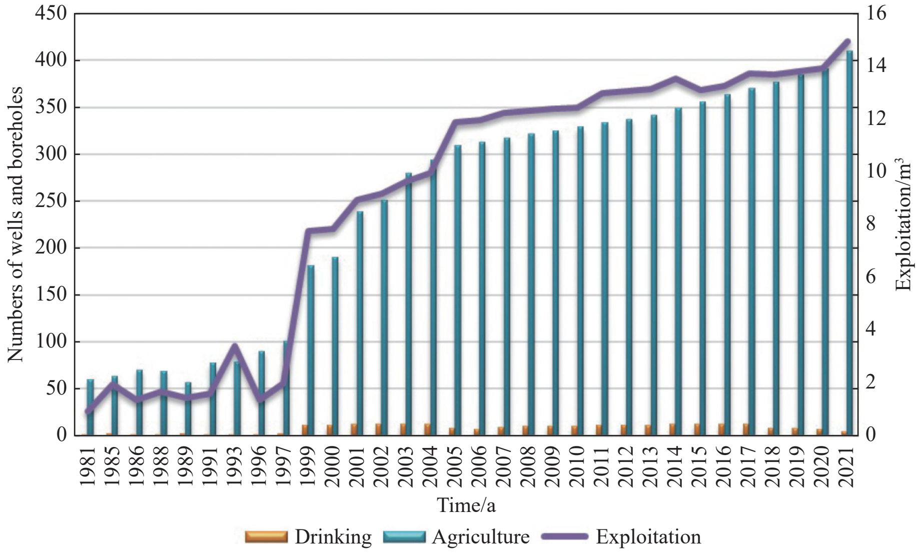


Fig. 3 Evolution of the exploitation rate according to the number of water wells in the Cheria aquifer

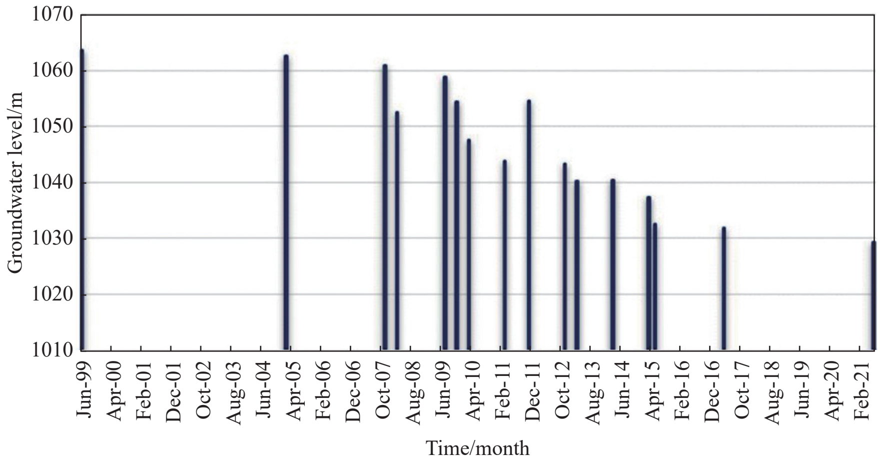


Fig. 4 Intermittent evolution of the groundwater level over time (1999–2021)

gular variations potentially resulting from temporary recharge, overexploitation or insufficient precipitation, but in the end the water level continues to fall (Water Authority Report, 2021).

2 Methods

2.1 Piezometry

The piezometric level of groundwater is closely influenced by several factors, including the climate, the degree of exploitation, and the contributions of surface water (Rodríguez-Rodríguez et al. 2021). In June 2021, a groundwater piezometric level measurement campaign was conducted at 26 boreholes (Fig. 5). The depth of the water table was measured using a graduated electric probe, and the geographical coordinates of the boreholes were recorded with a GPS handset - GARMIN 62S.

2.2 Groundwater modeling

Visual MODFLOW (VMOD) Flex is a robust three-dimensional groundwater modelling software designed for groundwater flow and contaminant transport. Using raw GIS data, Visual MODFLOW constructs both conceptual and numerical models, facilitating simulations on both regional and local scales with support of MODFLOW Local Grid Refinement (MODFLOW-LGR). The software environment offers environment offers simultaneous 2D and 3D views, enhancing the modelling experience (Waterloo Hydrogeologic, 2019).

2.2.1 Hydrogeological conceptual model

The hydrogeological conceptual model incorporates digital topography and the natural boundaries of the aquifer system. Vertical discretization is achieved using a monolayer approach, bounded by

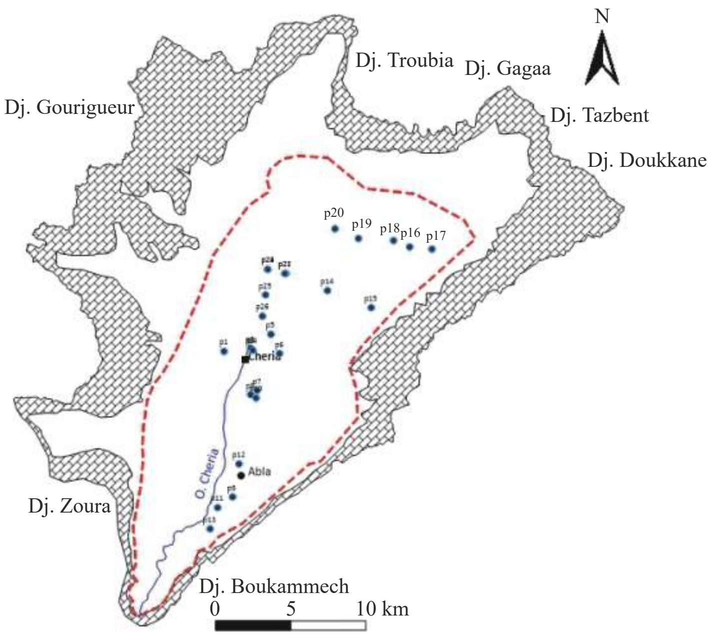


Fig. 5 Water point inventory map

the natural terrain on the top and impermeable bedrock at the base. The hydraulic properties were assigned based on the lithological information derived from geological and geophysical studies, specifically focusing on the limestone layer.

The model encompasses a total area of 318 km^2, represnted by a grid consisting of 50 rows and 40 columns, thus forming 2 000 cells on the x-y plane. Each cell measures 400 × 400 m. The model domain is characterized by a single homogeneous layer (Eocene limestones) in the z direction. The top elevation of the layer corresponds to the topographic surface elevation of the area, while the bottom elevation aligns with the top of the impermeable Danian marly layer. The thickness of the layer ranges from a few tens to a hundred meters, with an average thickness of 192 m (Fig. 6).

2.2.2 Boundary conditions

The boundary conditions are given by the piezo-

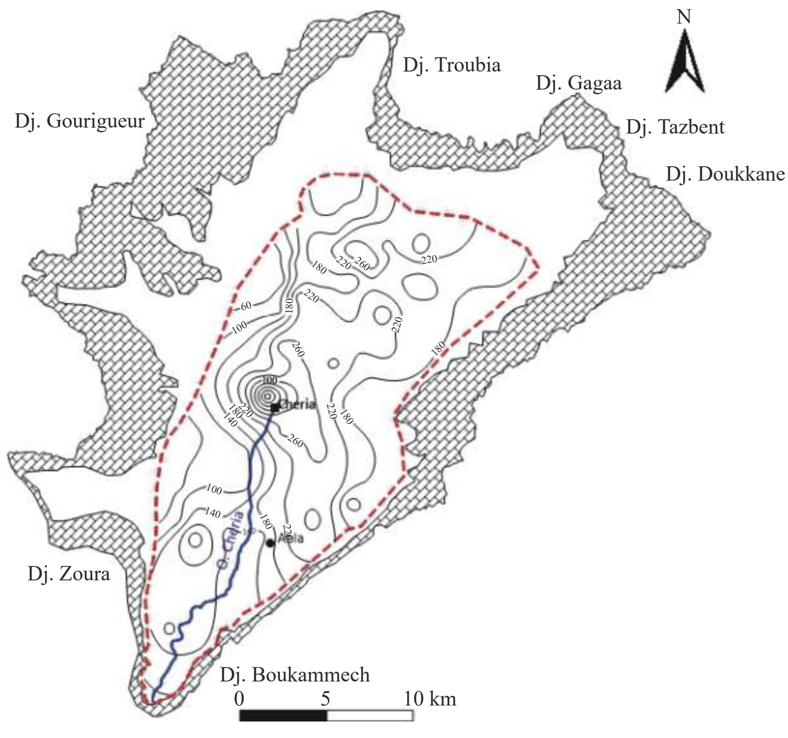


Fig. 6 Thickness distribution map

metric map. The lateral limits of the Cheria basin correspond to hydraulic potentials (Dirichlet) that establish the model's boundaries. All cells within the aquifer are designated as active, while cells outside the aquifer, representing the mountains surrounding the study area, are considered inactive. The inflows border meshes reflect the lateral input from the East, North-East, West, and North-West areas. Frontal and tributary recharges were treated in the model as specific flow limits, which are the Neumann boundary conditions (McDonald et Harbaugh, 1988). The Cheria River acts as a drainage boundary for the water table, particularly during high water periods, and is simulated using the Drain Package. The rest of the boundaries of the model are no-flow boundaries, with the southern boundary representing the system's outflow (Fig. 7).

Hydraulic parameters such as hydraulic conductivity (*K*), specific storage (*Ss*), specific yield (*Sy*), effective porosity, and total porosity were obtained

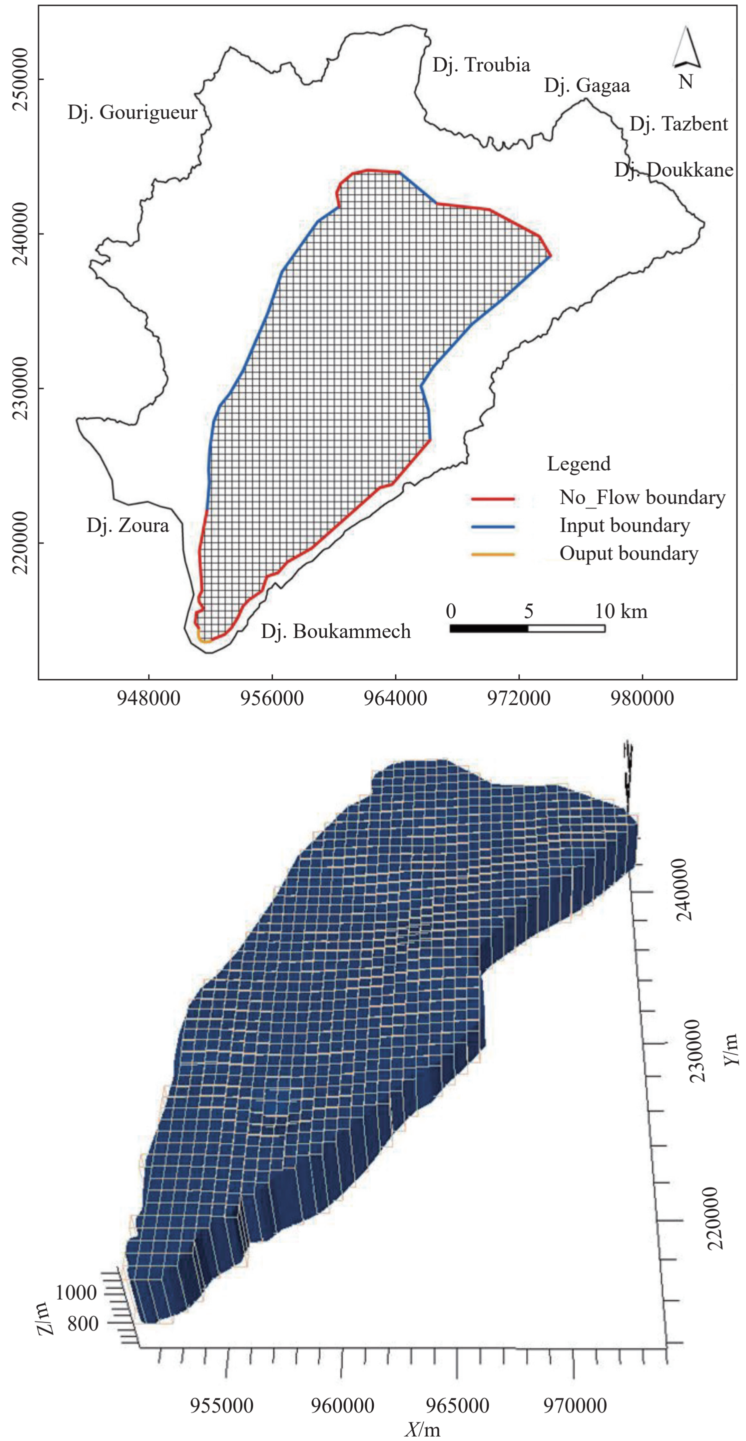


Fig. 7 a) Boundary conditions of the model b) 3D Numerical grid created for Eocene groundwater model

from pumping tests on a number conducted on several boreholes evenly distributed across the study area. The tests were performed at a constant flow rate, and the curve matching method was employed to interpret the drawdown data (WAR, 2021). The model layer's vertical hydraulic conductivity was set to one-tenth of the horizontal hydraulic conductivity. These parameter values were appropriately fitted during the model calibration (Table 2).

However, it should be noted that the number of transmissivity values available is insufficient (only 9 values), and these values are concentrated in the center of the area, making them less representative of the entire sector (WAR, 2021) (Table 1). Moreover, these measurements show significant variability from point to point.

Precipitation is modeled by the Recharge Package in MODFLOW. Groundwater abstraction was simulated through the Well Package.

2.2.3 Numerical model of groundwater flow

The finite-difference technique serves as the calibration standard for simulating groundwater flow in the Cheria study area. The first stage of the numerical model reproduced the observed hydraulic load configuration for 2021 under steady-state conditions, and the simulation results were used as initial conditions for the transient simulation.

A transient flow model is employed to simulate the evolution of the aquifer due to water extraction in the area over time. A total of 358 exploitation wells were identified in the Cheria aquifer. Among them, 70 observed wells with measured hydraulic heads were used for calibrating the model, by comparing them with the mode-calculated heads. The model parameters, including the initial head distribution, boundary conditions, and hydraulic parameters, were appropriately incorporated, consistent with the natural aquifer boundaries.

After model calibration, and to assess its behavior under transient conditions and define the future state of the water table along with its hydrodynamic variation over time, the simulation was conducted for a ten–years period. Three scenarios were proposed:

1st scenario: This scenario involves monitoring the piezometric level's evolution from 2021 to 2031, representing a long-term operation with constant well extraction rates and no recharge considered.

2nd scenario: In this scenario, pumping activities were ceased for ten years (2021–2031) to observe the recharge of the entire aquifer layer through effective infiltration, with an average rate of 17 mm/a. This value corresponds to approximately 6% of the average annual rainfall, determined using Thornthwaite's method.

3rd scenario: Implementation of an artificial recharge device. The simulation of the artificial recharge was performed under transient conditions over a ten-year period. Based on the data collected, an artificial recharge basin type was suggested as the method to capture and infiltrate floodwater from streams at two locations in the northern and southern areas (Fig. 8).

Site 1: In the north, near the subsidence of the Draa Douamis, the basin would be fed from the waters of three ephemeral rivers, Douamis, El Blilia, and El Goussa.

Site 2: In the south, where the Eocene limestone

Table 1 Hydraulic parameters layer

Layer	(k_x)Hydraulic conductivity/m/s	(k_z)Hydraulic conductivity/m/s	(*Ss*)Specific storage/m^{-1}	(*Sy*)Specific yield	Effective porosity/%	Total porosity/%
1	1.28×10^{-5}	1.28×10^{-6}	6.9×10^{-5}	0.14	10	20

Table 2 Transmissivity values of 09 boreholes

Well	X /m	Y /m	Z /m	T / m^2/s
F9 bis	964 075	235 215	1 133	2.58×10^{-3}
CH4	957 831	231 000	1 099	2.7×10^{-1}
CH1 bis	957 160	231 177	1 093	0.19×10^{-2}
CH5	960 529	233 045	1 103	8.05×10^{-1}
CH6	960 964	233 818	1 112	1.91×10^{-2}
Abla1	958 657	228 065	1 089	2.83×10^{-3}
HA1	959 413	228 508	1 138	1.513×10^{-3}
CH3	958 904	231 230	1 090	12.81×10^{-1}
T9	952 160	214 571	1 011	0.16×10^{-1}

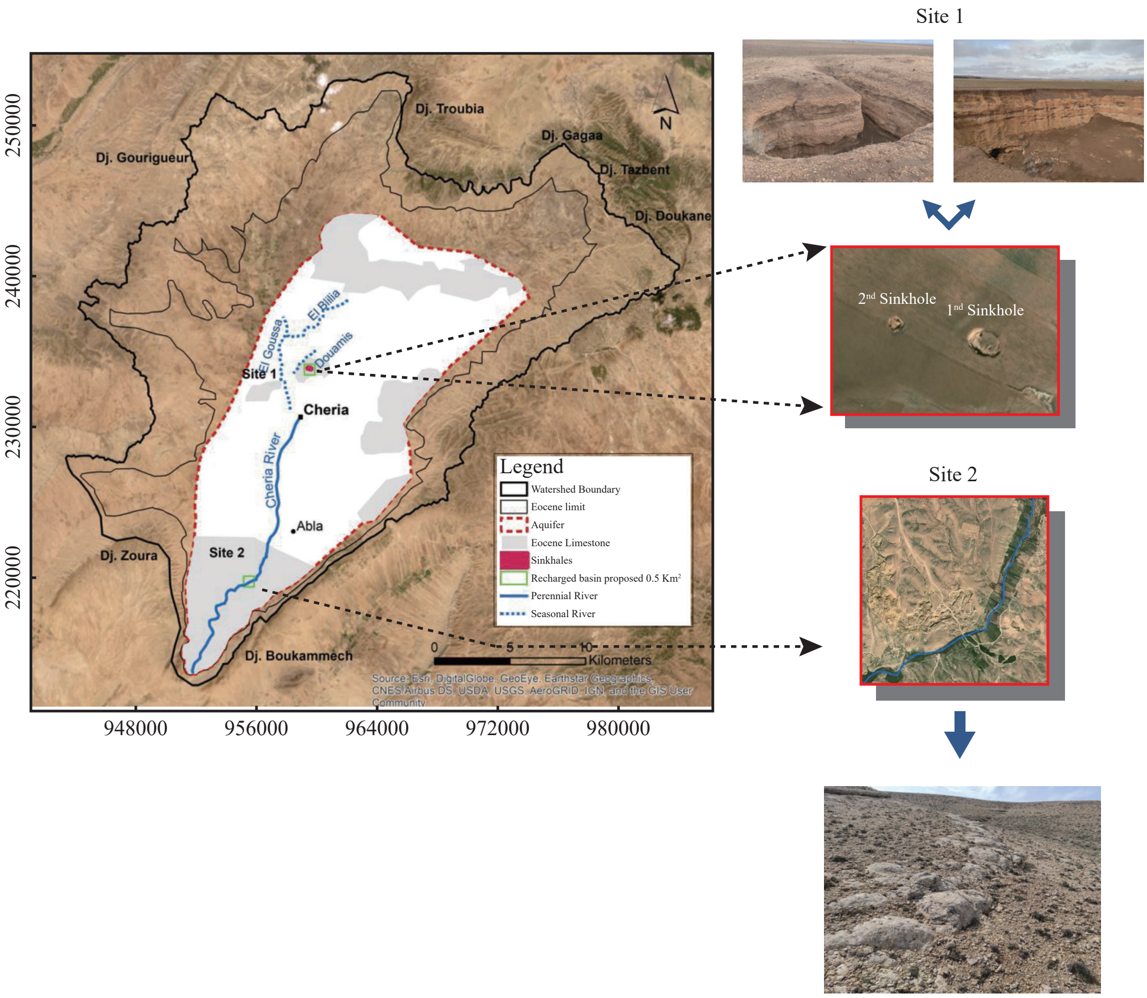


Fig. 8 Location of sites proposed for artificial recharge

Site 1: Sinkhole area site 2: Eocene limestone outcrops

outcrops, the basin would be fed from the main river in the Cheria area.

The heights of the artificial recharge were determined based on the volume of water discharged by the rivers during high flood conditions, considering a maximum flow rate of one hour per day for 20 days (representing days of high flooding over a year) at the surface of the proposed infiltration basin. The estimated infiltration rate was set at 80% of total water volume, accounting for the lithological characteristics of the recharge sites (Table 3).

3 Results and discussions

The comparison of two piezometric maps (Fig. 9a, b) shows that the flow converges toward the center of the basin. In the northern part of the basin, the flow direction changes from a northeast-south direction in 1999 to an east-west direction in 2021, char-

Table 3 Parameters of the artificial recharge of the Cheria aquifer for one year

		Site 1			Site 2
River		Douamis	El Blilia	El Goussa	Cheria
Flow / m^3/s		4.68 28.12	7.39	16.05	16
Annual inflows / Mm^3/an		2.02			1.15
Recharge to the water table 80%		1.62			0.92
Height of rechage /m	Area of 0.5 km^2	3.24			1.84

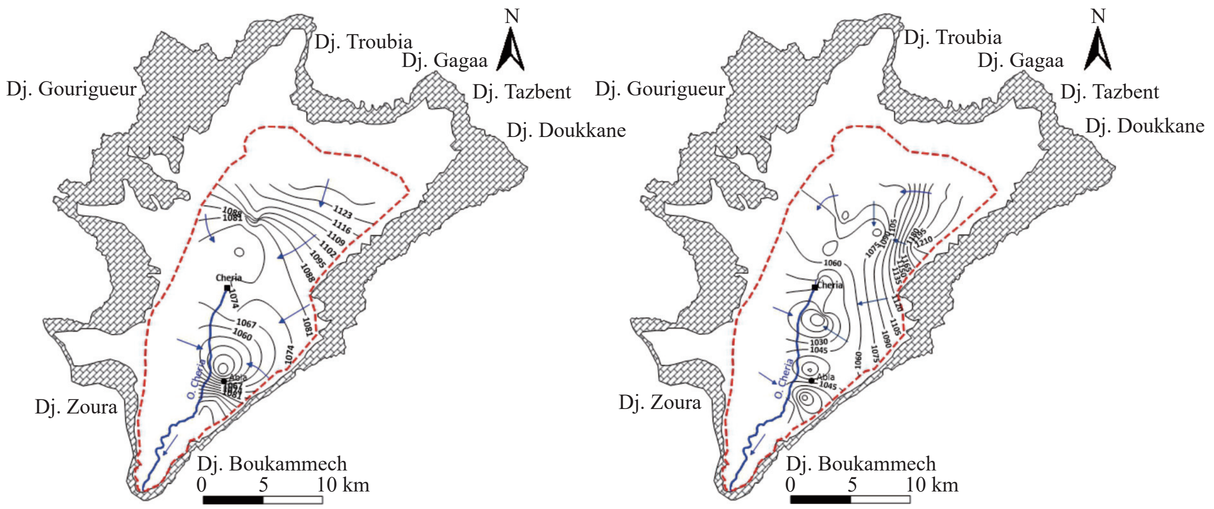


Fig. 9 a. Piezometric map, September 1999; b. Piezometric map, June 2021

acterized by tightly spaced isopiezometric lines, indicating the importance of the flow velocity. Despite the change in flow direction, the primary water supply still originates from the borders of the Maastrichtian limestone. Conversely, the flow pattern in the southern part remains consistent over the 22-year period, converging towards a drainage axis that corresponds to the Wadi Cheria in the southwest.

The examination of these maps also reveals two distinct zones: The first zone, located downstream of the plateau, which exhibit high flow velocities (feeder zone) evident by the closely spaced contour lines. The second zone, situated in the center part, is characterized by over-exploitation that has led to several depressions occurring on either side of Cheria River. This phenomenon can be attributed to the large number of boreholes supplying the population and extensive well drilling in the agricultural sector.

A comparison between the groundwater levels in 1999 and 2021 (Fig. 10) indicates a rise of 5–10 meters in the northeast feeder zones and a drawdown of 10–130 meters in the central zone due to

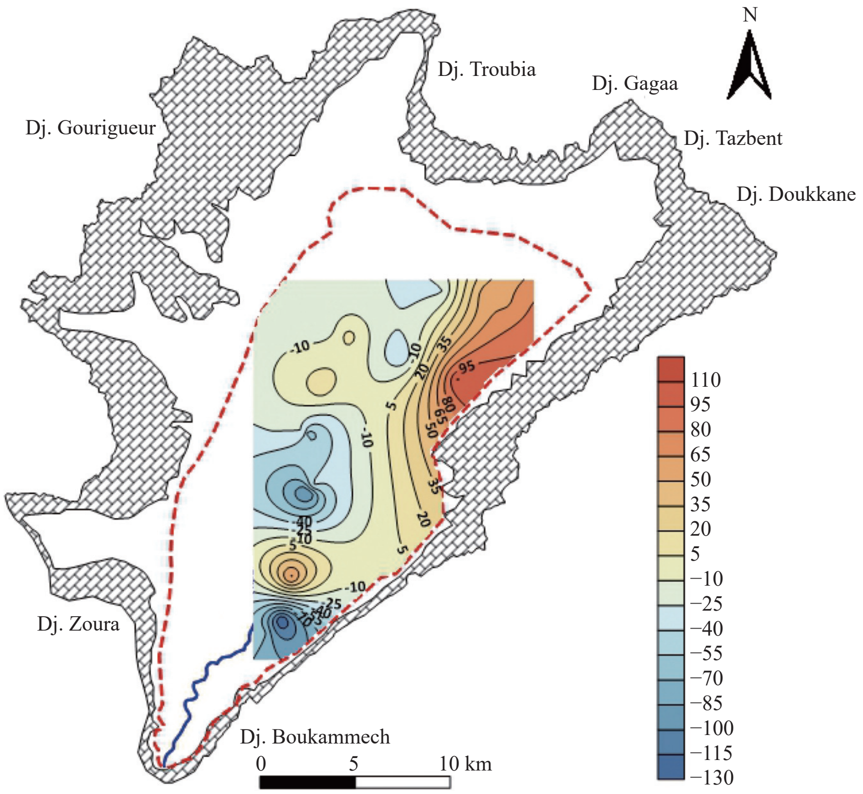


Fig. 10 Piezometric drawdown map between 1999 and 2021

groundwater overexploitation. This significant drawdown highlights to the stressed groundwater conditions in the region.

3.1 Calibration results

The simulated steady-state map shows a good match between the measured piezometry and the model-calculated one (Fig. 11), indicating the success of model calibration.

The transient simulation of the transitional aquifer, starting in 2021, reveals a potentiometric surface consistent in morphology with the observed data (Fig. 12). In the northern part, groundwater flow is from east to west, and a significant drawdown is evident at an equipotential of 970 meters altitude, indicating a cone of depression in this area. A very noticeable over-exploitation area occurs in the center, as indicated by the narrowing of the piezometric contour lines, likely attributed to a reduction in the flow section. Despite some discrepancies between the calculated and measured piezometric levels in some areas, the model remains valid, probably due to measurement inaccuracies, and to specific hydrogeological conditions. The linear correlation between the observed and calculated hydraulic heads (Fig. 13) yields an

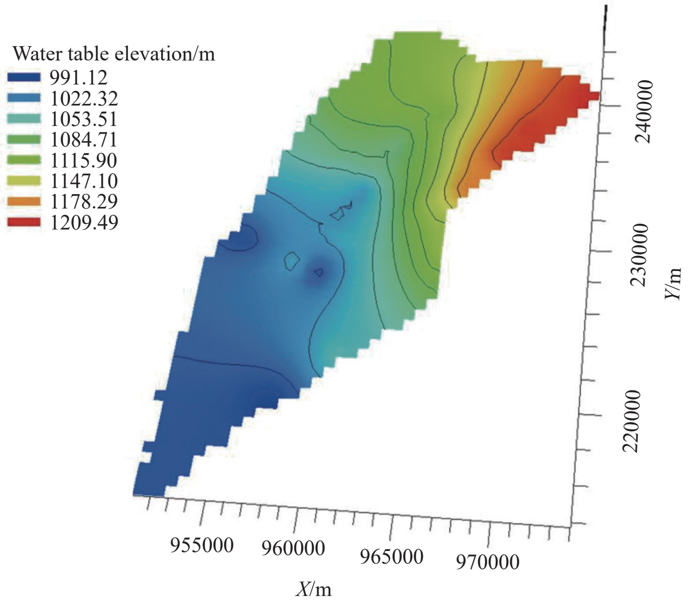


Fig. 11 Reconstitution of the piezometric state in steady state, June 2021

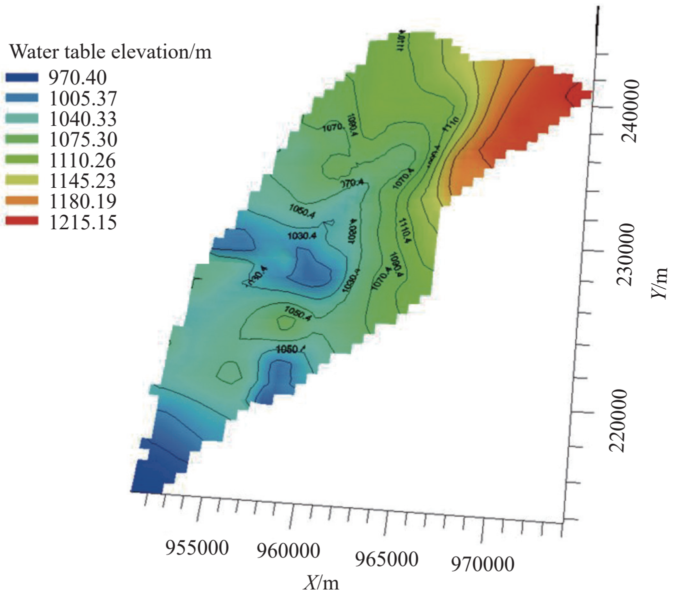


Fig. 12 Reconstitution of the piezometric state in transient regime, June 2021

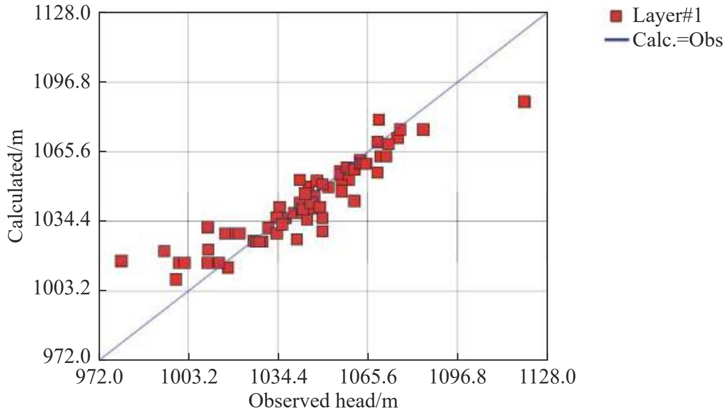
acceptable *RMSE* error of the order of 7.45%, considering the aquifer's constant and intensive exploitation.

The result of the first scenario (Fig.14) shows that with no recharge, the aquifer's piezometric shape and flow directions remain relatively stable, with estimated drawdowns of 3 m to 7 m in the northeast part and 8 m to 12 m in the central and southern parts. Notably, the drawdown in the study area increases, particularly around the city where boreholes are concentrated. The section of column 12 (AB), plotted in the areas with concentrated boreholes, shows a considerable decline in the water level, ranging from 48 m to 100 m from 2021 (step1) to 2031 (step 10).

The second scenario (Fig. 15) depicts a response to natural recharge over ten years, resulting in an increase in piezometric level by 2 m to 2.7 m in the northeast part and by 3 m to 3.62 m in the central and southern parts. However, it is evident that the water table's response to the natural recharge remains weak.

3.2 Effect of artificial recharge

Numerical simulations were conducted to explore the feasibility of implementing artificial recharge devices in the form of basins. Two zones were identified based on their height permeability (cracks and karst) and their proximity to rivers as surface resources. After several simulations, an optimal area of 0.5 km^2 was selected for each site.



Min. residual: 0.061 (m) at P48/1
Max. residual: 36.74 (m) at P14/1
Residual mean: −0.31 (m)
Abs. Residual mean: 7.38 (m)

Standard error of the estimate: 1.29 (m)
Root mean squared: 10.43 (m)
Normalized RMS: 7.45 (%)
Correlation coefficient: 0.92

Fig. 13 Scatter plot correlation for the corresponding model calibration for the year 2021

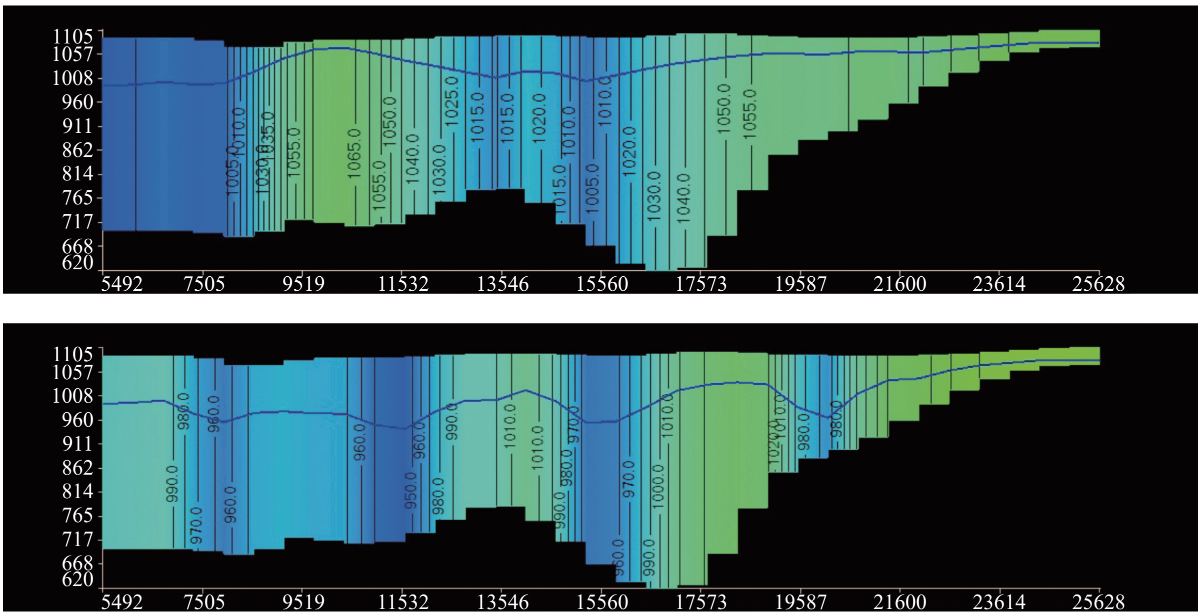


Fig. 14 Simulation of a long-term exploitation 2021-2031 without recharge

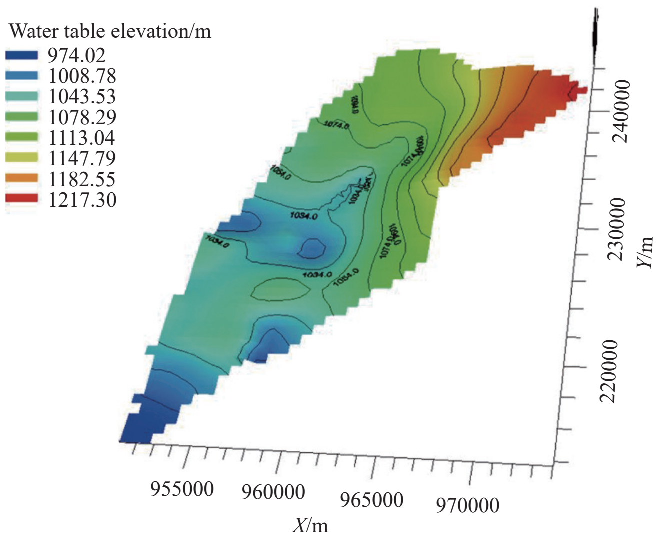


Fig. 15 Simulation with recharge (17 mm/a) without pumping 2031

All three rivers (Douamis, El Blilia, and El Goussa) together provided approximately an annual water supply of 2 Mm^3/a, which implies a required recharge height of 3 m in the first site and 1.8 m in the second one, provided by the Cheria river with a contribution of 1 Mm^3/a (Table 3).

The simulation results of the artificial recharge demonstrated the formation of a piezometric dome at both selected sites, indicating a substantial increase in the piezometric level. Over the course of a decade, the piezometric level has risen locally by 40 m in both sites, with a recharge rate of 4 meters per year (Fig. 16). The application of such a recharge system is expected to elevate the groundwater level even during periods of low flow and under the most severe rainfall conditions.

4 Implications for sustainable groundwater management

The Cheria region is facing a critical situation with acute drought and intensive exploitation, including illicit drilling, leading to both quantitative and qualitative degradation of the aquifer system, which causes the aquifer vulnerable to pollution. In response, the government has taken measures to protect the catchment areas and implement rigorous monitoring of groundwater exploitation to effectively control the depletion of aquifer storage.

To ensure the sustainability of groundwater management in the Cheria region, effective solutions include reducing water abstraction and adopting

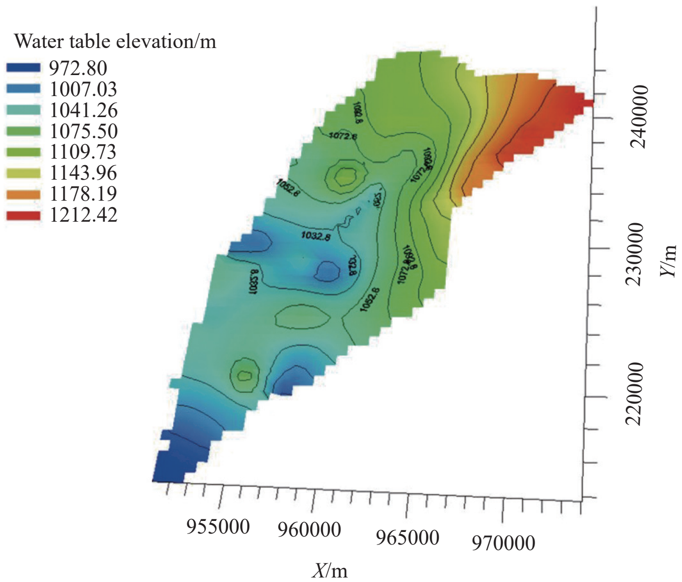


Fig. 16 Effects of artificial recharge, predictive model for 2031 assuming two recharge sites with an area of 0.5 km^2

artificial recharge approach, particularly during periods of high flooding. Compared to the scenario of pumping without recharge, the scenario of recharge from rainfall even at low levels without pumping, results in a recovery of the piezometric level. The artificial recharge scenario further improves this level. The artificial recharge using river water imported to infiltration basins in the most suitable sites, the Draa Douamis subsidence to the north of Cheria and the Eocene limestone outcrops to the south, presents an economically and ecologically viable approach for the region.

5 Model limitations and improvements

This study marks the first application of modelling applied to the Eocene aquifer in the Cheria area, allowing the development of a well-identified hydrogeological model at the surface. However, the vertical dimensions of the layer are still insufficiently known, and the hydrodynamic parameters only partially represent the Eocene limestone aquifer. To enhance the model's accuracy and reliability, future improvements and refinements should include:

(1) An appropriate geophysical study: To ascertain the vertical and lateral distribution of the aquifer formation.

(2) A test pumping campaign: To obtain a better understanding of the hydrodynamic parameters of the aquifer.

(3) Seasonal piezometric and extractive flow campaigns (the most complete): To provide comprehensive data for model calibration and validation.

(4) Consideration of hydrogeological limits such as the discontinuity of the karst environment and the subsidence process in future research.

These enhancements will enable a more precise and robust numerical model, making it a valuable tool for water resource planning and management.

6 Conclusion

In light of the water scarcity in the Cheria region, exacerbated by a semi-arid climate, overexploitation of groundwater has led to the decline of groundwater levels in recent years. To assess the potential of artificial groundwater recharge, a three-dimensional single-layer groundwater flow model (Visual MODFLOW Flex) was established to predict the changes in piezometric levels in the Cheria Eocene aquifer from 2021 to 2031. The model simulation showed that continued exploitation without recharge resulted in a significant decline in the groundwater level over time. On the other hand, natural recharge through rainwater infiltration led to a slight increase in piezometric level increased over the ten–year period. The third scenario, implementing artificial recharge from the rivers during high flood periods, demonstrated the formation of piezometric domes at selected sites, indicating a rise in the piezometric level. The results suggest that the application of such recharge systems will contribute positively to groundwater management in the Cheria area, supporting the sustainability of water resources in the region.

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