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Initial assessment of the groundwater flow and budget using Geographic Information System, MODFLOW-2005 and the FREEWAT modeling tool in Bouteldja coastal aquifer (Northern East of Algeria)

Valutazione iniziale delle caratteristiche del flusso e del bilancio dell'acquifero costiero di Bouteldja (Nord Est dell'Algeria) utilizzando sistemi informativi geografici, MODFLOW-2005 e lo strumento di modellazione FREEWAT

Harizi Khaled[a] , Menani Mohamed Reda[a], Chabour Nabil[b], Labar Sofiane[c]

[a]Laboratoire de mobilisation et de gestion des ressources en eau LMGRE; Batna II University, Algeria- email: *Khaledharizi5@gmail.com*
[b]Laboratoire de Géologie et Environnement Département des Sciences de la Terre, Faculté des Sciences de la Terre, de l'Aménagement et de la Géographie, Mentouri University, Constantine, Algeria
[c]Institute of Sciences of Nature and Life, University of El-Tarf, Algeria.

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Correspondence to:
Harizi Khaled
Khaledharizi5@gmail.com

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Parole chiave: acquifero costiero di Bouteldja, modellazione numerica, MODFLOW, FREEWAT, duomo piezometrico, ricarica delle acque sotterranee.

Riassunto

La falda acquifera costiera di Bouteldja è una delle più importanti risorse idriche sotterranee nel nord-est dell'Algeria. La regione ha un clima sub-umido con una piovosità media di 600-880 mm/a. L'acquifero non confinato è ospitato in formazioni sabbiose quaternarie. Le caratteristiche idrogeologiche presentate derivano da studi precedenti. Un afflusso molto importante ricarica l'acquifero al limite sud-orientale, in relazione a un sistema di faglie che collega la falda acquifera e la zona del lago Obeira.

Un altro afflusso al limite meridionale è da porre in relazione agli scambi con la falda acquifera alluvionale di Bouteldja. Lo scopo del presente studio è quello di fornire una prima valutazione del flusso delle acque sotterranee e del bilancio idrico di questa falda. Per raggiungere questo obiettivo, è stato sviluppato un modello numerico del flusso delle acque sotterranee utilizzando il codice MODFLOW-2005 e il software FREEWAT con i dati disponibili. Il modello è stato eseguito in condizioni stazionarie. La calibrazione è stata ottenuta utilizzando le misure piezometriche del maggio 2018 come target di calibrazione. Dopo diversi tentativi di calibrazione manuale, il modello ha simulato con successo le direzioni di deflusso delle acque sotterranee. La calibrazione mostra una buona concordanza tra conducibilità idraulica stimata e calcolata e andamenti piezometrici, tranne al limite orientale. L'analisi del budget calcolato con il modello, mostra che oltre alla ricarica meteorica, gli scambi con i corpi idrici superficiali, la falda acquifera alluvionale ed il sistema di faglie forniscono una quantità d'acqua rilevante. Questa significativa ricarica necessita di ulteriori indagini.

Questo esercizio di modellazione numerica con MODFLOW, il software FREEWAT e applicativi GIS ha raggiunto l'obiettivo di una descrizione preliminare del flusso delle acque sotterranee e rappresenta un accettabile punto di partenza per una più robusta caratterizzazione dell'acquifero costiero di Bouteldja.

Abstract

The Bouteldja coastal aquifer is one of the most important groundwater resources in North eastern of Algeria. The region is under a sub-humid climate with an average rainfall of 600-880 mm/y. The unconfined aquifer is constituted of Quaternary sands formations. The hydrogeological characteristics were determined based on previous reports. A very important inflow recharges the sandy aquifer in the Southeastern boundary, in relation to a fault network system linking the aquifer and the Obeira Lake area. Another inflow is observed at the Southern boundary in relation to the exchanges with the alluvial aquifer of Bouteldja. The purpose of the present study is to provide an initial assessment of the groundwater flow and water budget of this aquifer. To achieve this goal, a one-layer groundwater flow numerical model was developed using the MODFLOW-2005 code and the FREEWAT software, using the available data. The model was run in steady state conditions. Calibration was achieved using the piezometric measurements of May 2018 as calibration target. After several trials of manual calibrations, the model successfully simulated the groundwater flows directions and heads. Calibration efforts lead to an acceptable concordance (for the purpose of this study) between the estimated and calculated hydraulic conductivity and piezometric heads, except at the Eastern border. The analyses of the simulated inflow budget shows that aside the rainfall infiltration, exchanges with surface water bodies, the adjoining alluvial aquifer and the fault system provide a relevant amount of water. This significant recharge needs additional investigations. This numerical modeling exercise using MODFLOW, the FREEWAT software and GIS reached the objective of a preliminary description of the groundwater flow and it represents an acceptable starting point for more thorough hydrodynamic characterization of the Bouteldja coastal aquifer.

Inroduction

Groundwater is an essential resource for the supply of freshwater in many countries. It contributes half of the human drinking water supply and more than 40% of the irrigation water used for agriculture in the world (Famiglietti 2014; Alley et al. 2002). In addition, groundwater serves many environmental and natural functions, such as ensuring base flow for rivers and wetlands, and purifying soil (Knüppe et al. 2011). With increased groundwater use and climate changes impacts, water resources become more exposed to shortage and contamination, especially in coastal aquifers where groundwater is even under the risk of saline intrusion (Werner 2010, Petalas et al 2009; Sun Woo et al 2020; German et al 2017). Mainly, groundwater water resources sustainability relates to the balance between abstraction and recharge (Mays 2013). The sustainable management of the groundwater resource requires then an adequate knowledge of the aquifer system and the assessment of water inflows and outflows with regard to the geological formation and climate conditions (Dipankar et al 2018; Bayzidul et al 2017; Foster et al 2004).

Bouteldja coastal aquifer, also called the dune sand aquifer of Bouteldja, hosts one of the most important groundwater resources in the Northeast of Algeria. It is exploited for several uses by over 500 000 inhabitants of the El Tarf and Annaba provinces (Affoun 2006). Several studies mentioned the excellent quality of the groundwater of this aquifer: i) it shows Electrical Conductivity values not exceeding 400 µS/cm in large part, and ii) a high production capacity estimated at about 30 million m^3/year (Attoui 2014; Kherici 1985; Nouacer 1993; Ramdani 1996; Hani et al 2003). The aquifer has been exploited since 1970 more and more intensively to meet the various needs which are constantly increasing, leading to a drop in water levels (Hani et al 1997). Piezometric maps have been produced in the past: in October 1973, October 1982 (Kherici 1985), May and October 1988 (Nouacer 1993), October 1994 (Ramdani 1996), November 2016 (ABH 2019) and maps realized in the framework of this study. Compared to 1973 piezometric map, and assuming at that time the aquifer functioned only under natural conditions, the present morphology of the water table has changed due to its progressive exploitation. However, the basic scheme of the recharge, transit and discharge zones kept up the same form as in previous periods. In this paper we aim at characterizing the aquifer and calculating a preliminary water budget implementing a groundwater flow numerical model of the Bouteldja coastal sandy aquifer using the MODFLOW-2005 code (Harbaugh 2005) and the FREEWAT platform (Rossetto et al. 2015).

Material and Methods

After introducing the general characteristics of the study area (geographic and climatic), we describe the geological and hydrogeological characteristics in order to define the conceptual model. Further on, we describe the implementation of a one-layer groundwater flow numerical model, of Bouteldja coastal aquifer calibrated in steady state conditions. Hydraulic heads measurements from May 2018 have been used to calibrate the numerical model.

Geographic setting

The study region is located in the extreme Northeast of Algeria. It belongs administratively to the El Tarf Province and it covers an area of about 200 km² (Fig. 1). It is part of the large Mafragh catchment area (junction of El Kebir-East and Bounamoussa rivers), which includes the entire Northern side of the Medjerda River basin, extending for about 2660 km². The aquifer is situated inside the National Park of El Kala (PNEK), one of the world protected sites because of its high biodiversity values. The study area is generally composed of dune formations and is limited to the North by the Mediterranean Sea, to the South by the Alluvial Plain of Bouteldja and El Kebir-East River, to the East by the mountainous massif of the Numidian (Coursi Mounts and Cap Rosa) and, to the West, by the Mafragh River and the Mekrada wetland.

Climate characteristics

The climate of the area is sub-humid. The annual rainfall average for the period 1990- 2009 was 674 mm/year (weather station of the Salines - Fig. 1). For the same period of time the yearly minimum was 422.8 mm in 1996 and the maximum was 987.7 mm in 2004. The major rain events are not evenly distributed in the year, with most rain falling between September and May, and the summer period being almost entirely dry. The rainfall data series (Fig. 2) shows a simple moving average which indicates an increase from the beginning of 1990.The average temperature varies between 12°C during the winter period and 28°C during summer (July-August), with average annual temperatures of 18 °C. This results in having mild winters and hot dry summers (Hani 2003; Attoui 2014).

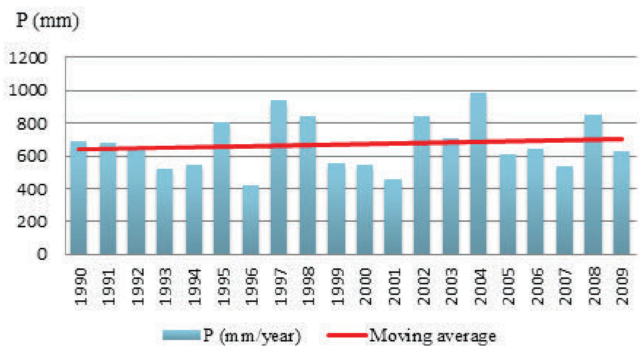

Fig. 2 -Cumulative annual rainfall for the period 1990-2009 at the Salines weather station.

Fig. 2 - Cumulata annuale delle precipitazioni per il periodo 1990-2009 alla stazione meteorologica di Salines.

Geological setting

Concerning the geological context (Fig. 3), the basin is included in the geological area of Tell, which extends from the Constantine region towards the Algerian-Tunisian borders. Several Authors studied the geology of the zone from a lithostratigraphic and structural point of view (Joleaud 1936; Hilly 1962; Vila 1980). The stratigraphy of the region

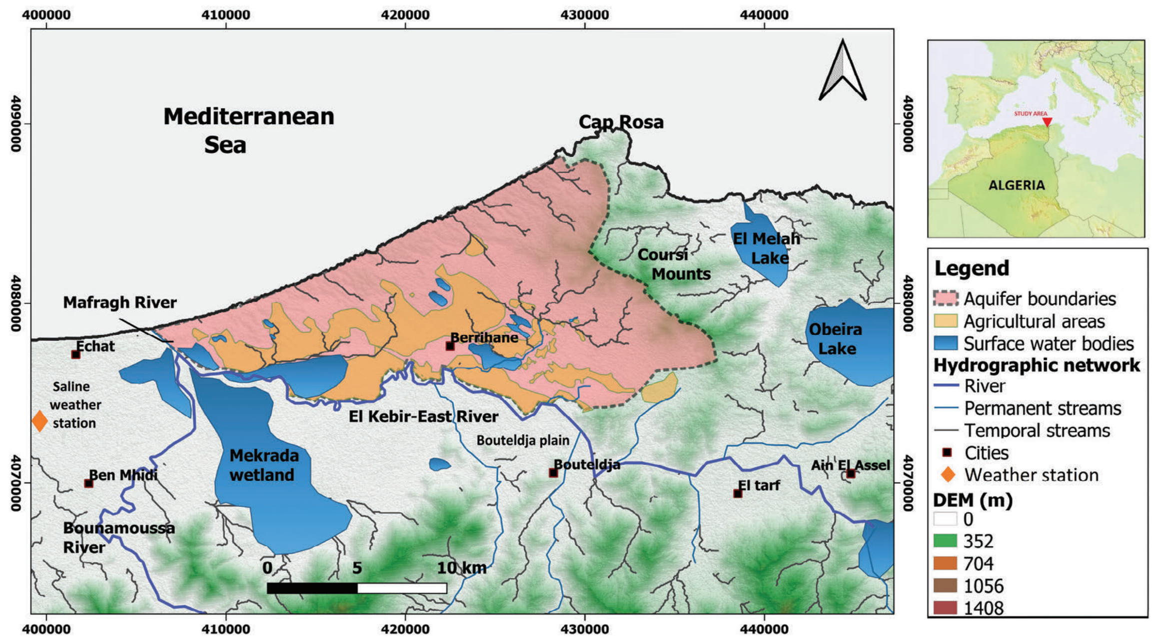

Fig. 1 - Geographical setting of the investigated area.
Fig. 1 - Assetto geografico dell'area di studio.

reveals three sets of terrains of different ages, ranging from the Secondary to the recent Quaternary:

- An Upper Cretaceous and Tertiary set: represented by the schist clay formations revealed by survey boreholes conducted nearby the study zone, and that outcrop more in the south, towards Guelma region;
- An Oligocene set, represented by the Numidian flysch that outcrops largely in the study area;
- A Miocene-Pliocene and Quaternary set constituted by the alluvial formations filling the basin of the Bouteldja and Annaba-El Tarf plains and the Quaternary sandy dunes.

Multiple orogenic and morphogenesis phenomena allowed the establishment of a horst-graben system oriented globally WSW-ENE in the north of El Kebir East River. The collapse ditches are the seats of subsidence dynamics, which permit the accumulation of a thick deposit of detrital sediments. Finally, the dune sand, composed principally by fine sands and lenses of clay, are the latest form of Quaternary deposits in this area (Fig. 4). The region presents numerous faults oriented according to two principal directions NW-SE and WSW-ESE.

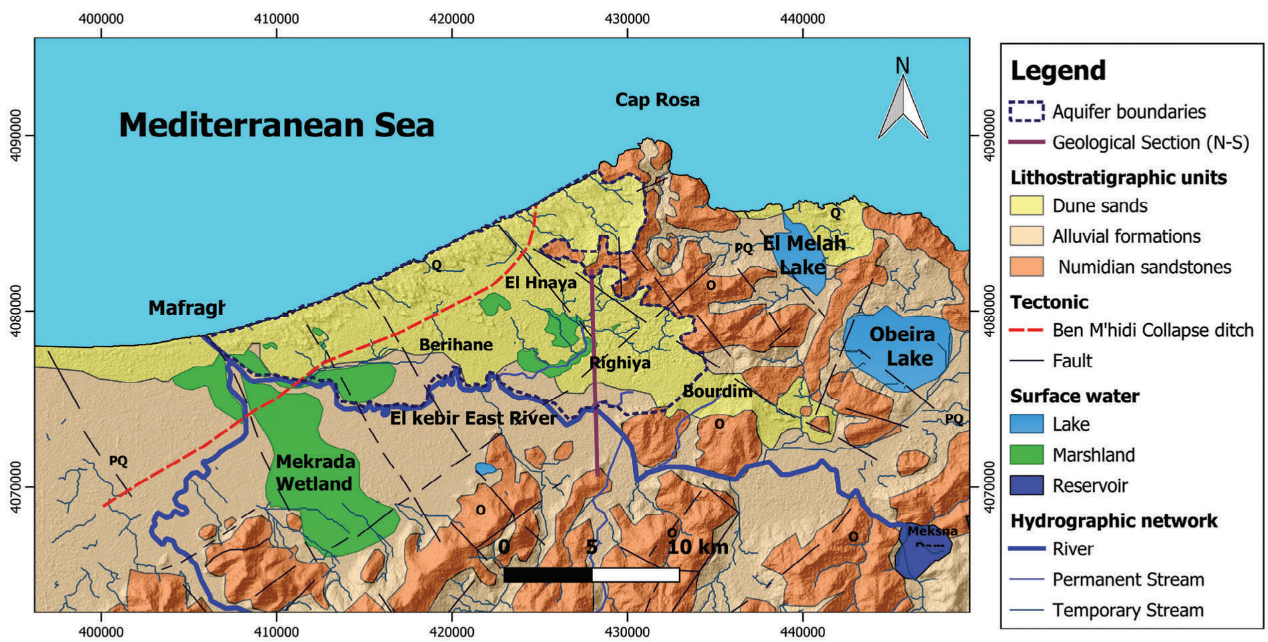

Fig. 3 - Geological setting of study area (from Vila 1980).
Fig. 3 - Assetto geologico dell'area di studio (da Vila 1980).

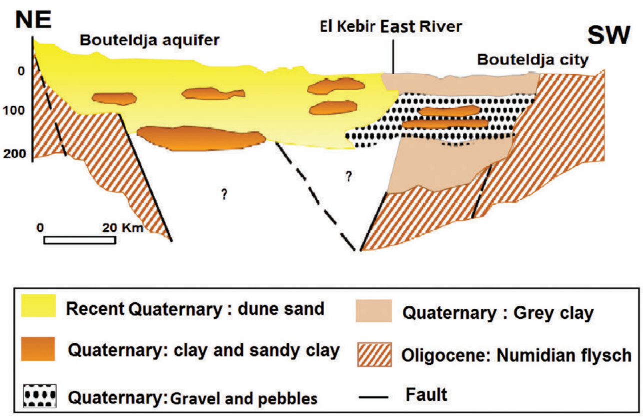

Fig. 4 - Geological cross section of Bouteldja area (from Hani 2003).

Fig. 4 - Sezione geologica dell'area di Bouteldja (da Hani 2003).

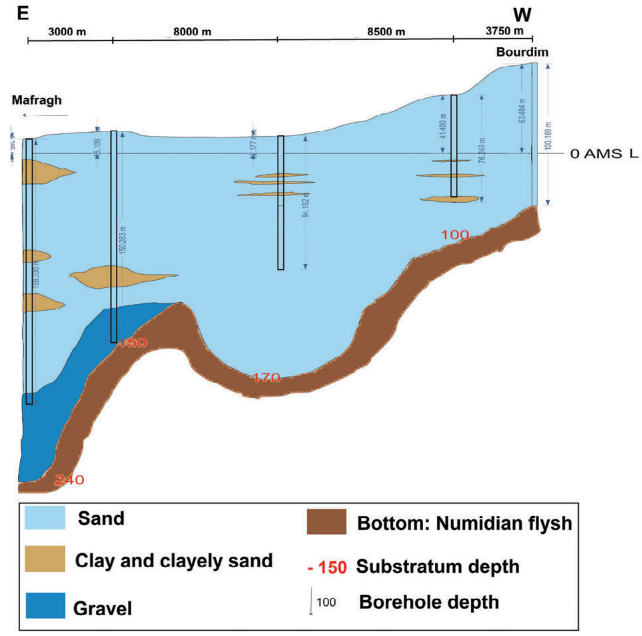

Fig. 5 - Hydrogeological cross section of the Bouteldja coastal aquifer.

Fig. 5 - Sezione idrogeologica dell'acquifero costiero di Bouteldja.

Hydrodynamics and hydrogeological characteristics. The conceptual model

The aquifer under study is mainly constituted by fine sands (Fig. 5). The dune sand aquifer reposes on Numidian flysch substratum and has a thickness that varies from 50 m in the east to more than 190 m in the west. In the central zone the aquifer thickness is relatively constant, in the order of 150 m. The geological and tectonic context constrains the hydrogeological behavior and the resulting groundwater levels and flow directions, especially in the Eastern edge of the aquifer. There, a network of faults exists, facilitating the hydraulic communication between the aquifer and Obeira Lake area. This particularity leads to the emergence of numerous springs with a permanent flow and the presence of piezometric domes in the Hnaya area (Fig. 6). To the south, another inflow comes from the alluvial aquifer of Bouteldja (Bourdim area).

Figure 6 shows the piezometric map derived from May 2018 data (produced using QGIS 2.18; QGIS development Team, 2009) based on data from Attoui (2014) and Saadali (2007). The aquifer recharge is mainly assured by the infiltration from effective precipitation as the aquifer is mainly constituted by fine sands.

In the eastern edge, all the piezometric data available show an important inflow positioned in Hnaya and Bourdim areas, marked by visible piezometric domes (Fig. 6). Previous

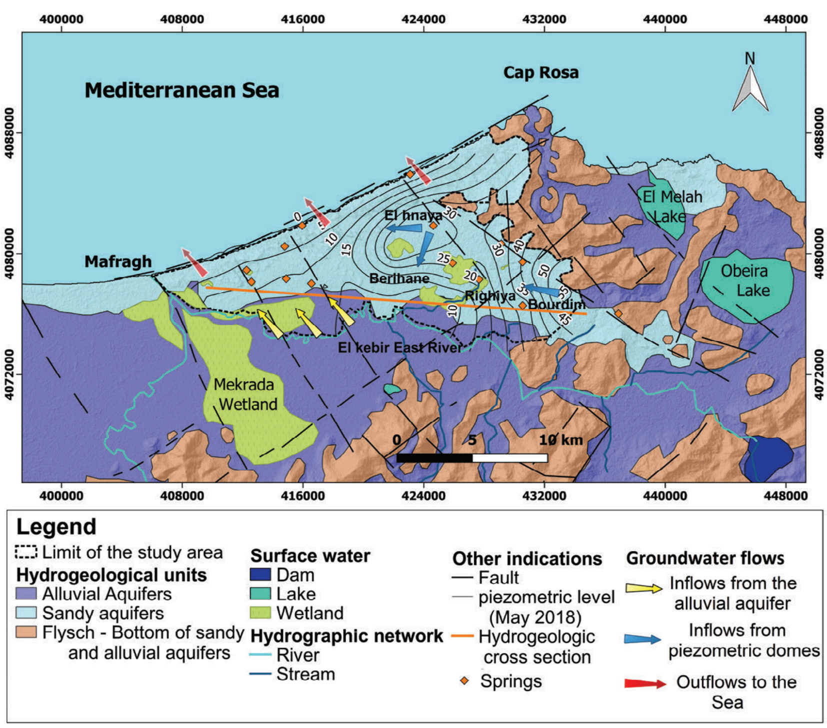

Fig. 6 - Hydrogeological sketch and piezometric lines (May 2018).

Fig. 6 - Schema idrogeologico e curve piezometriche (Maggio 2018).

studies (Kherici 1985; Ramdani 1996; Hani 2003) link this recharge directly with the infiltration of effective rainfall during the rainy season. The main water discharge zone is the Mediterranean Sea in the North, the Righia swamp and El B'haim stream in the center of the aquifer extension area.

It should be noted that the eastern boundary of the aquifer is affected by a complex fractured network, oriented, on the one hand Northeast to Southeast. This system of faults connects the sandy aquifer with the Numidian flysch. On another hand, this first set of faults is connected with a fault oriented southwest to northeast, in direction of the Obeira Lake. This second system facilitates the hydraulic connection between the aquifer and the Obeira Lake area in the Southeast. Indeed, faults can have hydraulic functions: 1) groundwater flow conduit, 2) groundwater storage due to porosity increase within the fault, and 3) barriers to groundwater flow (Bouhsine et al. 2016; De Dreuzy 1999; Rafini 2008; Kresic 2007). The spatial relation between the springs location and faults in the piezometric map (Fig. 6) permits to conclude that in the area faults act as groundwater flow conduit.

In the south, the study area is limited by El Kebir East River whose bottom reposes on grey clay formations. This limits the interaction between groundwater and surface water in this area (Fig. 4). To the southwest, an inflow coming from the Bouteldja alluvial aquifer (gravel aquifer) recharges the sandy aquifer.

The hydraulic parameters (transmissivity and hydraulic conductivity) of the dune sand aquifer were investigated in previous studies (Kherici 1985; Nouacer 1993; Ramdani 1996). Figure 7 presents the hydraulic conductivity zones produced in this work by interpolating pumping tests data performed on 27 points and reported in the work of Nouacer (1993). It shows values varying from 10^{-4} to 10^{-7} m/s. The transmissivities values vary between 3 10^{-3} and 5 10^{-3} m²/s in the Eastern part of the dune sand aquifer and between 10^{-3} and 3 10^{-3} m²/s in the central and in the north-eastern zones of the Bouteldja dune sand aquifer. The available data show that the average exploitation rate is around 20 to 25 L/s for a drawdown mainly less than 15 m; seventeen drawdown values out of a total of 27 wells are even below 10 m. The dune sand aquifer presents an average specific capacity of 2.5 10^{-3} L/s/m with a range of variation between 4.31 10^{-3} and 0.6 10^{-3} L/s/m.

Model implementation

We implemented the groundwater flow numerical model by means of the FREEWAT software (Rossetto et al. 2015; De Filippis et al. 2017; Foglia et al. 2018) using the MODFLOW-2005 code (Harbaugh 2005). FREEWAT is a free and open source platform, QGIS-integrated, allowing simulation of ground - and surface-water resources. The power of GIS program (QGIS V2.18) permits to manage a big database needed for model building in raster or vector data format. MODFLOW is one of the widest used model in the world for numerical simulation of groundwater flow in aquifers (Khadri et al 2016; Georgios 2012; El-Zehairy et al 2018). It solves the groundwater flow equation in three dimensions using a finite difference scheme. The FREEWAT software was used in many regions thorough the world for groundwater modeling; details may be found in, i.e., Positano et al. 2017; Dadaser-Celik and Celik 2018; Grodzynskyi et al. 2017; Kopač et al. 2017; Cannata et al. 2018; De Filippis et al. 2020; Joodavi et al. 2020; Rossetto et al. 2020. The implementation of the Bouteldja coastal aquifer numerical groundwater flow model is based on a robust conceptual model of the aquifer system developed from the analysis of a large database related to geology, geophysics, climate, pumping tests and hydrogeology. The extension of the modeled area identified as the active domain is composed by one layer representing the principal hydro-stratigraphic unit

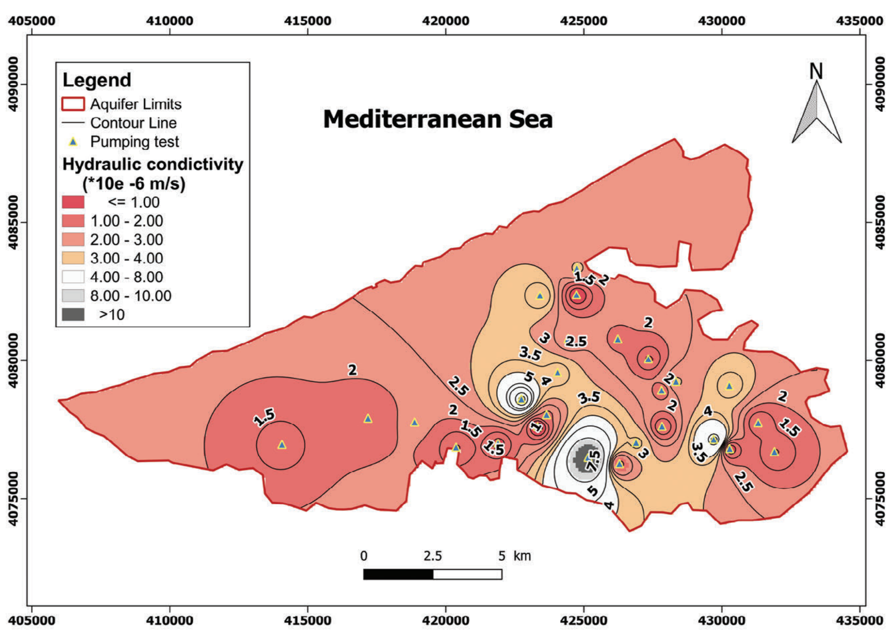

Fig. 7 - Hydraulic conductivity zones from pumping test.

Fig. 7 - Zone di conducibilità idraulica derivanti dalle prove di pompaggio.

constituted by quaternary sands. The domain was discretized horizontally in 150x150 m cells, for a total of 112 rows and 227 columns. The active field consists in 8668 cells covering a total area of 195 km² (Fig. 8). The model layer was defined as unconfined.

The implementation of a groundwater flow numerical model consists in a number of steps. In a first phase the definition of the horizontal and vertical extension of the domain to be modeled, by reconstructing the general morphology of the top and the bottom of the aquifer in each cell of the model, is performed. Building of model geometry close to reality is an important required step to expect obtaining realistic results. The use of SRTM DEM satellite image data (30 m resolution) allowed us to define the morphology of the top of the aquifer by assigning an elevation value in the center of each mesh of the model (Fig. 8) (https://earthexplorer.usgs.gov/; Karlovic et al 2021).

For the aquifer thickness and the bottom elevation, the QGIS software was used to produce the most accurate representation of the area to be modeled using interpolation techniques based on the available data of boreholes depth, the figure 9 represent the aquifer thickness model of the aquifer.

The hydraulic conductivity zones data (kx ,ky with anisotropy factor equal to 1) assigned in the model were obtained by interpolation of pumping test data (Fig. 7). These values were then modified during the calibration phase.

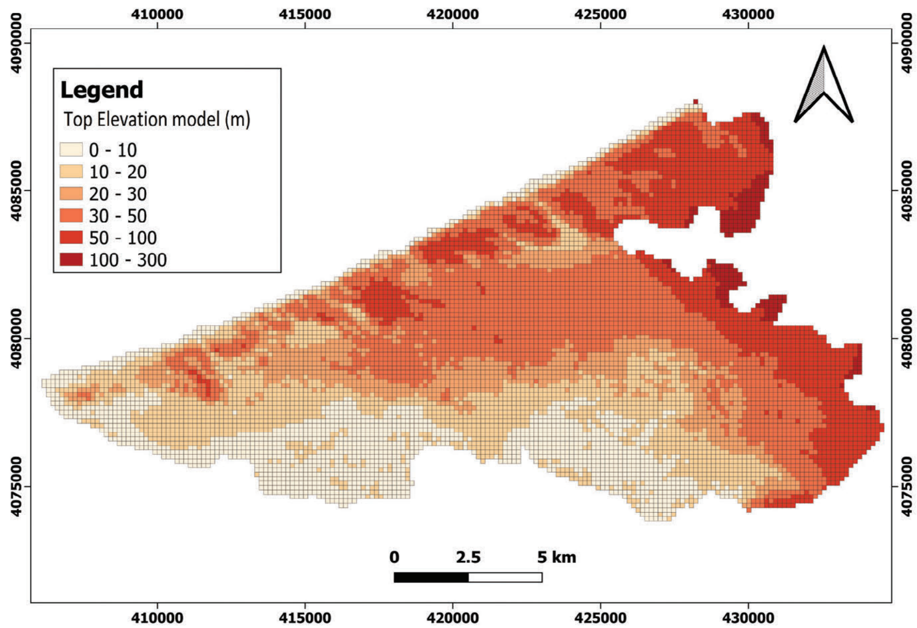

Fig. 8 - Elevation of the top of the model layer representing the aquifer.

Fig. 8 - Elevazione del tetto del model layer che rappresenta l'acquifero.

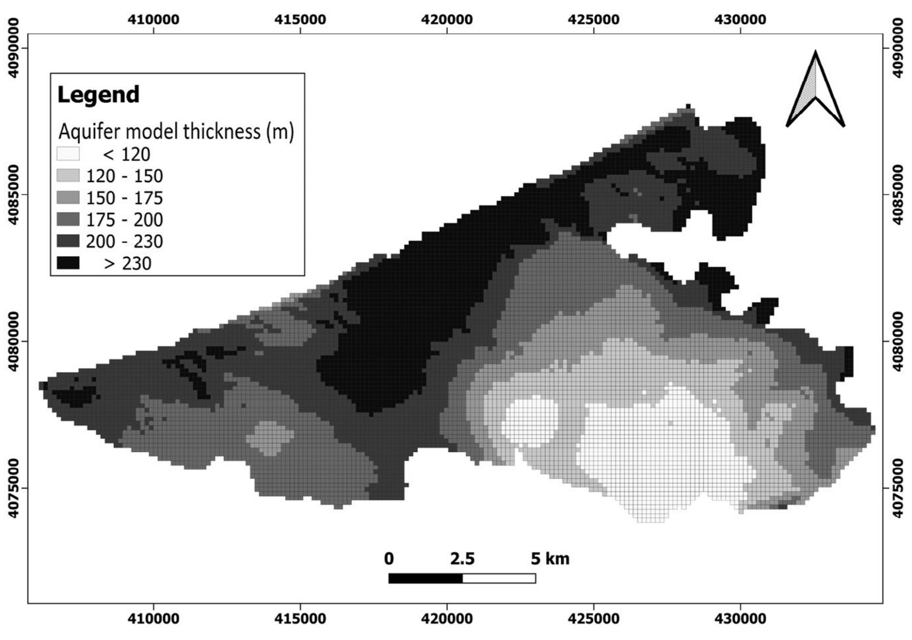

Fig. 9 - Aquifer thickness model.

Fig. 9 - Modello dello spessore dell'acquifero.

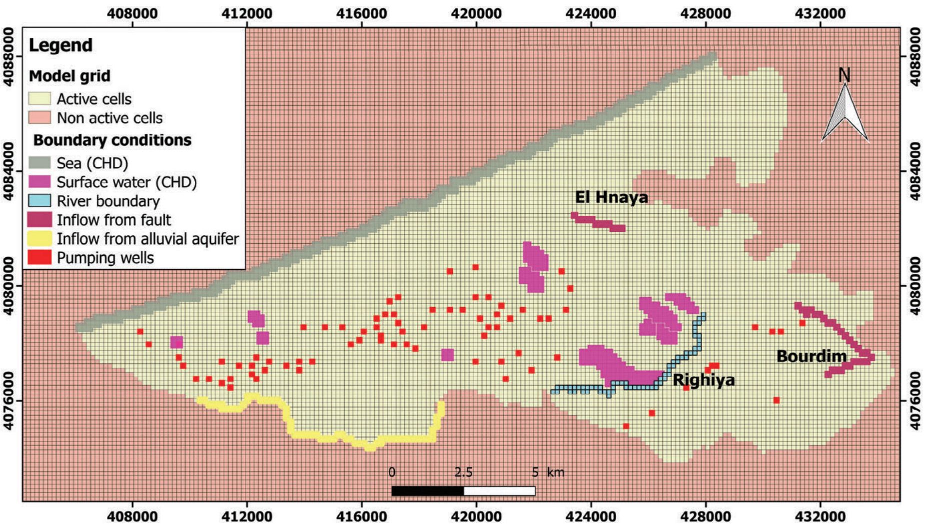

Fig. 10 - Model grid, aquifer boundary conditions, and source/sink terms.

Fig. 10 - Griglia del modello e condizioni al contorno e termini di pozzo/sorgente per l'acquifero in esame.

Aquifer Boundary conditions

The boundary conditions of an aquifer represent the different flows or head constraints at the boundaries of the investigated area. In order to represent the interactions of the modeled domain with the external system, in terms of groundwater outflows and inflows, the implemented groundwater model of Bouteldja coastal aquifer adopted the following boundary conditions (Fig. 10):

- Coastal boundary: The Bouteldja coastal aquifer discharges towards the Mediterranean Sea. From the northeastern to the western limit, a constant head condition (CHD) is applied along the coastline (0 m above mean sea level, AMSL).
- Alluvial aquifer boundary condition: To the southwest the sandy aquifer is limited by the alluvial aquifer of Bouteldja, the piezometric map (Fig. 6) shows an important groundwater inflow in this boundary. This recharge where simulated through recharge wells, applying the well package with positive flow rate.
- No-flow boundaries: All of the other boundaries and the bottom of the model are represented as no-flow boundaries.

Source/sink terms

Constant head boundary conditions: Furthermore, the area includes shallow wetlands of a total surface of about 4 km². According to Benslama 2007 all wetlands are hydraulically connected to the underlying sandy aquifer layer (Benslama 2007). The bathymetry of swamps surfaces was estimated from the DEM, at a level of 0.5 m AMSL.

River boundary conditions: The main water course in Bouteldja coastal aquifer is El B'haim stream in the Eastern part of the aquifer. The El B'haim stream originates at the foot of the Numidian flysch hills in the East. It drains waters of Tiri source as well as those of the aquifer that emerges in this sector. El B'haim stream crosses the dune zone over a distance of 3.5 km. El B'haim stream was modeled as third kind condition using the River boundary package (RIV) (Fig. 10). The river bottom elevations were extracted from the DEM. Based on our observation in the area; we estimated the river stage at 0.3 m above its bed. The hydraulic conductivity of the river bed sediments was implemented with a value of 8.64 m/day and then changed during the calibration process.

Well boundary conditions: The Bouteldja coastal aquifer is principally exploited for agricultural and domestic purposes while the industrial use is poor. According to the available data collected at the water resources directorate of El Tarf province, we estimated that groundwater pumping occurs mainly from 80 wells whose daily average pumping rates varies between 70 to 4000 m^3/day. The Well package (WELL) was used to simulate withdrawals (negative rates).

Aquifer recharge: Meteorological time series of data for the period 2017/2018 were used to estimate the aquifer recharge value using the Thornthwaite method: it was estimated to be around 206 mm/year (Thornthwaite 1948). This value was applied as constant all over the active domain. The recharge package (RCH) was used to simulate rainfall recharge. On the other hand, the hydrogeological description (Fig. 6) shows a groundwater recharge in Hnaya and Bourdim area in the East, marked by piezometric domes and a lateral inflow from the alluvial aquifer in the south. Inflows were, simulated through recharge wells, applying the well package with positive flow rate. Then, in the calibration phase the trial and error approach was used to estimate the groundwater flows.

Evapotranspiration: The Evapotranspiration package (EVT) was used to reproduce the conjunctive effects of vegetation transpiration and direct evaporation from groundwater. The EVT package requires the implementation of the following parameters (elevation of the evapotranspiration surface, maximum evapotranspiration flux, and evapotranspiration extinction depth). For the steady state model, the potential evapotranspiration used was 0.001 m/day and the extinction depth of 0.5 m, set as constant values for all active domains.

Results and discussion

The model was run in steady state. Because groundwater monitoring is not periodically run, the equilibrium state groundwater model was calibrated with static water level record of water supply boreholes. The groundwater head data collected during the period of May 2018 were used as calibration target. This period was marked by minimal exploitation and little fluctuation of groundwater level.

The model was run activating the following packages: WELL, RCH, EVT, CHD and RIV. The starting hydraulic head (STRT) was set to 25 m for each cell; this value was set according to the mean groundwater level. STRT should be at least above the BOTTOM surface of the model layer to avoid that cells are dry at the beginning of the simulation. The numerical solver used in MODFLOW was the Preconditioned Conjugate Gradient (PCG), using 100 outer interactions and 50 inner interactions.

The model was calibrated comparing measured (May 2018) and simulated hydraulic head at 25 targets. The visual comparison between the piezometric map produced with data gathered on May 2018 and the head map of the model helped the calibration process. To calibrate the model and generate an acceptable fit between measured and simulated head, the following parameters were modified: the hydraulic conductivity data (Kx, Ky), the groundwater inflow from fault in Hnaya and Bourdim area and from the alluvial aquifer, and the hydraulic parameters of the riverbed sediment. In the calibration phase the trial and error approach was used to estimate these parameters.

After successive calibration trials, the simulated values were generally close to the estimated ones obtained by pumping tests (Fig 11). Figure 12 presents measured and simulated values of the hydraulic conductivity values at the target wells. For hydraulic conductivity, the calibrated data ranged between 0.1 and 13 m/day. These data provide the main hydrodynamic characteristics of sandy formation.

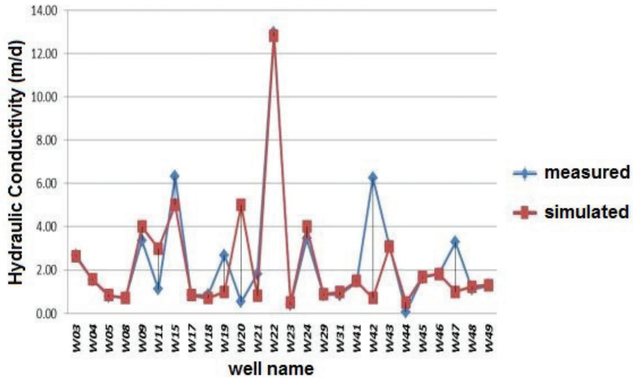

Fig. 12 - Comparison between simulated and field estimated hydraulic conductivity from pumping test. Fig.12

Fig. 12 - Confronto tra i valori di conducibilità idraulica simulati e quelli stimati nei test di pompaggio.

Figure 13 shows an overlaying of the measured piezometric map and that simulated by the MODFLOW model. It shows that the groundwater model is sufficiently representative of the aquifer system and a good relation is observed in the major part of the aquifer, except in its east to southeast border, corresponding to a recharge limit, where inflows need to be better calibrated. The diagram of the Figure 14 shows good fit between measured and simulated heads, the average residual error is 1.11 m where 60 % of measured wells marked a value between 0.1 and 0.87 m. The simulated piezometric map (Fig. 13) shows a divergence in head contour lines in Bourdim and Hnaya area and a lateral recharge in limit with the alluvial aquifer as postulated in the conceptual model.

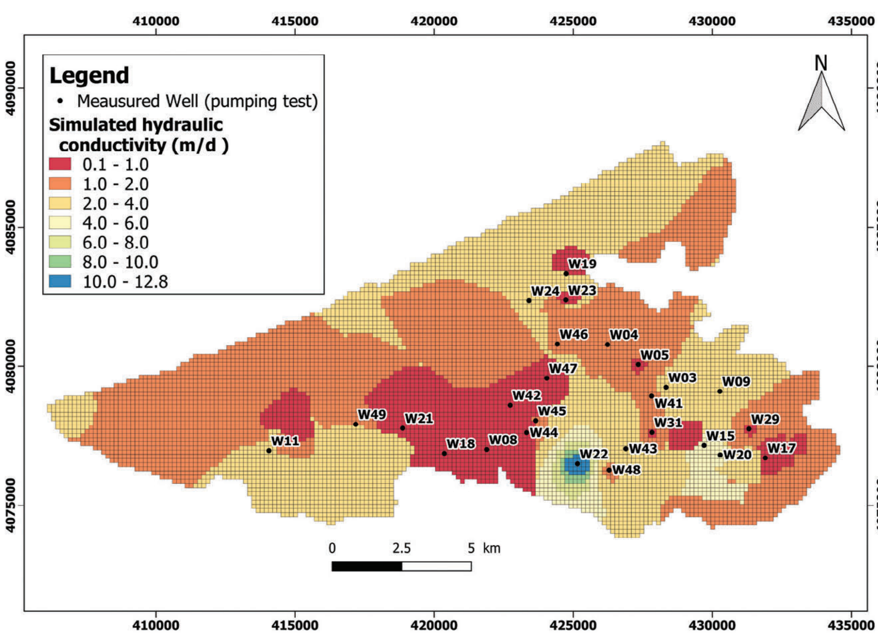

Fig. 11 - Calibrated hydraulic conductivity zones.

Fig. 11 - Zone conducibilità idraulica derivanti dal processo di calibrazione.

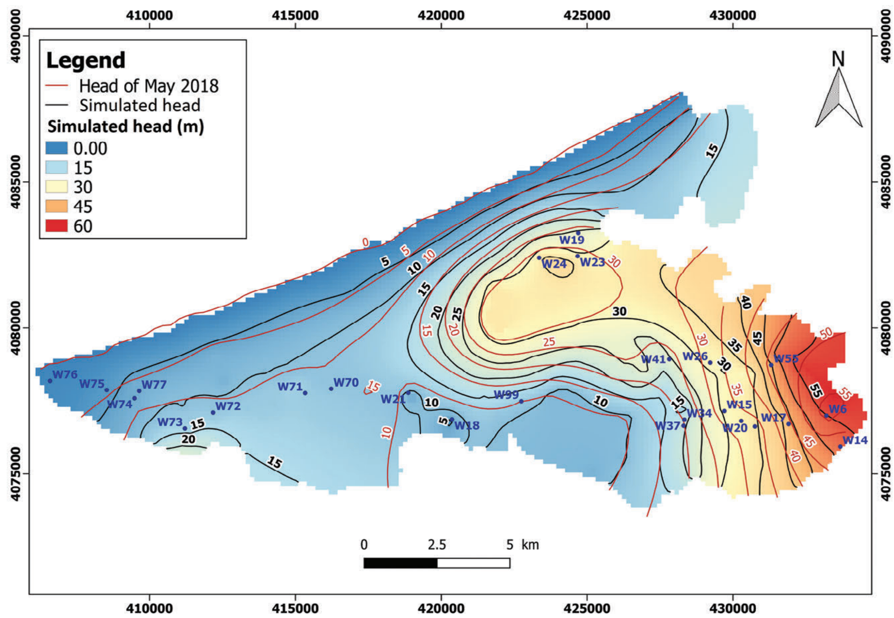

Fig. 13 - Piezometric map in May 2018 and hydraulic head simulated in steady-state Condition.

Fig. 13 - Mappa piezometrica di maggio 2018 e andamento del carico idraulico simulato in condizioni stazionarie.

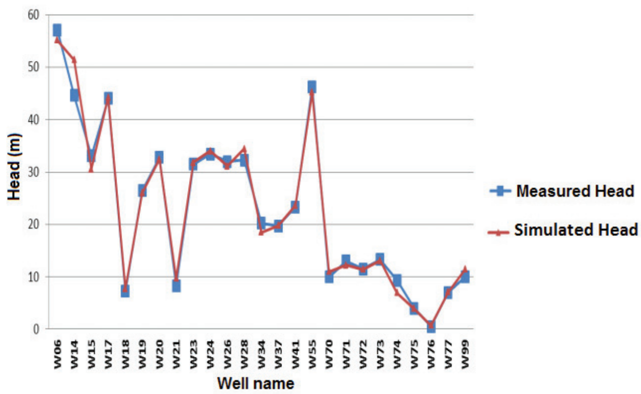

Fig. 14 - Observed vs simulated values for the hydraulic head measured in May 2018.

Fig. 14 - Valori del carico idraulico osservati rispetto a quelli simulati nel Maggio 2018.

Table 1 presents the simulated water budget. Examining the simulated CHD boundary, the implemented FREEWAT model assesses inflows at 31500 m^3/day and outflows at 98400 m^3/day, assuming that the most volumes are discharged towards the sea. The daily infiltration from precipitation was simulated at about 86900 m^3/day and the evapotranspiration at about 25200 m^3/day. Withdrawals by pumping were estimated at about 33300 m^3/day. Finally; the water budget calculated with FREEWAT software (Tab. 1), from Hnaya, Bourdim and the alluvial aquifer were estimated respectively at 20000, 13000 and 11300 m^3/day.

For the assessment of the surface- ground-water exchanges that occur in El B'haim stream, the main parameter required is the hydraulic conductivity of river bed material. The calibrated model asses a value of 0.0026 m/day, when the outflow from El B'haim stream obtained was about 5700 m^3/day. Chaffai et al 2012 suggest that the measured flow was about 13000 m^3/day. Our low rate may be due to the present over exploitation of the groundwater resource in the area for the agricultural purpose.

Conclusions

The Bouteldja coastal aquifer in the Northeast of Algeria is one of the main groundwater resources for Annaba and El Tarf provinces. A MODFLOW-2005 groundwater flow model for Bouteldja Coastal aquifer was implemented using the open source software FREEWAT and GIS (QGIS 2.18). The model was run under steady state conditions. The simulated groundwater flow is oriented toward the Mediterranean Sea along the coastline limit in agreement with the conceptual model. The recharge from adjoining groundwater bodies occurs in Hnaya and Bourdim areas (East to Southeast boundaries) and from the alluvial aquifer in the Southeast. In the center, the area is represented by depression that allows water flow towards El B'haim Stream and Righia swamps (one of the outflows of the aquifer). By using the piezometric measures of May 2018 as a reference, the calibration leads to an

Tab. 1 - Groundwater budget of the MODFLOW model.

Tab. 1 - Bilancio delle acque sotterranee dal modello MODFLOW.

Inflow (m^3/day)		Outflow (m^3/day)	
Rainfall recharge (RCH)	86914	EVT (Evapotranspiration)	25204
CHD (wetland)	31534	CHD (Sea and wetland)	98488
WELLS (GW Inflow)	44300	WELLS (water abstraction)	33366
		River Leakage	5736
Total Inflow (m^3/day)	162748	**Total Outflow (m^3/day)**	162794

acceptable fit between the measured and calculated hydraulic conductivity and heads for the purposes of this study. This is not true for the Eastern border where the inflows need to be better calibrated. The high rate of evapotranspiration, in the order of 9 million m^3/year, is explicated by the existence of numerous swamps and wetlands and by the shallow groundwater depth characterized a large area of the aquifer with a depth varies between 0.5 and 2 m).

The current withdrawals are in the order of 33000 m^3/day, which can be considered as very low compared to the abstraction rate in the past (which is about 90000 m^3/day). This numerical modeling modelling exercise using MODFLOW, the FREEWAT software and GIS reached the objective of a preliminary description of the groundwater flow and represents an acceptable starting point for more thorough hydrodynamic characterization of Bouteldja coastal aquifer.

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Competing interest

The authors declare no competing interest.

Author contributions

Conceptualization, Harizi K , Menani R and Chabour N; methodology, Harizi K ,Menani R, Labar S; software, Harizi K; validation, Harizi K and Menani R; formal analysis, Menani R and Labar S; investigation, Harizi K; data curation, Harizi K.; writing-original draft preparation, Harizi K and Menani R; writing-review and editing, Harizi K, Menani R and Labar S; visualization, Harizi K; supervision, Menani R, Chabour N, Labar S; project administration, Menani R. All authors have read and agreed to the published version of the manuscript.

Additional information

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